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Detecting the Legacies of Climatic Extremes through Radial Growth Releases in *Pinus kesiya* Royle ex Gordon in Shillong, Meghalaya, Northeast India

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ABSTRACT

Tree ring width index (TRWI) of Khasi pine (*Pinus kesiya* Royle ex Gordon) was developed from Motinagar area of Shillong, Meghalaya, Northeast India, encompassing 124 years of data spanning from 1896 to 2019. The descriptive statistics (e.g., series-intercorrelation, 0.338, mean sensitivity, 0.177, standard deviation, 0.170, signal-to-noise ratio, 6.037) of TRWI indicate the significant potential of the species for dendroclimatology in the region. Moreover, the growth release detection analysis carried out using the radial-growth averaging (GA), the boundary-line (BL), and the Splechtna (SP) methods showed a large number of growth releases, with moderate growth releases of 24%, 34.6%, and 10% as detected by GA, SP, and BL methods, respectively. These detected growth releases reflected the legacy effects of recorded flood and drought events within the study area and its vicinity. High precipitation events (i.e. flood years) recorded after drought events exhibited a positive impact on tree radial growth and were observed as growth release events. For a more comprehensive understanding of the specific requirements of this species under changing climatic conditions and to contribute to the development of improved forest management strategies, it is advisable to conduct further detailed studies on growth release analysis, supported by inventory data related to forest management operations.

Keywords Tree rings, Growth releases, Legacy effect, Climate extremes, Forest management.

INTRODUCTION

Forests play a crucial role in mitigating the impact of climate change by regulating the carbon cycle and controlling regional water flow (Canadell and Raupach 2008, Ma *et al.* 2015, Upadhyay *et al.* 2021), and serve as a significant source of income, particularly for forest-dependent communities, supporting the livelihoods of millions (Blackie *et al.* 2014, Mokria *et al.* 2017, Ao *et al.* 2021). Despite significant roles played by these forests, they are facing high degree of threat due to overexploitation making them more susceptible to negative environmental conditions

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(Knoke *et al.* 2016, Ao *et al*. 2023). Further, climate change-induced alterations in the patterns of rainfall and temperatures have emerged as growing concerns (IPCC 2007, Allen *et al.* 2015) for these forests in different parts of the world. These alterations are jeopardising the ability of these forests to store carbon (Sulieman and Buchroithner 2009, Hiltner *et al.* 2016) and render ecosystem services to the society (Tripathi 2010), which further exacerbating the direct and indirect implications on forest disturbances (Seidl *et al.* 2017).

The growth of trees is influenced by various factors such as sufficient light availability, increased atmospheric CO_2 concentration, rising temperatures, and increased precipitation, which create favorable growth conditions for trees (Pretzsch *et al.* 2014). Experimental evidence has indicated that increased CO_2 concentration can have a fertilizing effect, leading to improved water use efficiency (Van der Sleen *et al.* 2015) and increased tree growth in many tropical and subtropical tree species (Ciais *et al.* 2008). However, the effects of carbon fertilization may be offset by environmental stressors like insufficient precipitation (Wagner *et al.* 2016), resulting in a net decrease in biomass accumulation (Battipaglia *et al.* 2015). Therefore, achieving sustainable management of these forests is imperative to enhance their role in hosting regional biodiversity, increasing carbon storage capacity, and improving livelihoods options to the society (Di Sacco *et al.* 2021). However, to attain this goal, it is essential to develop a profound understanding of tree growth behavior and its response to environmental and climatic changes.

