

Tree Ring Analysis of Mexican Weeping Pine (*Pinus patula* Schiede ex Schltdl. and Cham.) from Nagaland, Northeast India

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ABSTRACT

In this study, tree ring analysis of Mexican weeping pine (*P. patula*) from Kohima Botanical Garden of Nagaland, Northeast India was carried out. Tree ring-width chronology for 39 years extending from 1983 to 2021 was developed. The developed chronology exhibited high potential of the species for dendro-climatological studies and to understand the tree growth patterns in relation to changing climate. The ring-width chronology indicated occurrence of common event years mostly related to the drought records in the region. Further, the resilience component analysis demonstrated low resistance of the species to extreme event years, particularly drought, as indicated by significant reduction in growth and recovery rate. In conclusion, the tree growth and development in the region were severely impacted by moisture deficit events, and therefore, future policy formulation needs to be developed considering water

management plans for climate resilient forestry and agriculture in the region.

Keywords Tree rings, Event years, Climate variability, Resilience component analysis, Forest management.

INTRODUCTION

Climate change phenomena, particularly changing patterns of precipitation and temperature have been reported to noticeably altering the structure and functioning of forest ecosystems (Lindner *et al.* 2014, Upadhyay *et al.* 2019a, Kholdaenko *et al.* 2022). On one hand, such changes are directly affecting the regeneration of vegetation by enhanced mortality of species in different regions of the world (Breshears *et al.* 2005, Lutz and Halpern 2006, van Mantgem and Stephenson 2007, van Mantgem *et al.* 2009). On other hand, they are indirectly affecting the functioning of forest ecosystems by increased intensity, extent, and frequency of forest disturbance events such as drought, heavy rain and extreme warm or cold conditions (McKenzie *et al.* 2004, Gedalof *et al.* 2005, Hicke *et al.* 2006, Littell *et al.* 2009). Interesting to that extreme events such as severe droughts wield a more pronounced influence on ecosystem reactions than gradual alterations in average climatic conditions, such as gradual rise in air temperature (Reyer *et al.* 2013). An illustrative case highlighting this phenomenon has considerable reduction in net prima-

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ry productivity in the Europe following the extreme drought of the year 2003 (Ciais *et al.* 2005). Retrospective studies employing tree-ring analysis prove to be a valuable tool to comprehensively understand how trees might navigate the projected shifts in average climate alongside the anticipated escalation in both the frequency and intensity of climatic extremes (Babst *et al.* 2012, Upadhyay and Tripathi 2019). Such studies provide insights into how trees have historically responded to varying climate conditions.

In the traditional landscape of tree-ring studies, the focus has been on exploring the long-term relationships between tree growth and climate parameters, achieved through methods like correlation or response function analyses (Upadhyay *et al.* 2021, Babushkina *et al.* 2021). However, these analyses tend to uncover only average connections between tree growth and climate factors, often neglecting the infrequent and time-dependent growth-limiting factors experienced during extreme events (Lebourgeois *et al.* 2010). Consequently, an alternative method known as “pointer-year” analysis has gained traction in recent years. This approach delves into exceptional tree-growth responses and has shown that extreme tree rings can act as ecological indicators, offering quantitative insights into how trees react to extreme events (Desplanque *et al.* 1999, Weber *et al.* 2013, Upadhyay *et al.* 2019b). Within the framework of pointer-year analysis, “event years” are those that witness remarkable growth increases or reductions at the individual-tree level, while “pointer years” represent years marked by extraordinary growth responses at the stand level (Schweingruber *et al.* 1990).

