Increased Drought Sensitivity Results in a Declining Tree Growth of *Pinus latteri* in Northeastern Thailand

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Abstract: Climate change may lead to alterations in tree growth and carbon cycling. Interpreting the response of forest growth to climate change requires an understanding of the temporal and spatial patterns of seasonal climatic influences on the growth of tree species. However, the effects of climate change on pine forest dynamics in tropical region of Thailand remain poorly understood. This study develops three new tree ring-width chronologies of *Pinus latteri* (Tenasserim pine) in northern and northeastern Thailand and analyzes their climate-growth relationships and temporal stability. Ring-width chronologies of *P. latteri* at three sites showed significantly positive correlations with precipitation, relative humidity and self-calibrated Palmer Drought Severity Index (scPDSI) during the dry season (previous November to current April) and early rainy season (May–June). Conversely, significantly negative correlations were found between ring-width site chronologies and air temperatures (mean, maximum and minimum) from April to August. Therefore, our results revealed that radial growth of Tenasserim pines from northern and northeastern Thailand was mainly limited by moisture availability during the dry-to-wet transition season from April to June. Moving correlations revealed that Tenasserim pines in the lowland area of northeastern Thailand became more sensitive to moisture availability in recent 30 years (1985–2017) as compared with early period (1951–1984). Accompanying the shifted growth sensitivity to climate change, growth synchrony among trees was increasing and tree growth rates of Tenasserim pines have been declining during recent decades at two more moisture-limited sites in northeastern Thailand. Recent rapid warming and increasing drought during the transition season (April–June) together intensify climatic constrains on tree growth of Tenasserim pines in the lowland area of northeastern Thailand. Considering continued regional climate change, pine forests in tropical lowland areas may encounter intensified drought stresses, and thus, become more vulnerable to future climate change. Our results serve as an early indicator of potential effects of climate change on tropical pine species and raise concerns about sustainable managements of pine forests under a changing climate.

1. Introduction

Tropical forests play an important role in global carbon cycle [1]; thus understanding the dynamics of tropical forests under a changing climate is of importance [2,3]. Global warming, altered precipitation amounts and distribution and increased nitrogen deposition are influencing tree growth and may alter the future composition and functioning of forests [4–6]. Tree-ring analysis provide long-term, high-resolution tree growth data and thus represent a powerful method to evaluate effects of climate change on tree growth and forest productivity [7,8]. Furthermore, sensitivity analyses of climate-growth responses and their temporal stationarity provide an important insight for evaluating the impacts of climate change on tree growth [9].

In tropical Southeast Asia, many tree species have been identified with high dendrochronological potential [10]. In lowland tropical forests in Southeast Asia, however, analyses of tree growth variability and climate responses has mainly focused on Teak (*Tectona grandis*) [11–13], pine species (*Pinus latteri* and *Pinus kesiya*) [14–16], *Toona ciliata* [17] and *Chukrasia tabularis* [7,18]. Previous studies revealed that moisture availability during pre-monsoon season is the predominant climatic factor that controlling radial growth of tree species in tropical Southeast Asia [10,14,18]. Teak growing in Thailand [19] and in Myanmar [11,13] are mainly influenced by rainfall during the pre-monsoon season (March to May). Buckley et al. (2007) [14] found that the tree growth of *P. latteri* in Laos may be limited by light availability due to high cloud cover in summer season. Other studies show that moisture availability during pre-monsoon season determine the growth of *Fokienia hodginsii* [20] and tropical pine species (*P. latteri* and *P. kesiya*) [16].

Several tree-ring studies from Thailand investigated climate-growth relationships [12,15,21] and reconstructed past forest dynamics [22], but most of them are confined to the north and northwest regions of Thailand. Buckley et al. (1995) [12] found that pine growth in northern and northwestern Thailand is influenced by rainfall and temperature during the beginning of the wet season. Pumijumnong & Eckstein (2011) [21] developed a tree-ring network of *P. latteri* and *P. kesiya* in Northwest Thailand and found that pine growth is limited by high temperatures during the pre-monsoon (March to May) season. Pumijumnong & Wanyaphet (2006) [16] found that the cambial activity of two pine species (*P. latteri* and *P. kesiya*) started during the dry-to-wet transition season (April to May) and soil moisture was the main limiting factor in cambial activity.

Tree growth sensitivity to climate can vary over time according to the strength of climatic harshness and magnitudes of climate change [23,24]. Therefore, analyses assessing the stationarity of climate-growth responses are necessary to determine the impact of climate change on tree growth. Globally, tree growth became more limited by atmospheric water demand, while growth sensitivity to temperature decreased at cold-dry environments [25]. Reduced moisture availability in more recent decades has influence deciduous tree growth in northeast Germany [25,26]. While an increasing number of studies investigated changes in tree growth sensitivity in the temperate and boreal forests [26–28], however, such studies are rare in tropical forests [18].

Pinus latteri (Tenasserim pine) is widely distributed in Southeast Asia and is considered as one of the most important tree species with respect to the reforestation of watershed areas and forest conservation [29]. In Thailand, natural *P. latteri* forests are mainly distributed in the mountainous areas in north and west Thailand. We develop tree ring-width chronologies of Tenasserim pine at three sites from northwest to northeast Thailand and evaluate their climate-growth relationships. Our aims are (1) to investigate the dominant climatic factors that influencing radial growth of Tenasserim pine in Thailand, (2) to examine the temporal stability of climate-growth relationships of Tenasserim pine,

(3) to detect long-term growth trends of Tenasserim pine and identify potential climatic factors that driving growth variability.

## 2. Materials and Methods

2.1. Study Area and Climate

Thailand's climate is influenced by the tropical monsoon climate. The southwest monsoon brings moist air from the Indian Ocean causing abundant rainfall over the country from mid-May to October. A distinct seasonality is prevalent with a wet season (May–October), a cold-dry season (November–February) and a hot-dry season (March–April). Approximately 90% of total annual precipitation occurs during the wet season (May–October), while only about 10% of total annual precipitation occurs during the dry season (November–April). Monthly precipitation accounts less than 60 mm during the cold-dry season (November–February) and less than 100 mm during the hot-dry season (March–April).