Forest disturbance refers to any discrete event that occurs within a specific timeframe, leading to the disruption of ecosystem, community, or population structures, and resulting in alterations to available resources, substrate availability, or the physical environment (Pickett and White 1985). Disturbances are central to forest dynamics and shape the ecological trajectories (Wyse *et al.* 2018). Understanding disturbance history is vital for estimating regional disturbance frequencies and comprehending forest succession (Kramer *et al.* 2001). Accurate records of disturbance history are typically limited to recent events, highlighting the importance of tree-ring reconstructions for gaining insights into the long-term effects of disturbances on forest dynamics and variations in disturbance regimes (Druckenbrod *et al.* 2019, Upadhyay and Tripathi 2019, Kholdaenko *et al.* 2022). Dendroecology offers a range of techniques to detect and date past forest disturbances (Carter *et al.* 2021), which are often linked to changes in canopy structure and abiotic conditions, including climate extremes, commonly result in shifts in radial growth patterns (Nowacki and Abrams 1997). The sudden increases in radial tree growth offer a fundamental method for assessing the history of forest disturbances caused by natural or human-induced factors (Abiyu *et al.* 2018, Altman 2020). This phenomenon is known as "growth release," which is expressed by the tree favourable conditions through growth and development (Altman 2020). However, defining the scale of disturbances can be a challenging task, as growth releases vary due to various silvicultural attributes (such as tree species, age, shade tolerance and light saturation point, tree size), and spatial locations within the disturbance, as well as the severity and size of the disturbance (Lorimer and Frelich 1989, Nowacki and Abrams 1997, Wiser *et al.* 2005, Thorpe *et al.* 2007, Stan and Daniels 2014, Samonil *et al.* 2016).

This study aims to: (a) create a tree-ring width chronology for *Pinus kesiya* trees from Shillong, Meghalaya, and (b) assess the capability of the Khasi pine tree rings to capture historical extreme events as detected by growth releases.

MATERIALS AND METHODS

Study site

The study site is located in the Motinagar area of Shillong, Meghalaya (25.56°N and 91.90°E), at an average elevation of 1620 m amsl. This region has a subtropical highland climate (Köppen: Cwb), characterized by pronounced differences between summer and winter. The area experiences cool and extremely rainy summers, followed by cool and dry winters. The place is subjected to the unpredictability of the monsoon, typically starting in June and lasting until late October. The average temperature ranges from 4°C in winter to 23°C in the summer months (Fig. 1).

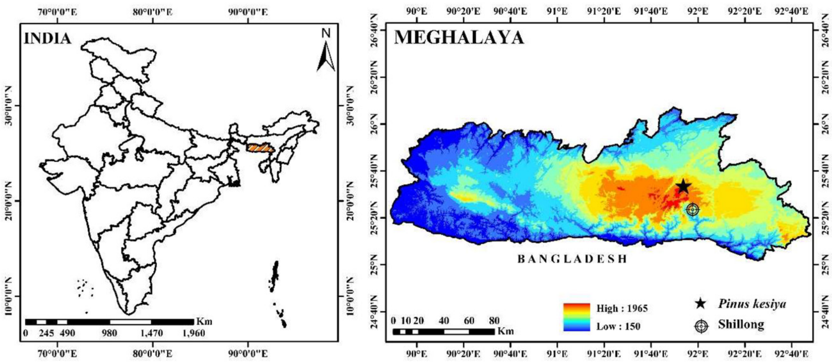

Fig. 1. Site map.

Sample collection, preparation, and measurements

Tree cores were collected from breast height (1.37m) using a Haglof increment borer, with two cores extracted per tree. These collected cores were then carefully placed in paper straws to ensure their safe transport to the laboratory. We followed the standard dendrochronological procedure to prepare the samples for the final analysis (Speer 2010). The collected cores were air-dried to prevent issues related to shrinkage. Subsequently, these air-dried cores were affixed to wooden mounts using water-based glue. To make the ring boundaries more distinct and visible under both a microscope and scanner, the samples underwent a polishing procedure involving various grades of sandpaper. The polished samples underwent scanning using a professional Epson Expression 12000XL scanner. The ring widths of each series were measured with a high precision of 0.001 mm using the WinDendro program on a computer. Each ring was meticulously counted from the pith to the bark, and precise calendar dates were assigned to individual rings using the skeleton plot cross-dating technique (Stokes and Smiley 1968). The accuracy of dating and measurement was maintained through a validation process that utilised the "COFECHA" computer program, following the methods outlined by Holmes (1983) and Grissino-Mayer (2001). Any poorly dated tree core series were either excluded or re-dated after a through review to identify and rectify potential errors. Further, we used the ARSTAN computer program (Cook 1985) to generate standardised ring-width records that eliminate age-related growth trends and stand dynamics while keeping climate-related fluctuations. Raw measurements of each series were power transformed and smoothed using a 1st Friedman super smoother and alpha curve (Friedman 1984). First-order autocorrelation was removed using autoregressive modelling. Finally, the tree ring width index was developed by averaging individual series using a robust bi-weighted mean function. The most reliable time span of the chronology was identified by subsample signal strength (SSS) criteria with a threshold value of 0.85 as recommended by Wigley *et al.* (1984).