Current climate models predict heightened variability in climate patterns, foretelling an increase in the frequency and intensity of extreme occurrences such as droughts, heavy rainfall, and extreme warm or cold events (IPCC 2007). The intensified frequency and/or heightened intensity of these stress-inducing events possess the capacity to push ecosystems beyond biological thresholds, which may result in unconventional responses and shifts within ecosystems (Scheffer *et al.* 2001, Folke *et al.* 2004). Such shifts vary between ecosystems and trees, and thus, their ability bounce back to normal conditions called “resilience”. Resilience is broadly defined as the ability

of the ecosystem or tree to rebound post-disturbance and regain its pre-disturbance structure and function that hinges on several factors. Analyzing shifts in resilience provides a means to comprehend the cumulative effects of recurrent stressful incidents like the frequency and intensity of past disturbances, which in turn affect the abiotic environment, life cycles, and physiological performance of organisms (Sousa 1984, Runkle 1985, Zedler *et al.* 1983).

The resilience analysis typically requires quantitative assessments that involves comparison of states before and after disturbance event. Alternatively, it can be based on assessing how the values of indicator variables in disturbed ecosystems approach those of undisturbed as control systems (Herbert *et al.* 1999, Orwin and Wardle 2004, DeClerck *et al.* 2006, Griffiths *et al.* 2000, Wardle *et al.* 2000, Lindberg and Bengtsson 2006, Bee *et al.* 2007). However, a potential limitation with these estimates lies in their failure to fully account for the impact inflicted by the disturbance itself that may potentially be leading to an underestimation of resilience in heavily affected ecosystems (DeClerck *et al.* 2006).

At an individual level, post-disturbance recovery is often influenced by a combination of stochastic external factors, such as competition and neighbour mortality, intrinsic factors, including physiological and genetic factors, as well as microsite conditions. For instance, intrinsic factors like individual age or size may induce either positive or negative responses to disturbances (Lloret *et al.* 2004, Mueller *et al.* 2005, Kolb *et al.* 2007, Zhirnova *et al.* 2022). If intrinsic or microsite factors play a dominant role, there should be a positive correlation between performance of an individual pre- and post-disturbance event. This intricate interplay between various factors highlights the complexity of post-disturbance recovery dynamics.

The recent surge in instances of drought-related die-back and forest mortality on a global scale is a concerning trend (Allen *et al.* 2010). This surge has been attributed to the mounting temperatures and associated drought conditions (van Mantgem *et al.* 2009). Interestingly, this trend might signify these uncharacteristic responses of ecosystems to these stressors. Accumulating evidence suggests

that drought events can trigger significant ecophysiological memory effects and delayed tree mortality (Peñuelas *et al.* 2000 Galiano *et al.* 2011, Bigler *et al.* 2006, 2007, McDowell *et al.* 2010). Nonetheless, our understanding of the extent to which these uncharacteristic responses are linked to the cumulative impact of recurrent drought events remains relatively limited (Lloret *et al.* 2004, Bigler *et al.* 2007). This becomes particularly crucial considering that the effect of repeated stressful incidents at the individual level is yet to be thoroughly documented.

In forest ecosystems, recurring episodes of extreme low growth are viewed as disturbance events due to their cyclical occurrence and potential to bring about significant changes in forest structure. While community-level resilience has been correlated with factors like diversity and resource availability, the impact of these repetitive low-growth periods on individual-level ER has received limited attention. More frequent disturbances are anticipated to erode tree resilience, leading to environmental changes and depleting individual resources needed to endure and recover from stressful periods. Empirical evidence supports this hypothesis, illustrating instances of slow forest-canopy recovery or shifts in community

structure following increased fire frequency and the cumulative effects of successive disturbances (Díaz-Delgado *et al.* 2002, Zedler *et al.* 1983, Payette and Delwaide 2003).

To comprehend the complex mechanisms that underlie these patterns of resilience, researchers have disentangled resilience into various constituent elements. These elements encompass resistance, recovery, resilience, and relative resilience. This study hypothesizes dendroclimatological potential of *Pinus patula* and its ability to adapt under extreme environmental conditions in hilly states of Nagaland, Northeast India. The present study was conducted i) to investigate the dendroclimatological potential of *Pinus patula* from new provenance in Nagaland, India, ii) to assess the ability of tree species in capturing the extreme climatic events, and iii) to understand the response of tree species to such extreme climatic conditions.