The study was conducted in three regions in Thailand, named the Ban Watchan (BWJ), Khong Jiam (KJ) and Nong Koo (NK). The Ban Watchan site (BWJ, 19.08° N, 98.33° E, 1100 m a.s.l.) is located at a moderate slope in Watchan Royal Project Development Center in the Chiangmai province, northwestern Thailand. The Khong Jiam site (KJ, 15.44° N, 105.48° E, 170 m a.s.l.) is located at a relatively flat area in Ubon Ratchathani province, northeastern Thailand. The Nong Koo site (NK, 14.68° N, 103.76° E, 165 m a.s.l.) is located at the low land area in Surin province, northeastern Thailand. Vegetation types at the three study sites are characterized as dry Dipterocarpus forest, where *P. latteri* is associated with other dry Dipterocarpus tree species (Figure 1).
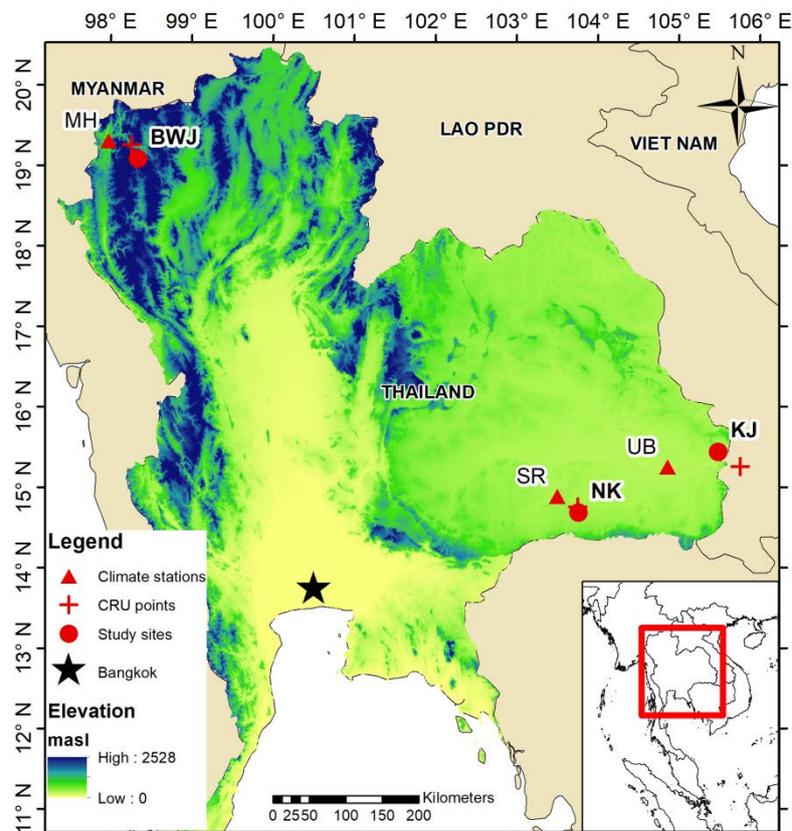
Figure 1. Map showing sampling sites of *P. latteri* (circles) at Ban Watchan (BWJ), Khong Jiam (KJ) and Nong Koo (NK), climate stations (triangles) and climatic research unit (CRU) grid points (crosses) in northwest and northeast Thailand.

Annual total precipitation recorded at Mae Hong Son (MH, 19.18° N, 97.58° E, 273 m a.s.l.), Ubon Ratchathai (UB, 15.15° N, 104.52° E, 127 m a.s.l.) and Surin (SR, 14.53° N, 103.3° E, 150 m a.s.l.) stations for the period of 1951 to 2017 are 1287 mm, 1603 mm and 1374 mm, respectively, with precipitation during monsoon season from May to October accounts for over 87% of total precipitation (Figure 2, Figure S1). Annual mean relative humidity of MH, UB and SR stations are 74.23%, 72.11% and 72.73%, respectively. Annual mean temperature at MH, UB and SR are 26.12 °C, 27.47 °C and 27.31 °C, respectively. The hottest month throughout the year is April with daily maximum temperature over 35 °C. April to June represent the transition period from hot-dry to hot-wet season.
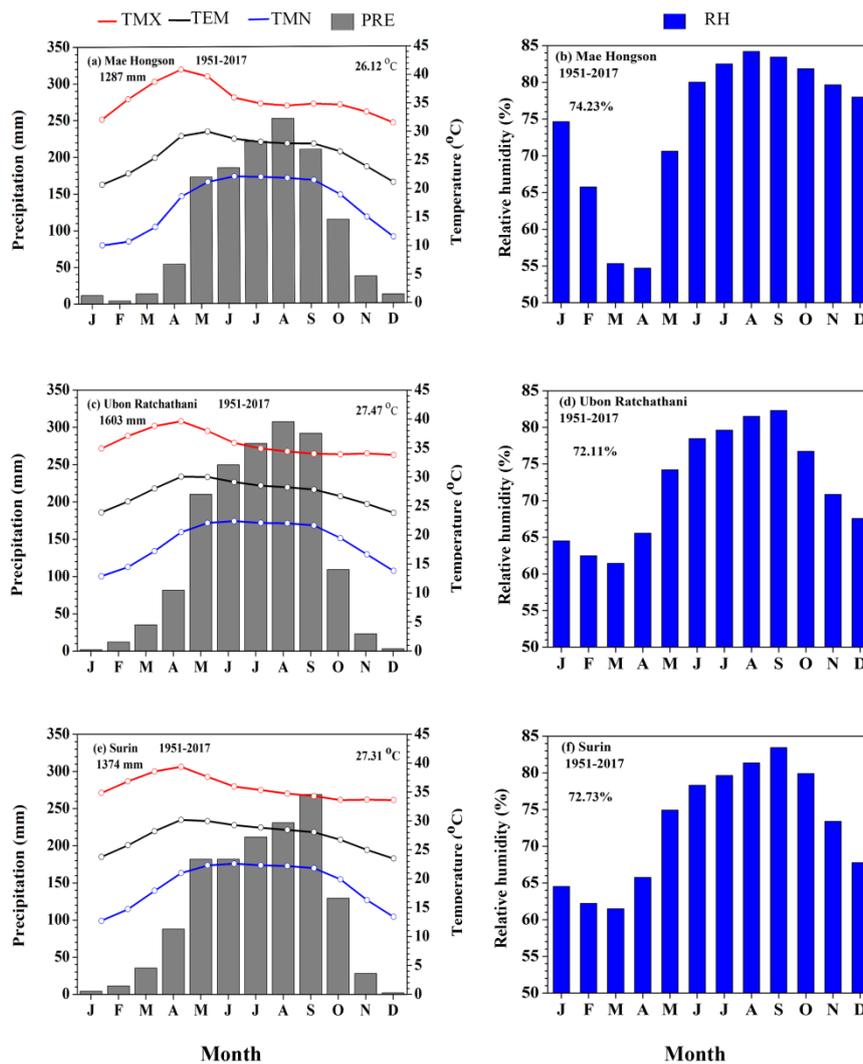
Figure 2. Climate diagrams showing monthly means of minimum (blue line), mean (black line) and maximum (red line) temperature and precipitation (grey bar) and monthly relative humidity (blue bar) between 1951–2017 at Mae Hong Son (**a**,**b**), Ubon Ratchathani (**c**,**d**) and Surin station (**e**,**f**) in Thailand. The capital letters J to D stand for the month's name, starting from January to December.