Growth release detection

Growth release detection was done using three different techniques including (a) the radial-growth averaging method (GA, Nowacki and Abrams 1997), (b) the boundary-line method (BL; Black and Abrams 2003), and (c) the Splechtna method (SP), which combines radial growth averaging and boundary-line techniques, as presented by Splechtna *et al.* (2005).

In the radial-growth averaging method, the calculation of the percent growth change (percent GC) is based on two averages: The average radial growth over the 10-year period preceding an event (M1) and the average radial growth over the subsequent 10-year period (M2), excluding the target year. The formula for percent GC is expressed as:

$$\text{Percent GC} = [(M2 - M1) / M1] \times 100$$

This approach has the benefit of being broadly applicable even for a small number of samples, and it does not need knowledge regarding species autecology. The generality of radial-growth averaging, on the other hand, may result in both the identification of false releases and the rejection of actual releases (Black and Abrams 2003, Fraver and White 2005).

The boundary-line approach is a variant of the growth-averaging method (Lorimer and Frelich 1989, Nowacki and Abrams 1997). The boundary-line method adjusts growth release rates based on the growth rate prior to the disturbance. In the Boundary-Line (BL) method, the average radial growth over the previous ten years is computed. The BL is then created by dividing the data for previous growth into 0.5 mm segments, and the top ten values of percent growth change (%GC) are averaged within each segment. Ultimately, a curve is fitted to all the positive segment averages using a function that yields the highest R^2 value. The equation applied for the boundary line is as follows:

$$y = 5.0067\, e^{-0.664x}$$

Here, y represents the growth change in percentage, and x signifies the prior growth in millimeters.

The Splechtna approach (Splechtna *et al.* 2005) combines the concepts of growth-averaging and boundary-line procedures. Its primary aim is to employ a more meticulous approach to identify growth releases, thereby minimizing the risk of false-positive detections. In this method, potential growth releases are defined as growth pulses that surpass a 50% growth change threshold, in accordance with Nowacki and Abrams (1997). Subsequently, only these potential growth releases are scrutinized concerning the boundary line.

RESULTS AND DISCUSSION

Tree-ring width index (TRWI)

The tree-ring width index of *P. kesiya* extended from 1896 to 2019, covering a total period of 124 years. The series intercorrelation (SIC) value of 0.338 demonstrated the accuracy of cross-dating tree rings to the calendar year. The developed chronology exhibited a high mean sensitivity (MS) of 0.177, a high standard deviation (SD) of 0.170, and a low first-order autocorrelation of 0.113, and displayed promising characteristics for dendroclimatological studies (Speer 2010, Upadhyay *et al.* 2019).

The high signal-to-noise ratio (SNR) of 6.037 indicated a strong common signal, while the expressed population signal (EPS) exceeded the recommended threshold of 0.85 (Wigley *et al.* 1984), confirming agreement between the sample chronology and the population chronology. The sub-sample signal strength (SSS) crossed the recommended limit of ≥0.85 from the year 1971, indicating a reliable time span of the chronology (Table 1, Fig. 2). The TRWI statistics showed agreement with other *P. kesiya* chronologies developed from Shyrwat Reserved Forest, Short Round Protected Forest, Riat Khwan Reserved Forest, Laitkor Protected Forest, and Upper Shillong Reserved Forest of Shillong, Meghalaya (Chaudhary and Bhattacharyya 2002).

Table 1. Sampling site and RWI statistics.