MATERIALS AND METHODS

Study site

The study site is located in the Kohima Botanical Garden of Nagaland (25.65°N and 94.10°E) at an average elevation of 1638 m (Fig.1, Table 1). The area

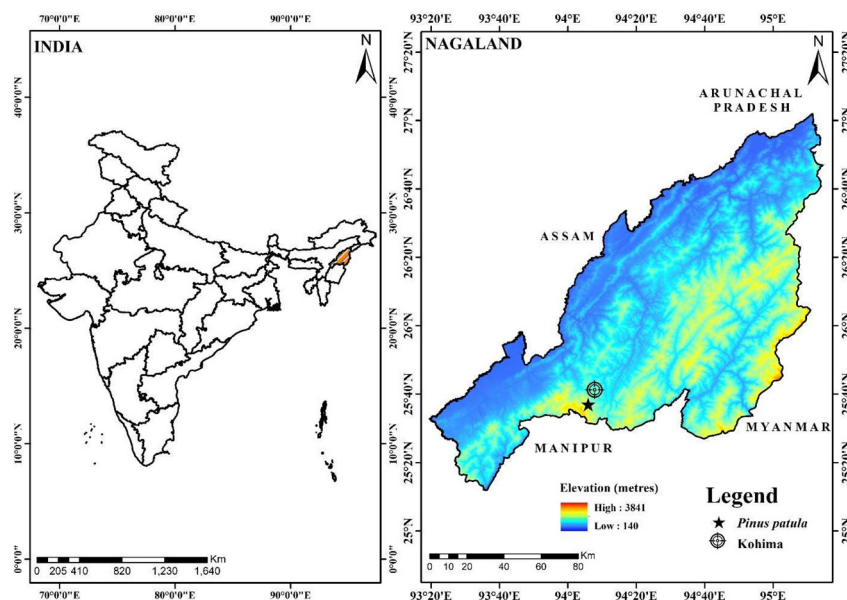


Fig.1. Sampling site of *P. patula* at Kohima Botanical Garden, Nagaland, India.

Table 1. Details of sampling site.

Site name	Kohima Botanical Garden
Lat (°N)	25.65°N
Lon (°E)	94.10°E
Elevation (m)	1638
SL	Moderate
NT/NC	31/61

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, NT/NC = Number of trees/number of cores.

experiences a subtropical highland climate (Köppen: Cwb), with greater contrast between summer and winter. The area receives the majority of precipitation from June to September. The coolest months are from December to February, with the occurrence of frost in lower hills and possible occasional snowfall in higher-altitude areas. The warmest months are June to August, where the average temperature ranges from 18–27 °C, with heavy and frequent rainfall. Winters in the study area are generally pleasant with little rainfall.

Species

The present study was conducted on *Pinus patula*, also known as Mexican weeping pine, spreading-leaved pine, or Mexican weeping pine. This species is native to the highlands of Mexico. In the native range, Mexican weeping pine is found at elevations ranging from 1,800 to 2,700 m amsl. The mature specimens of this tree can reach impressive heights of up to 30 m. This resilient species can withstand short periods of freezing temperatures as low as -10°C but grows faster in warm climates. In its natural range, Mexican weeping pine experiences an annual average rainfall ranging from 750 to 2000 mm. The species has been introduced to various regions across the globe, particularly at high altitudes including Ecuador (around 3500 m), Bolivia, Colombia (around 3300 m), Kenya, Tanzania, Angola, Zimbabwe, Papua New Guinea, and Hawaii (at 3000 m). However, *P. patula* has also been successfully cultivated at lower altitudinal regions of Southern Brazil, South Africa, India, and within the Argentine provinces of Córdoba and San Luis uncommon to its natural range. In Kohima Bo-

tanical Garden, it is growing alongside species like *Eucalyptus hybrid*, *Prunus cerasoides*, *Rhododendron arboretum*, *Bischofia javanica*, *Prunus napaulensis*, *Grevillea robusta*.