2.2. Tree-Ring Sampling and Chronology Development

Pinus latteri (Tenasserim pine) is a native species to mainland of Southeast Asia region, distributed in Myanmar, Cambodia, Vietnam, Thailand and Hainan island of China [29]. In Thailand, Tenasserim pine grows naturally in the mountains or on high land from 400–2000 m a.s.l., e.g., from the Phetchaburi province up to the Mae Hong Son province in northern Thailand [21]. Tenasserim pine can also be

found in low land from 150–200 m a.s.l. in the Surin province up to the Ubon Ratchathani province in northeastern Thailand.

Tree-ring increment cores of Tenasserim pine were sampled from three sites i.e., Ban Watchan (BWJ), Khong Jiam (KJ) and Nong Koo (NK) (Figure 1, Table S1). A total number of 32 healthy living trees of Tenasserim pine at each site were sampled at breast height using an increment borer (Table 1). Two cores per tree were taken to account for growth variability within trees. All samples were air dried then fixed on wooden sample holders with transverse axis exposed. Wood surface was polished with sanding papers of different grades until the ring boundaries are clearly visible, following standard dendrochronological techniques [30].

Table 1. Characteristics of study sites and chronology statistics calculated from the whole chronology length in the three different sites in Thailand. AGR, average radial growth rate; MSL, mean segment length; MS, mean sensitivity; AC1, first-order autocorrelation; Rbar, mean inter-series correlation; EPS, Expressed population signal. BWK: Ban Watchan site BWJ, KJ: Khong Jiam site, NK: Nong Koo site.

Site	Latitude (°N)	Longitude (°E)	Elevation (m)	Cores/Trees	Span	AGR (mm)	MSL	MS	AC1	Rbar	EPS
BWJ	19.08	98.33	1100	56/29	1646–2017	2.233	140	0.279	0.462	0.355	0.862
KJ	15.44	105.48	170	60/32	1854–2017	2.941	74	0.277	0.384	0.253	0.9
NK	14.68	103.76	165	64/31	1886–2017	2.71	63	0.312	0.385	0.359	0.95

Tree ring-width were measured under the stereomicroscope connected to the LINTAB measuring system (LINTAB[TM] 6, Rinntech, Germany) with a resolution of 0.001 mm. All the tree ring-width measurements were dated to the calendar year of their formation and cross-dated by visually matching growth patterns and statistical tests in TSAP-Win [31] and COFECHA [32]. To remove age-related growth trends, tree ring-width series were standardized to non-dimension indices while preserving growth patterns that may be related to climate variability using the program ARSTAN [33]. Prior to standardization, the variance of each series was stabilized by using the data-adaptive power transformation to reduce the heteroscedastic behavior [34]. The transformed series were detrended by applying a negative exponential curve [33]. To reduce the influence of outliers, all detrended series were averaged to develop a chronology by computing the bi-weight robust mean [30]. The variance was stabilized with the Rbar-weighted method to reduce the potential influence of decreasing sample depth [35]. The residual chronology was chosen for further growth-climate response analyses [36].

We invoked a mixed modelling approach innovated by [37] to assess the temporal variation in ring width synchrony within studied sites [37,38]. Growth synchrony (shared growth variation, $\hat{a}_c$) was calculated during 30-year moving windows with 5-year increments using the *sync.trend* function provided in the *Dendrosync* R package [38,39].

2.3. Climate-Growth Responses

Climate data (temperature, precipitation and relative humidity) were obtained from nearest meteorological stations (Mae Hong Son station (MH) nearby BWJ site, Ubon Ratchathani station (UB) nearby KJ site and Surin station (SR) nearby NK site). The self-calibrated Palmer drought severity index (scPDSI) gridded data at half-degree spatial resolution nearby our sampling sites was obtained from the global Climatic Research Unit (CRU3.25, http://crudata.uea.ac.uk/cru/data/drought/) [40]. To identify the predominant factors contributing to tree growth variability, we calculated bootstrapped Pearson's correlation coefficients between residual chronologies and monthly climatic variables over the 15-month time window starting from the previous August to current October over the period 1951–2017.

To assess the temporal stability of the climate-growth relationships, the bootstrapped correlation coefficients were calculated for 30-year moving windows lagged by two years. The stationary of climate-growth relationships were also investigated by calculating bootstrapped correlations between site chronologies and climate variables (temperature, precipitation, scPDSI) for the transition season (April to June) for two sub periods during 1951–1984 (34 years) and 1985–2017 (33 years) for the

season from April to July. All climate-growth analyses were conducted with the '*bootRes*' package in R software [41].

2.4. Long-Term Growth Trends

Ring-width measurements were converted to basal area increment (BAI) using the function bai.out in the R package dplR [42]:

$$BAI_t = \pi R_t{}^2 - \pi R_{t-1}{}^2 \tag{1}$$

where R is the tree radius and t is the year of tree-ring formation. Subsequently, BAIs was detrended using generalized additive mixed models (GAMMs) to remove the age- and size-related trends [43,44]. BAI values were log-transformed to improve the normality of their distributions. The structure of the GAMMs is as:

$$\log (BAI) \sim \log (BA) + s(Age) + (1|TreeID) + corAR1 \tag{2}$$

where BA is the basal area and TreeID is the random effect of the tree. An autoregressive term, AR1 (autoregressive order p = 1, moving average order q = 0), was added to account for temporal autocorrelation. We constructed one model for each site separately. The BAI residuals were calculated as:

$$BAI_{residuals} \sim \log (BAI_{observed}) - \log (BAI_{predicted}) \tag{3}$$

The trends of BAI residuals were assessed by linear mixed-effects models (LME) as:

$$BAI_{residuals} \sim Year + (1|TreeID) + corAR1 \tag{4}$$

According to long-term trends of climate variables at three study regions in Thailand (Figure S1) and the results of moving correlations, we found clear shifts of climate variability and climate-growth relationships at around 1980s (Table S2). Thus we investigated long-term growth trends of *P. latteri* by performing the LME models for two sub periods 1951–1984 and 1985–2017. The GAMM models were constructed with the *mgcv* [45] package and the LME models were performed with the *nlme* [46] package in R software [41].

3. Results

3.1. Tree-Ring Chronology Statistics

Descriptive statistics of *P. latteri* ring-width chronology in three sites were shown in Table 1. The average growth rate (AGR) is higher in two low elevation sites (KJ, 170 m; NK, 165 m) than that in the high elevation site (BWJ, 1100 m) (Table 1). The first-order autocorrelation values (AC1) of BWJ, KJ and NK sites were 0.462, 0.384 and 0.385, respectively. The mean sensitivity (MS) values are relatively high compared with other coniferous species in cold and humid regions. The high average inter-series correlation (Rbar) and expressed population signal (EPS) indicate reliable quality of our chronologies for dendroclimatological analysis (Table 1, Figure S2).