Site name	Motinagar, Shillong, Meghalaya
Lat (°N)	25.56°N
Lon (°E)	91.90°E
Elevation (m)	1620
SL	Moderate
NT/NC	24/39
RWI statistics	
SIC	0.338
MSL	53.0
TS (Yrs)	1896-2019 (124)
SD	0.170
MS	0.177
AC-1	0.113
SNR	6.037
SSS	0.855 (1971)
EPS	0.858

SN = Site name, SC=Site code, Lat (°N) = Latitude in degree north, Lon (°E) = Longitude in degree East, Elev (m) = Sampling site elevation in meter, SL = Slope of the site, AS = Aspect of the sampling site, SIC = Series intercorrelation, MSL = Mean segment length, TS = Time span, NT/NC = Number of trees/number of cores, SD = Standard deviation, MS = Mean sensitivity, AC-1 = Auto-correlation of first order, SNR = Signal to noise ratio, SSS = Sub sample strength, EPS = Expressed population signal.

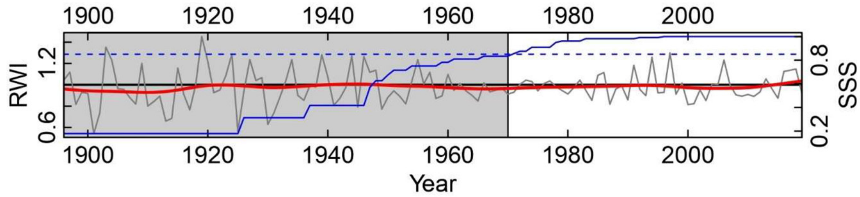

Fig. 2. Tree-ring width index (RWI) of *P. kesiya* from Meghalaya. The red curve illustrates a 10-year spline-smoothing pattern, while the blue curve represents the sub-sample strength (SSS).

Growth releases and their link with climate extremes

The analysis detected variable amount of growth releases by different methods. The GA method detected a total of 25 growth releases, out of which 24% were denoted as moderate releases. Similarly, through SP method, a total of 26 growth releases were detected out of which 35% showed moderate growth releases (Figs. 3a, b). However, maximum number of growth releases of 29 were detected through BL method with only ca. 10% showed moderate growth releases.

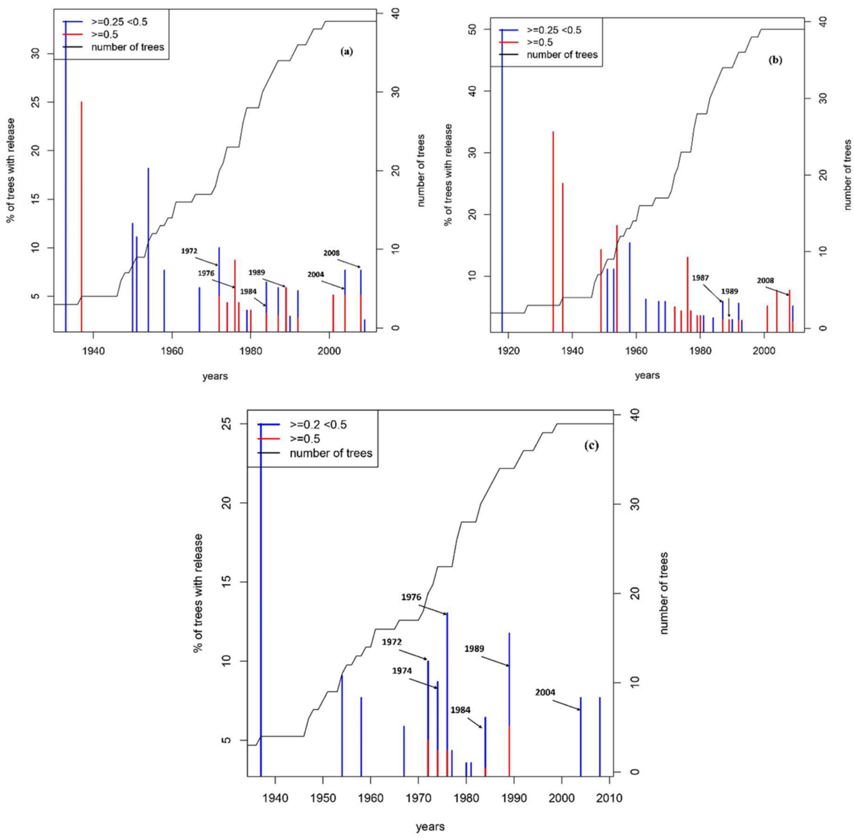

Fig. 3. Growth release events observed by (a) GA, (b) BL, and (c) SP methods. Years marked with arrow denote the moderate growth release events.