Sample collection, processing, and acquisition of data

Tree cores were obtained using a Haglof increment corer, primarily from breast height (1.3 m), with two cores per tree (Table 1). Standard dendrochronological techniques were applied (Speer 2010). Cores were air-dried to prevent shrinkage and mounted in grooved wooden mounts using water-based glue. All samples underwent polishing with various grades of sandpaper to enhance the visibility of growth ring boundaries under a microscope. Polished samples were scanned using Epson expression 12000XL professional scanner. Ring width was measured with 0.001 mm precision using Win Dendro™ Density program and a PC. Rings were counted from pith to bark, and cross-dated using skeleton plot technique (Stokes and Smiley 1968) to assign precise calendar dates for each ring.

Ring-width chronology development

We assessed the measured ring-widths of all dated tree cores to ensure accuracy in dating and measurement. This validation process was conducted using the “COFECHA” computer program, following the methods outlined by Holmes (1983) and Grissino-Mayer (2001). Any poorly dated series were either removed or re-dated after a thorough review for possible errors.

To create standardized ring width series that eliminate age-related growth trends and stand dynamics while preserving climate-related variations, we utilized the ARSTAN computer program (available at <https://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software>). In this standardization process, raw measurements of each series underwent power transformation and then were smoothed using a 1st Friedman super smoother and alpha curve (Friedman 1984). Autoregressive modelling was applied to remove first-order auto-correlation.

After detrending, we averaged individual time

Table 2. Statistics of tree-ring chronology developed from Nagaland, Northeast India.

SIC	0.443
MSL	34.0
TS (Yrs)	1983-2021 (39)
NT/NC	31/61
MS	0.130
AC-1	0.310
SSS	0.876 (1985)
EPS	0.930

SIC = Series intercorrelation, MSL = Mean segment length, TS = Time span, NT/NC = Number of trees/number of cores, MS = Mean sensitivity, AC-1 = Auto-correlation of first order, SSS = Sub sample strength, EPS = Expressed population signal.

series using a biweight robust mean function, as described by Cook (1985) and Cook and Kairiukstis (1990), resulting in the creation of tree-ring indices. The Expressed Population Signal (EPS; Wigley *et al.* 1984), was measured to assess the agreement between sample chronology and population chronology. Further, we employed the subsample signal strength (SSS) criteria, as recommended by Wigley *et al.* (1984), with a threshold value of 0.85 to identify the most reliable time span of the chronology. The statistics for *P. patula* tree-ring chronology is presented in Table 2.

Event year and resilience components analysis

In this study, we identified both positive and negative event years at the individual tree level. These event years were crucial as they served as representations of extreme events, particularly related to climatic conditions (Upadhyay *et al.* 2019b). To calculate these event years, we followed the Neuwirth method, as outlined by Maaten-Theunissen *et al.* (2015). Further, the concept of resilience in ecological analysis involves assessing the impact of disturbances on ecological properties. However, there is no universally standardized measure for this, leading to varied procedures being used for comparisons between disturbed and undisturbed systems. However, tree rings can offer insights into individual-level resilience. In this study, we analyzed different indices such as resilience, resistance, recovery, and relative resilience, based on changes in tree ring width, providing a multi-dimensional approach to estimate various interrelated aspects of resilience. These resilience indices focus on

specific time frames relative to the disturbance event, with ecological performance assessed over fixed periods, e.g., four years. They provide a comprehensive understanding of resilience, with resilience directly related to resistance and recovery. These multiple indices offer a more thorough exploration of resilience than single estimators. The analysis was performed using R program using various functions to compute and visualize tree resilience metrics as proposed by Lloret *et al.* (2011). These metrics encompass resistance, recovery, relative resilience, as well as those introduced by Thurm *et al.* (2016), such as recovery period and total growth reduction, and by Schwarz *et al.* (2020), including average growth reduction and average recovery rate. Here, resistance quantifies the relationship between growth during and before an extreme event, while recovery measures the ratio between growth after and during an extreme event. Resilience, on the other hand, assesses the ratio between growth after and before an extreme event. Lastly, relative resilience offers a resilience metric that accounts for the growth reduction experienced during an extreme event, providing a comprehensive set of metrics for analyzing tree resilience.