3.2. Growth-Climate Relationships

Correlation analyses revealed radial growth of Tenasserim pine was strongly and negatively ($p < 0.05$) correlated with maximum and mean temperatures during April–May of the current year and were consistent in all the three study sites (Figure 3). The strength of growth response to minimum temperature during April–May and during wet season (June–September) is slightly different between sites. Tree growths were also limited by high temperatures during previous dry season (i.e., previous October to December). Precipitation in the pre-monsoon season (April) in the current year showed positive relationships with tree growth at all three sites, although the correlation was not significant at NK site. Tree-ring chronologies of Tenasserim pine showed strong positive correlations with current

year relative humidity and self-calibrated Palmer drought severity index (scPDSI), thus moisture availability, across all the three sites (Figure 3).
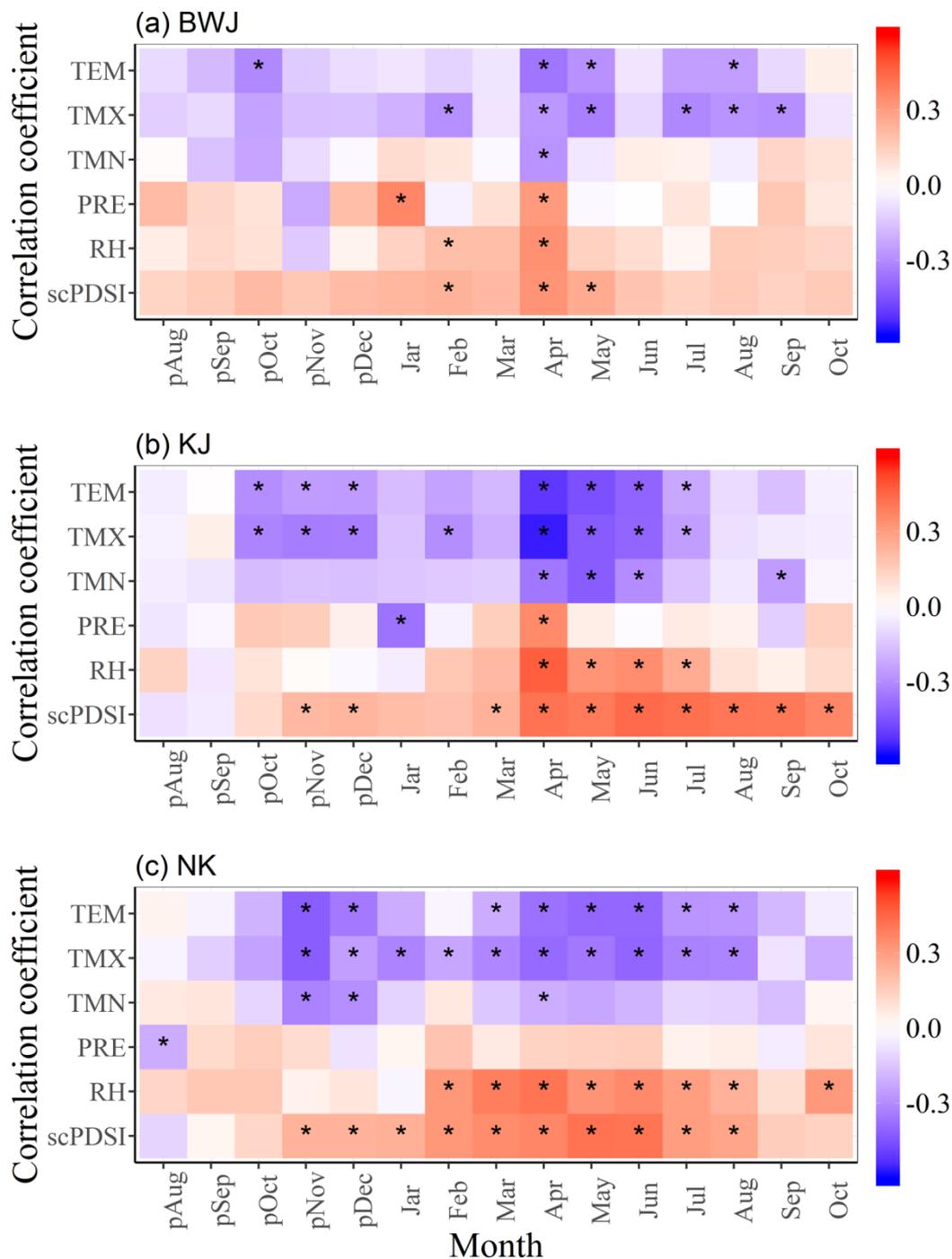
Figure 3. Correlation coefficients (bootstrapped) between tree-ring residual chronologies and climate data for the BWJ (**a**), KJ (**b**) and NK (**c**) sites in Thailand. Climate data include mean (TEM), maximum (TMX) and minimum temperature (TMN), precipitation (PRE), relative humidity (RH) and self-calibrated Palmer drought severity index (scPDSI). Correlations were calculated over the period 1951–2017 for a 15-month window from previous August to current October. Scale bars show the ranges of correlation coefficients; asterisks indicate significance at $p < 0.05$ level.