Table 2. Extreme climatic events* and their legacy on growth releases.

Moderate growth releases		High precipitation events		Drought events	
Detection method	Detection year	Meghalaya	Neighbouring region	Meghalaya	Neighbouring region
GA method	1972	1970	Manipur (1971)	1969	Manipur (1968)
SP Method			Assam (1971)		Mizoram (1968)
					Assam (1967)
SP method	1974	1973, 1974	Assam (1974)	-	Mizoram (1972)
			Manipur (1974)		Assam (1972)
					Tripura (1972)
					Manipur (1972)
GA method	1976	1974, 1975	Assam (1974)	-	Mizoram (1972)
SP Method			Manipur (1974, 1975)		Assam (1972)
					Tripura (1972)
					Manipur (1972)
GA method	1984	1982, 1984	Tripura (1984)	-	Manipur (1981)
SP Method			Manipur (1982)		Tripura (1981)
					Nagaland (1982, 1983)
BL method	1987	1986, 1987	Tripura (1984)	-	Nagaland (1985, 1986)
			Mizoram (1987)		
			Assam (1987)		
BL method	1989	1988, 1989	Tripura (1988, 1989)	-	Assam (2001, 2002)
-					
SP Method					
GA method	2004	2002, 2003, 2004			Manipur (2004)
SP Method					Tripura (2004)
GA method	2008	-	Manipur (2007, 2008)	2006	Assam (2006)
					Manipur (2006)
BL method			Mizoram (2008)		Nagaland (2006)
					Tripura (2006)

* Extreme climatic events data source: Kumre *et al.* (2020) and Bora *et al.* (2021).

This method showed unbalanced results because of expressing a greater number of growth releases with smaller number of moderate growth releases (Fig. 3c). This observation is consistent with findings of Müllerová *et al*. (2016) in oaks growing in the Bohemian Karst PLA, Czech Republic.

Further, the moderate growth releases observed in this study were compared with the extreme events reported in Meghalaya and neighbouring states (Table 2). It was found that the detected growth releases observed just after the high precipitation events occurred in previous years as well as in the current year. Interestingly, these high precipitation events coincided with the drought events reported in Meghalaya and neighboring states around the same years. In Northeast India, the Khasi pine typically undergoes three growth flushes, resulting in the development of three whorls of branches annually. Further, xylem production takes place over an extended growing season, spanning from mid-March until the last week of November, with a period of dormancy observed from December to February (Singh and Venugopal 2011). Many researchers from India and the neighbouring southeast Asian region have reported that the radial growth in *P. kesiya* is mainly governed by precipitation and soil moisture, and mainly moisture favors the growth of the species in the early and later parts of the growth season (Pumijumnong and Wanyaphet 2006, Shah and Bhattacharya 2012, Upadhyay 2019, Pumijumnong *et al.* 2021). Further, Thomte *et al.* (2022) reported a legacy effect of previous year October-December precipitation on radial stem growth of the current year in *P. kesiya* from the West Karbi Anglong region of Assam, northeast India, a neighbouring state of Meghalaya. Therefore, the sudden increase in radial growth following high precipitation events, often in the wake of drought occurrences, underscores the critical role of moisture in creating optimal growth conditions for this species. These results highlight the legacy effect of high precipitation events (flood) on consecutive growth releases in *P. kesiya* in Meghalaya, Northeast India.

CONCLUSION

This study underscores the potential of *P. kesiya* as a valuable tree species for comprehending the impact of climate variability on forest tree growth and development in the region. Descriptive statistics of Tree ring width index (TRWI) indicate that the growth of *P. kesiya* at the study site is primarily influenced by common environmental factors. Moreover, the analysis of growth releases in this species reveals a clear connection between extreme climatic disturbances, such as high precipitation and droughts, and the years when significant growth releases occur. Notably, high precipitation events, observed after drought events, exhibit a lasting effect on the radial growth of *P. kesiya,* often leading to growth releases in the species. These results could be further validated with supporting data from forest silvicultural operations, which will aid in comprehending the specific requirements of this species under changing climatic conditions and contribute to the development of improved forest management practices in the region.

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