RESULTS AND DISCUSSION

Tree-ring width chronology

The final dataset comprised of 61 successfully cross-dated series from 31 trees, which are exhibiting high correlation with the master series chronology. This developed chronology spans from 1983 to 2021, covering a total of 39 years. The series mean inter-correlation for *P. patula* stands at 0.443, indicating a substantial degree of commonality among the individual series contributing to the site chronology.

In dendroclimatological studies, a tree-ring chronology with low autocorrelation, high mean sensitivity, and a substantial standard deviation holds promise. The mean sensitivity quantifies the relative difference in width between consecutive rings measuring 0.130. The standard deviation observed for tree-ring width chronology of *P. patula* was 0.134. High mean sensitivity values and moderate to high standard deviation values in the ring width chronology signal the presence of considerable high-frequency

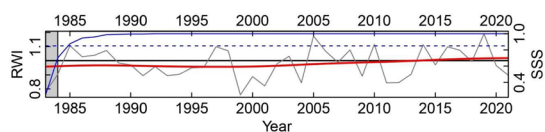


Fig. 2 The tree-ring width index (RWI) of *P. patula* from Nagaland. The red curve represents a 10-year spline-smoothing curve and a blue curve denotes the sub-sample signal (SSS).

variance, rendering its suitability for dendroclimato-logical investigations (Upadhyay *et al.* 2021).

Autocorrelation within a tree-ring chronology is an essential statistical parameter indicating the extent to which the growth of a year is influenced by the growth of preceding year, as opposed to external factors. The first order autocorrelation in ring width chronology of *P. patula* amounted to 0.310, suggesting that the climatic factors of current year primarily drive the growth of species in this region. Similar observations were recorded for other species in the region (Upadhyay *et al.* 2019 a and b, Upadhyay *et*