Compared with the BWJ site which located at a higher elevation, the two low elevation sites (KJ and NK) showed stronger correlations, as well as wider season windows, with temperatures (negative) and moisture availability (positive). Moving correlation analysis also showed that the radial growth of *P. latteri* at the three study sites respond negatively to temperatures but positively to precipitation and scPDSI, especially during dry season (previous November to current April) and early monsoon season (May to July) (Figure 4).
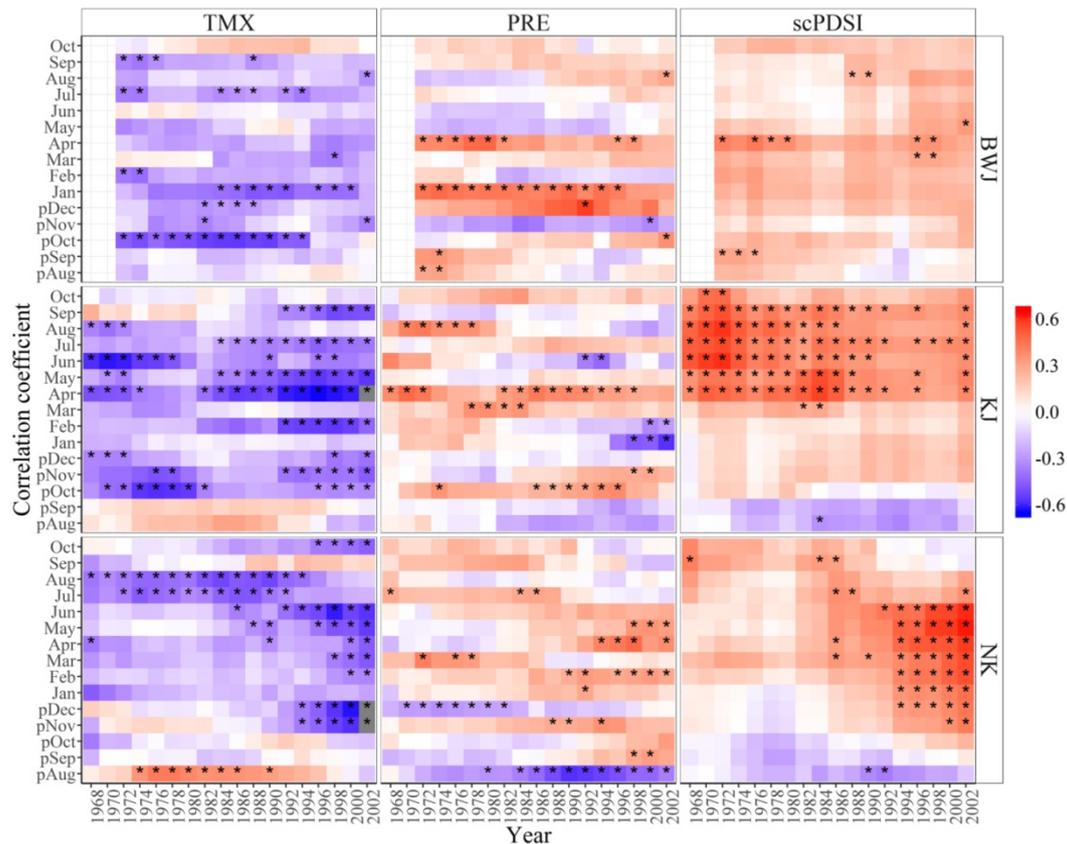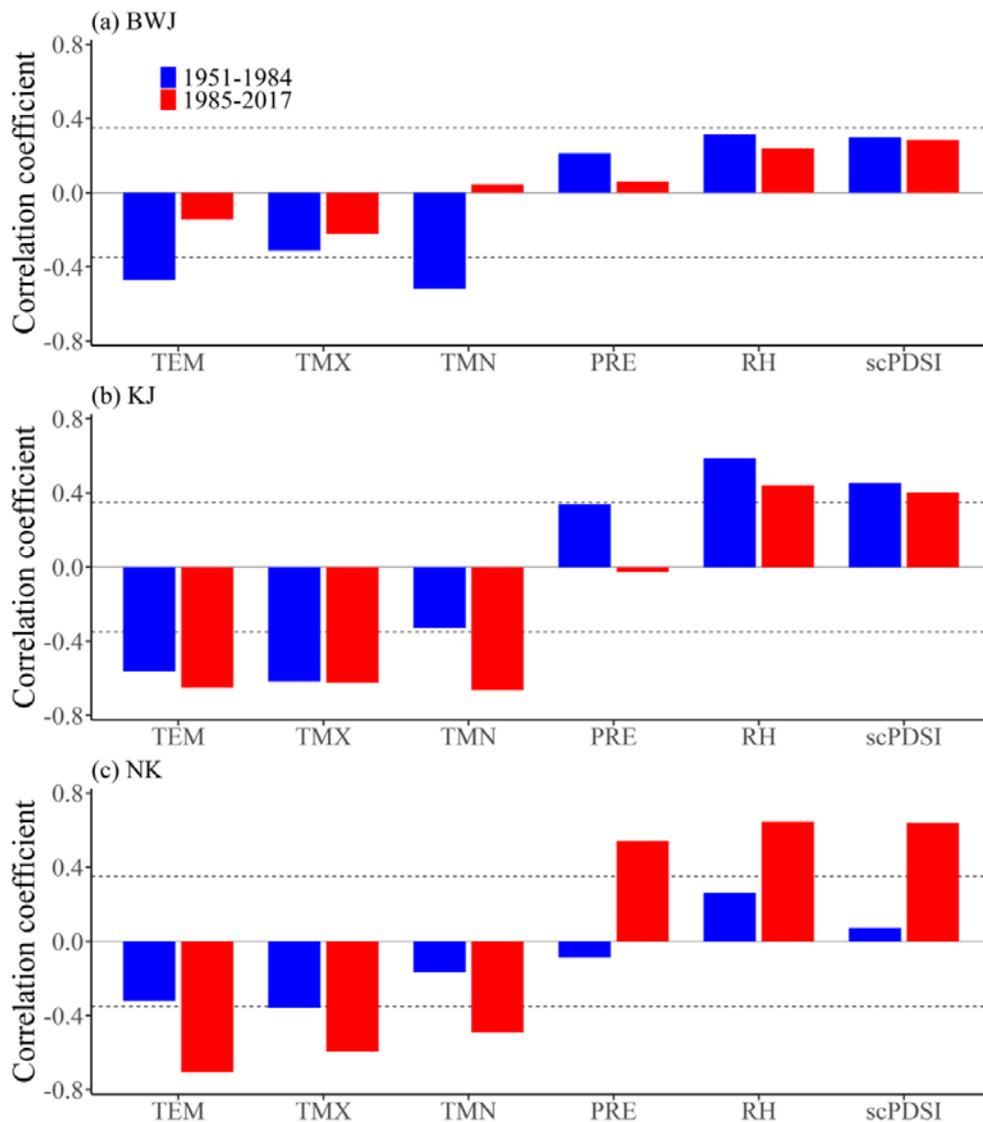

Figure 4. Moving correlations (bootstrapped) between tree-ring residual chronologies and climate data (TMX: maximum temperature, PRE: precipitation, scPDSI: self-calibrated Palmer drought severity index) for the BWJ, KJ and NK sites in Thailand. Correlations were calculated for a 30-year moving window with 2-year overlaps for the period 1951–2017. Scale bars show the ranges of correlation coefficients; asterisks indicate significance at *p* < 0.05 level.

3.3. Temporal Stability of the Climate-Growth Relationships

Moving correlation analyses was used to show the temporal stability of climate-growth relationships during the study period 1951–2017 (Figure 4). In the northern and high elevation site (BWJ), no clear temporal shifts were observed for the correlation between residual chronologies and climatic variables. However, at the northeastern and lower elevation sites (KJ and NK), the climatic drivers of tree radial growth were not stable throughout the observed period. In the KJ site, correlations with maximum temperature during early growing season (February to May) became stronger during recent decades, although the responses to precipitation and scPDSI did not show clear temporal patterns. In the NK site, tree growth showed positive correlations with precipitation and scPDSI during the early growing season (February to June); the strength of this relationship has increased since the 1980s. Meanwhile, the negative correlations between tree growth and maximum temperature during early growing season (February to June) became stronger after 1980s.

Temporal stability of climate-growth relationships was also analyzed by correlating residual chronologies and climatic variables during the pre-monsoon season (April to June) for two sub-periods,

i.e., 1951–1984 and 1985–2017 (Figure 5). In the two low-elevation (KJ and NK) sites, tree growth showed stronger negative correlations with temperatures for the early growing season (April to June) for the period 1985–2017 than for the period 1951–1984. At the NK site, the correlations between tree growth and moisture availability (precipitation, relative humidity and scPDSI) shifted from non-significant to significant during the later period of 1985–2017 (Figure 5). In BWJ site, the correlations with temperatures (TEM, TMN, TMX) was stronger during the early sub-periods (1951–1984). Thus, tree growth in the lowland area of northeastern Thailand shifted to more sensitive to moisture availability during the recent years.


Figure 5. Correlation coefficients between tree-ring residual chronologies and climate factors for the transition season from April to June for the two sub periods of 1951–1984 and 1985–2017 at three sites (BWJ, KJ and NK) in Thailand. Climate factors include mean temperature (TEM), maximum temperature (TMX), minimum temperature (TMN), precipitation (PRE), relative humidity (RH) and self-calibrated Palmer drought severity index (scPDSI).

3.4. Growth Synchrony and Long-Term Trends

Temporal variation in ring-width synchrony among trees showed an increasing trend of synchrony (shared growth variation, $\hat{a}_c$) since 1980s for the two low elevation sites (KJ and NK), indicating an

intensification of shared climatic constraints on tree growths (Figure 6). However, this phenomenon was not obvious at the high elevation site (BWJ) (Figure 6). Long-term trends were detected by applying the linear mixed-effected models on the residuals of basal area increments (BAI residuals) for the periods of 1951–1984 and 1985–2017, respectively (Figure 7, Table 2). Tree growth did not change significantly during the period 1951–1984 at BWJ and KJ site but showed a slightly increasing trend at NK site. However, during the later period 1985–2017, radial growth of Tenasserim pine showed a significant increasing trend at BWJ site in northwestern Thailand, but a significant decreasing trend at KJ and NK sites in northeastern Thailand (Figure 7, Table 2). The increasing trend at BWJ site and the decreasing trend at KJ and NK sites are also observed during recent years for the ring-width residual chronologies (Figure S2) and raw basal area increment (BAI) (Figure S3), especially the period after 1980s.
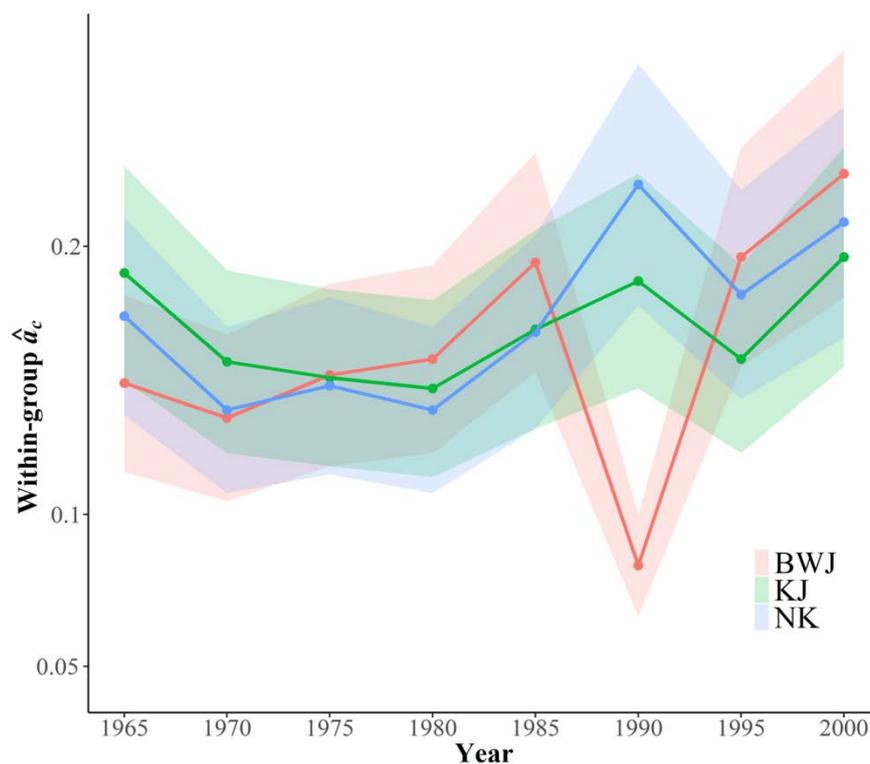
Figure 6. Temporal variation in ring-width synchrony (within-group $\hat{a}_c$) of *P. latteri* for three sites (BWJ, KJ and NK) in Thailand, estimated within 30-year windows incremented by 5 years during the period 1951–2017. The shaded areas indicate change in the standard error of synchrony.

Table 2. Summary of linear mixed-effects models for long-term trends of log-transformed BAI residuals (log BAI residuals) for the periods 1951–1984 and 1985–2017 for three study sites (BWJ, KJ, NK) in Thailand. Linear mixed-effects models were built for each period and each site, with log BAI residuals as dependent variable, year as fixed factor and individual tree as random factor. Significance at $p < 0.05$ and $p < 0.01$ levels are in italic and bold respectively. AIC: Akaike's Information Criterion.