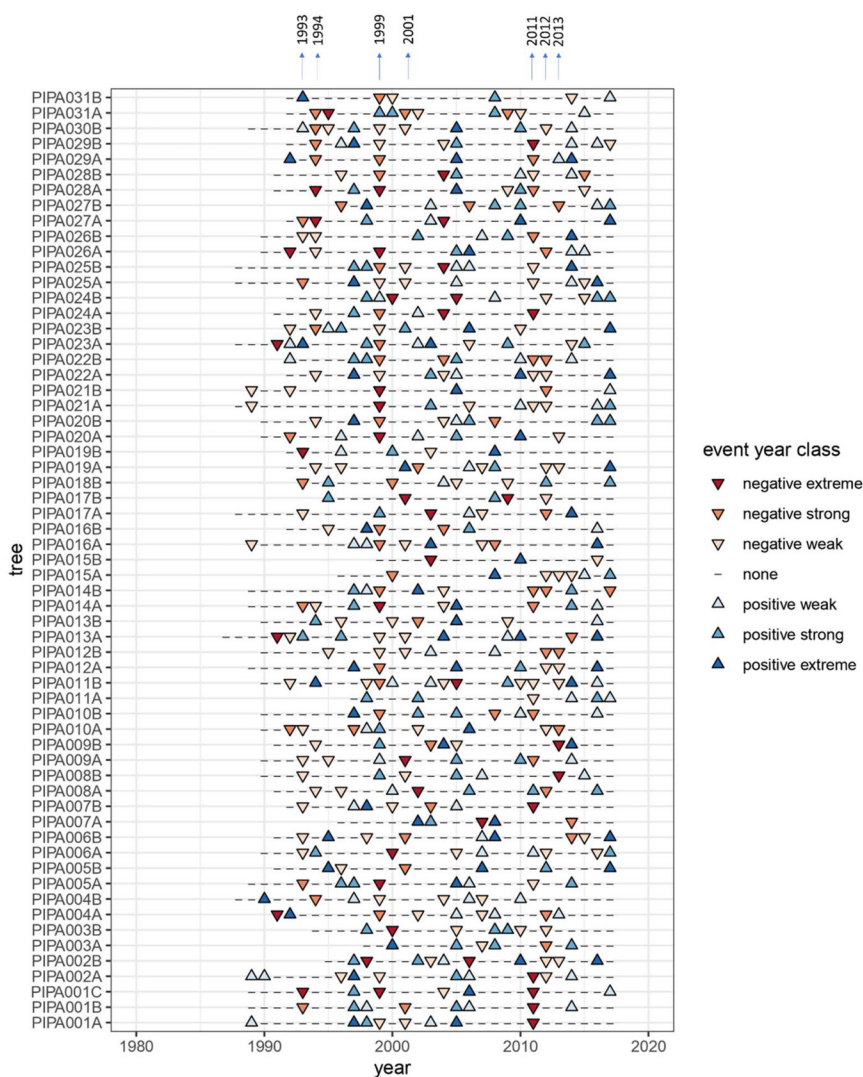


Fig. 3. Dot plot illustrating event years for individual *P. patula* trees at the Kohima Botanical Garden site. Negative event years are denoted by filled triangles pointing down, while positive event years are represented by triangles pointing up. Non-event years are marked with minus signs.

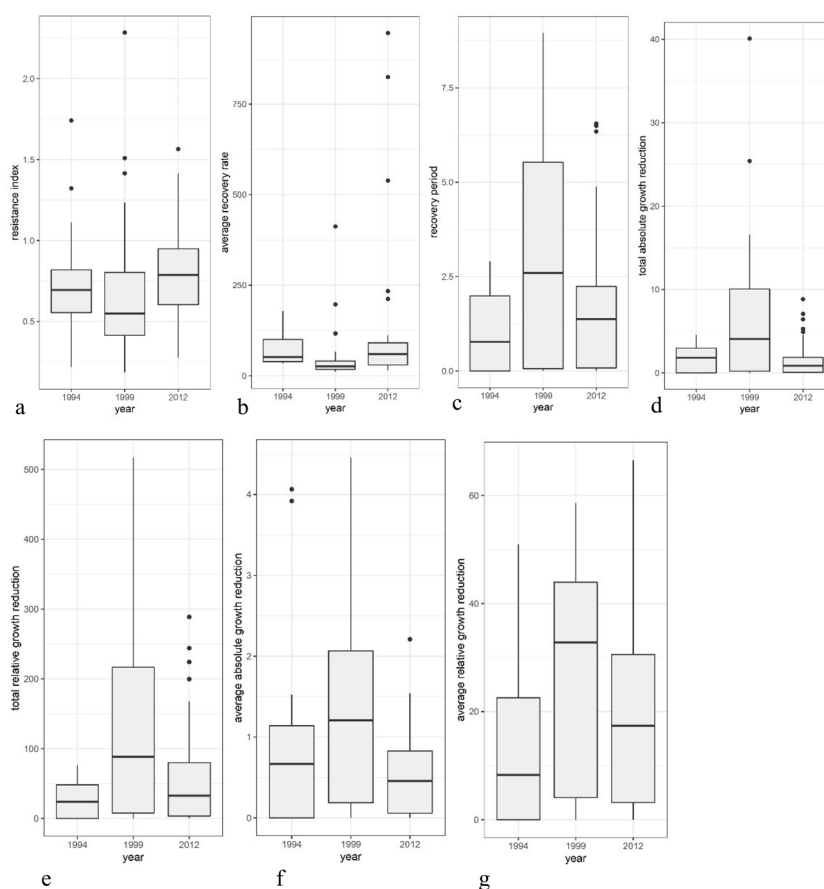


Fig. 4. Box plots of (a) Resistance, (b) Average recovery rate, (c) Recovery period, (d) Total absolute growth reduction, (e) Total relative growth reduction, (f) Average absolute growth reduction and (g) Average relative growth reduction for years identified as negative pointer years.

al. 2021).