Site	Period	Estimate	Standard Error	*df*	*t* Value	*p*	AIC
BWJ	1951–1984	0.00238	0.00151	1671	1.577	0.115	929
	1985–2017	0.00579	0.00153	1438	3.782	**<0.001**	759
KJ	1951–1984	0.00193	0.00124	1627	1.558	0.119	747
	1985–2017	−0.00585	0.0.00163	1485	−3.601	**<0.001**	1041
NK	1951–1984	0.00297	0.00146	1753	2.039	*0.042*	980
	1985–2017	−0.00516	0.00132	1652	−3.891	**<0.001**	1559
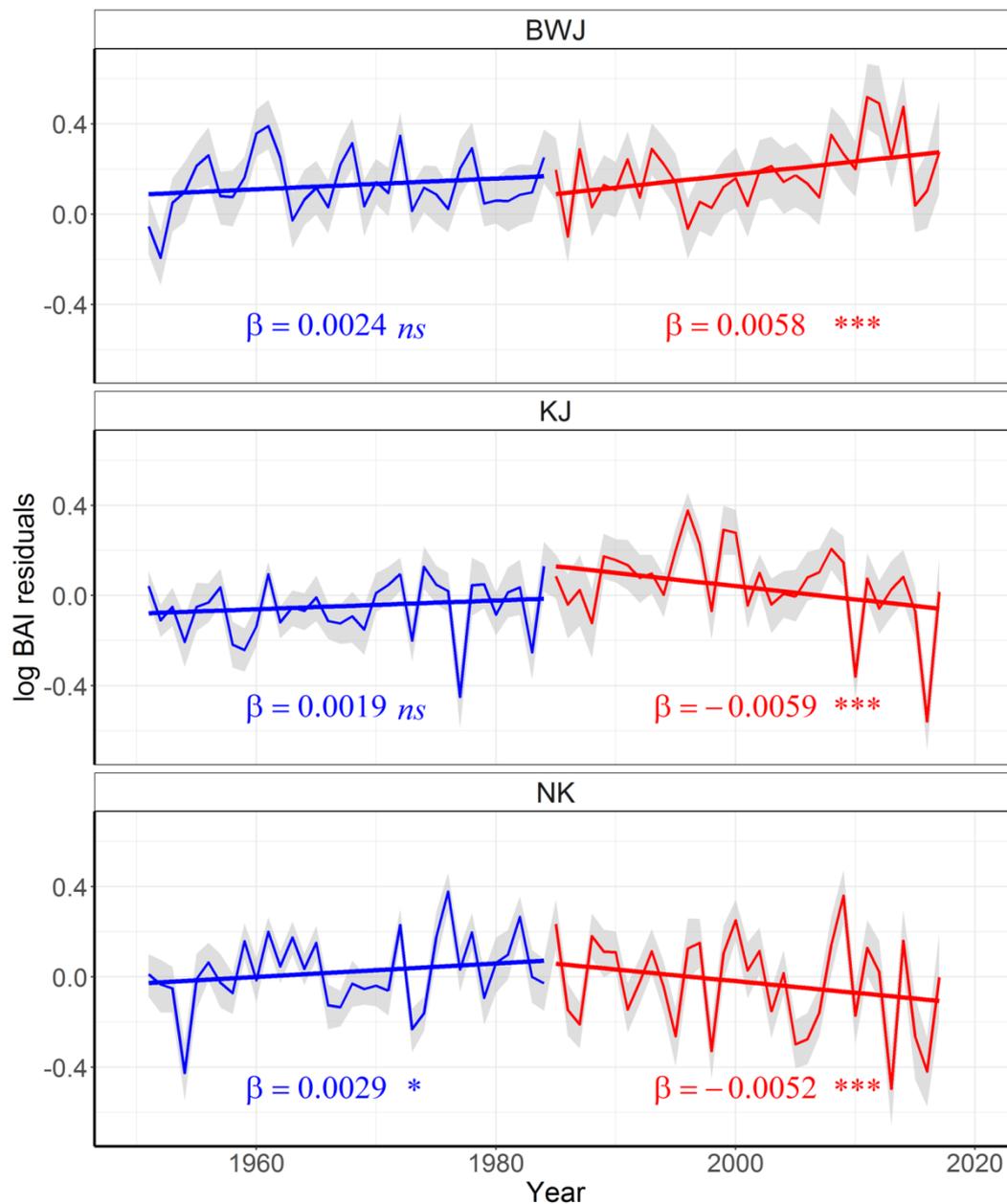
Figure 7. Long-term trends of tree growth (log BAI residuals) of *P. latteri* during the periods 1951–1984 (blue lines) and 1985–2017 (red lines) at three study sites (BWJ, KJ, NK) in Thailand. Shade area represents 95% confidence intervals. Lines represent effects of fixed effect "Year" (slope "β") and their significance as shown in Table 2.

4. Discussion

4.1. Dominant Climate-Growth Relationships

Correlation analysis revealed that radial growth of *P. latteri* in Thailand correlated negatively with temperatures but positively with precipitation, humidity and scPDSI, especially during months from April to June (Figure 3). These together suggest that moisture availability during the transition season (April- June) was the main factor that limited tree growth in all study sites. Pumijumnong & Eckstein (2011) [21] showed that radial growths of *P. kesiya* and *P. latteri* in northwestern Thailand were negatively associated with temperatures during the pre-monsoon season (March to May). Rahman

et al. (2018) [18] found that growth of a tropical tree species *Chukrasia tabularis* in Bangladesh was influenced by temperatures mainly during the early growing season. Similarly, radial growths of four tropical broad-leaved tree species in the Huai Kha Khaeng Wildlife Sanctuary in western Thailand are limited by wet-season high temperatures and dry-season precipitation [7]. During the pre-monsoon season, temperature is generally high (peak in April) in Thailand (Figure 2). High temperature enhances evapotranspiration and reduce air humidity; decreasing humidity can significantly affect surface soil moisture [47–49], which induce internal tree water deficit and limit cambium activity, thus limit radial growth of trees [50,51]. In addition, high temperatures may also lead to leaf heating beyond the optimum temperature for photosynthesis and increase photorespiration, thus reduce net photosynthesis and tree growth [2].

We observed a strong positive effect of moisture availability (precipitation, relative humidity and scPDSI) on radial growth of Tenasserim pine (Figure 3). Similarly, Hutameta & Pumijumnong (2003) [52] found a positive correlation between rainfall in March/April and tree-ring width of Tenasserim pine in northern Thailand. The cambium of Tenasserim pine became active in April–May and progressed though the rainy season up to October; radial growth of Tenasserim pines at Hung Boung area in northern Thailand depended positively on rainfall amount during the transition season (May to June) [16]. Peng et al. (2019) [53] found that tree growth of *Pinus armandii* in the in central China were negatively correlated with temperatures in May and positively correlated with precipitation in July-September. Cai et al. (2020) [54] found high temperatures during current growing season have negative impacts on tree growth of *Pinus massoniana* and *Pinus taiwanensis* at low elevations in the Dabie Mountains at subtropical China. All the above studies together with the present study indicate that the moisture availability during the transition period (April to June) strongly limits pine growth in Southeast Asian monsoon regions.

4.2. Temporal Shift of Growth-Climate Sensitivity

The responses of tree growths of Tenasserim pine to climatic variables were unstable along time. More specifically, tree growths at the low elevations sites (KJ and NK) in the lowland area of northeastern Thailand were found to be more sensitive to moisture availability during recent decades (1985–2017) compared with early decades (1951–1984) (Figure 4, Figure 5). Air temperatures at three study regions in Thailand is increasing over the recent decades, while relative humidity recorded at both Ubon Ratchathani (near KJ site) and Surin (near NK site) and precipitation at Surin station have been decreasing significantly during 1985–2017 (Figure S1, Table S2). Rapidly warming temperature together with decreasing precipitation and relative humidity may reinforce water stress on pine trees in the lowland area of Thailand. This is even more severe during the transition season (April to June) when soil moisture is still low, and evapotranspiration is very high (Figure 2). Inter-sites differences in the temporal response of the pine tree growth could be due to differential mean climate and magnitudes of the climate changes. At the high elevation site (BWJ), tree growth showed a relatively weak sensitivity to climate variables and an unclear temporal shift of growth sensitivity to climate change, which implies that the magnitudes of local climate changes at such mountainous area still not surpassed the threshold that Tenasserim pine could tolerate [55].

Changes of tree growth sensitivity to climate change has also been reported for other species and regions, such as white spruce (*Picea glauca*) in Alaska [27], *Abies alba* in northern Spain [56], red pine (*P. resinosa*) in northern Ontario, Canada [57], pine species (*P. nigra*, *P. sylvestris* and *P. uncinata*) in Iberian Peninsula [58] and European larch in the Italia Alps [24]. In the Baltic Sea region, summer moisture availability became increasingly important for the growth of oak (*Quercus robur*) and European beech (*Fagus sylvatica*) in the latter 20th century [26]. Increasing growth sensitivity to spring season moisture availability or drought conditions is becoming predominant during recent years for the *Abies spectabilis* and other conifer species in the central and western Himalaya, along with weakening responses to growing season temperatures [59–61]. Radial growth of *Fokienia hodginsii* in southwest China shows increasing responses to summer temperature (negative) and precipitation (positive) under a warming

and drying climate [62]. Rahman et al. (2018) [18] reported that radial growth of *Chukrasia tabularis* in the lowland forests in Bangladesh showed increased sensitivity to early growing season temperatures and atmospheric water demand in recent decades, probably due to a significant warming trend and an increasing dry season length.

4.3. Growth Synchrony and Long-Term Trends

The temporal variation in ring-width synchrony among trees showed an increasing trend of synchrony since 1980s for the two low elevation sites (KJ and NK) (Figure 6), which implies an intensification of shared climatic constraints on tree growths [28]. An increasing growth synchrony has also been detected in Mediterranean Spain [28], boreal Siberia [37], *Pinus pinea* in South Iberia [63], in western North American ecosystems [64] and in high-elevation sites of the Southeast Tibetan Plateau [65]. An increasing in temperature and decreasing moisture availability at the lowland area in Thailand would likely brings more severe drought stresses for Tenasserim pine and thus triggers more synchrony among trees.

Our trends analyses detected significant decreasing growth trends during recent decades (1985–2017) at two low elevation sites (KJ and NK) in northeastern Thailand and a slightly increasing trends at one high elevation site (1100 m a.s.l., BWJ) in northwestern Thailand (Figure 7). The decreasing growth trends at two low elevation sites (KJ and NK) are consistent with stronger growth synchrony (Figure 6) and increasing growth sensitivity to moisture availability found at these sites (Figure 4, Figure 5). According to trend analyses of climate data, we observed an increasing trend of temperature from all three climate stations nearby the study sites and decreasing precipitation during recent period (1985–2017) at Surin station near NK site (Figure S1, Table S2). With the increasing of air temperature and decreasing of moisture availability particularly during the early growing season, Tenasserim pine growing in the lowland areas may suffer from intensified drought stress and thus reduce their radial growth rates. However, for the high elevation area in northwestern region, Tenasserim pine may get benefit from the warming climate. Since the water supplies for the tree in this area may still sufficient, an increasing temperature may be correlate with increased photosynthesis which results in an increased tree growth.

Declines of diameter growth rates may result in a decrease in the overall forest productivity and carbon capture capacity [66,67]. Increasing moisture limitation in the lowland area of northeastern Thailand is inversely affecting productivity and carbon sequestration of pine forests [68]. Previous studies indicate that temperature induced drought condition has resulted in negative impacts on pine forest growth in different Asian regions. For example, *Pinus taiwanensis* and *Pinus massoniana* at low elevations in the Dabie Mountains in subtropical China shows negative growth trends recently [54]. Radial growth of Korean pine (*Pinus koraiensis*) on Changbai Mountain in northeast China has decreased at lower elevations under climate change characterized by warming and drought [69]. Our results are also consistent with studies from tropical tree species which showed a warming-induced growth decline [7,18]. Further investigations of growth sensitivity to climate changes and their temporal stability of other widely distributed tree species may shed more light on the productivity and dynamics of tropical forest in a climate change context.

5. Conclusions

We developed three new chronologies of *Pinus latteri* (Tenasserim pine) from northwestern and northeastern regions in Thailand and analyzed their temporal stability of climate-growth relationships. Our results revealed that tree growth of Tenasserim pine was predominantly limited by moisture availability during the transition season from April to June, with negative effects of temperatures and positive effects of precipitation and relative humidity. Under the background of rapidly increasing temperature and decreasing precipitation and relative humidity, Tenasserim pine growing in the lowland area in northeastern Thailand became more sensitive to moisture availability during recent decades. Changes in climate sensitivity might be linked to intensified (warming-induced) drought

stress under rapid changing climate in recent decades. Intensified drought stress has resulted in an increasing growth synchrony among Tenasserim pines and a declining growth trends in the lowland area in northeastern Thailand. We detected an increasing growth trend at the high elevation site in northwestern Thailand, where the Tenasserim pine trees may suffer less water stress and benefit from the warming climate. However, for long term growth analysis of Tenasserim pine in high elevation region more sampling sites are needed. Our results provide more insights into the variability of forest productivity of Tenasserim forests and raise the concerns of pine forest vulnerability in lowland Thailand under a changing climate.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/11/3/361/s1. Table S1: Means and standard deviations of diameter at breast height, tree height and tree age of *Pinus latteri* at Ban Watchan (BWJ), Khong Jiam (KJ) and Nong Koo site (NK) in Thailand. Table S2: Statistic of long-term trends of mean temperature, precipitation and self-calibrated Palmer drought severity index (scPDSI) for the transition season (April–June) for two periods (1951–1984 and 1985–2017) at Mae Hong Son, Ubon Ratchathani and Surin station in Thailand. Linear regressions were performed with climate factor as dependent variable and year as predictor. Bold values show significance at $p < 0.05$ level. Figure S1: Long-term trends of mean temperature (a), precipitation (b), relative humidity (c) and self-calibrated Palmer drought severity index (d, scPDSI) during the transition season (April to June) for the period 1951–1984 and 1985–2017 at Mae Hong Son, Ubon Ratchathani and Surin station in Thailand. Figure S2: Tree-ring width residual index (blue lines), number of cores (green dashed lines), inter-series correlation (Rbar, green dot-lines) and expressed population signal (EPS, purple dot-lines) of *Pinus latteri* during 1900–2017 at (a) Ban Watchan site (BWJ), (b) Khong Jiam site (KJ) and (c) Nong Koo site (NK) in Thailand. Grey shaded area shows the standard deviation among cores. Rbar and EPS were calculated for 30-year window with 15-year overlaps. Figure S3: Basal area increment (BAI, blue lines) chronologies of *Pinus latteri* during 1900–2017 at Ban Watchan site (BWJ), Khong Jiam site (KJ) and Nong Koo site (NK) in Thailand. Shade areas represent 95% confidence intervals; red lines are 15-year cubic splines.

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