The Expressed Population Signal (EPS), as proposed by Wigley *et al.* (1984), measures the agreement between sample chronology and population chronology. An EPS value of ≥ 0.85 is considered favorable for dendroclimatic reconstructions. The subsample signal strength (SSS) criterion with a threshold value of ≥ 0.85 was applied to determine the most reliable time span within the chronology (Table 2, Fig. 2).

Event year analysis

Event year analysis observed a number of years as negative event years in the tree ring series of *P. patula*, where the majority of tree ring series showed an extreme to a weak negative response in their growth

rate (Fig. 3). These identified negative event years align with the findings of Kumre *et al.* (2020) and Bora *et al.* (2021), who characterized these specific years (1993, 1994, 1999, 2001, 2011, 2012, and 2013) as periods marked by moderate to severe drought. Event years (1994, 2011, 2012, and 2013) recorded in tree ring width corresponded well with drought years observed in the climatic data of the Nagaland-Manipur-Mizoram-Tripura meteorological subdivision. Further, these negative years of growth also corresponded well with drought events reported in the Assam and Meghalaya (1994, 2001, 2009, 2011, and 2013) and Arunachal Pradesh (1992, 1994, 1999, 2001, 2009, 2011, and 2013) meteorological subdivisions. These findings underscore the response of species to moisture-limiting conditions, underscoring its significance in dendroclimatological investigations.

Such event years can serve as a valuable scientific foundation for addressing the growing challenges of moisture stress in agriculture and forestry within the region (Upadhyay *et al.* 2019b).

Analysis of resilience components

Resilience component analysis was conducted following the method proposed by Lloret *et al.* (2011), Thurm *et al.* (2016), and Schwarz *et al.* (2020). This involved calculating resilience components with a focus on a 4-year period both before and after disturbance events, with a maximum recovery period of 10 years. In this analysis, we computed various resilience components, including the resistance index, average recovery rate, recovery period, total absolute and total relative growth reduction, as well as average absolute and average relative growth reduction. Resistance index is a ratio between growth during and before a disturbance event. This demonstrated species resistance to drought during all three assessed drought events i.e., in 1994, 1999, and 2012. The species resistance to drought events is reported to be associated with a slower recovery rate, a pattern also observed in *P. patula* in Nagaland. This slower recovery rate and extended recovery period could be attributed, in part, to the drought events of 1999, 2001, 2005, and 2011, which have been documented in previous studies (Kumre *et al.* 2020; Bora *et al.* 2021). Further, a significant total (absolute and relative) and average (absolute and relative) growth reduction observed in the year 1999 is likely linked to a higher frequency of moisture-limiting events both before and after the 1999 drought disturbance event (Fig. 4a-g). The growth of Mexican weeping pine is primarily influenced by temperature, especially at higher altitudes (2500-2877m, Reyes-Cortés *et al.* 2019), but at lower elevations (1600-2580m), it is influenced by both temperature, particularly mean minimum temperature, and rainfall pattern (Belay 2016). This indicates that the growth of *P. patula* is controlled by both temperature and moisture. Consequently, the species has demonstrated resilience to drought events in the region but has experienced significant reductions in growth and slower recovery rates.

CONCLUSION

This study demonstrates dendroclimatic potential

of *P. patula* in new introduced provenance to the Nagaland, Northeast India. The descriptive statistics of tree-ring width chronology suggested common environmental factors like changes in temperature and precipitation pattern affecting the signal in the series. The negative event years of tree ring width series were connected to drought events in the region. Further, the resilience component analysis of species showed resistance to extreme events and a significant reduction in growth with slower recovery rate. The study indicates increasing frequency of drought events in the region and their negative influence on tree growth. The findings establish *P. patula* as resistant species for drought conditions and can be used for plantations in moisture limiting areas. Further, the findings can also help policy makers in developing effective strategies for water management to overcome the negative impacts of extreme events (drought) on forestry and agriculture sectors in this region.

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