DENDROCLIMATIC ANALYSIS OF FOREST TREE GROWTH IN RELATION TO CLIMATIC DRIVERS IN NORTHEAST INDIA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Ph.D. REGISTRATION NO: MZU/Ph.D./1340 OF 26.07.2019

DEPARTMENT OF FORESTRY
SCHOOL OF EARTH SCIENCES AND NATURAL RESOURCES MANAGEMENT
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ABSTRACT

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BY
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Submitted
In partial fulfillment of the requirement of the Degree of Doctor of Philosophy
in Forestry of Mizoram University, Aizawl.

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Certificate

This is to certify that thesis entitled **“Dendroclimatic analysis of forest tree growth in relation to climatic drivers in northeast India”** submitted by **Mr. Rockfillinroy Kharmawlong (Ph.D. Regn. No. MZU/Ph.D./1340 of 26.07.2019)**, in partial fulfilments of requirements for the award of Degree of Doctor of Philosophy in Forestry Department of the Mizoram University, Aizawl embodies the record of his original investigation under my supervision. He has been duly registered and the thesis presented is worthy of being considered for the award of the Doctor of Philosophy (Ph. D) Degree. The thesis or part of these work has not been submitted by him for any degree to this or any other university.

(Keshav Kumar Upadhyay)
Supervisor

DECLARATION

MIZORAM UNIVERSITY

APRIL, 2024

I **Rockfillinroy Kharmawlong**, hereby declare that the subject matter of this thesis entitled "**Dendroclimatic Analysis of Forest Tree Growth in Relation to Climatic Drivers in Northeast India**" is the record of the work done by me, that the contents of this thesis did not form basis of the award of any previous degree or to the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University / Institute.

This is being submitted to the Mizoram University for the degree of **Doctor of Philosophy** in Forestry.

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Place: Aizawl

Date: (Rockfillinroy Kharmawlong)

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Acronym	**Description**
AC-1	First Order Autocorrelation
CO_2	Carbon dioxide
et al.,	Et alia, ‘and others’
Etc	Et cetera
EW	Earlywood Width
gm cm^{-3}	Gram per centimetre cube
i.e.	That is
IPCC	Inter-Governmental Penal on Climate Change
ITRDB	International Tree Ring Data Bank
MADA	Monsoon Asia Drought Atlas
MODIS	Moderate Resolution Imaging Spectroradiometer
MS	Mean Sensitivity
MSL	Mean Segment Length in Years
MXD	Maximum Latewood Density
NDVI	Normalized Difference Vegetation Index
NT/NC	Number of Trees/ Number of Tree Cores
RD	Ring Density
SD	Standard Deviation
SIC	Series Inter-Correlation

SSS	Sub Sample Strength
SST	Sea Surface Temperature
TRW	Tree Ring Width
TS (YRS)	Time Span of the Chronology (years)
Tmax	Maximum temperature
Tmin	Minimum temperature
DTR	Diurnal Temperature Range
GHGs	Greenhouse Gases
NEI	Northeast India
MEA	Millennium Ecosystem Assessment
FAO	Food and Agriculture Organization
UNFCCC	United Nations Framework Convention on Climate Change
MoEF	Ministry of Environment and Forests
Mt	metric tonnes
FSI	Forest Survey of India
CDM	Clean Development Mechanism
PDSI	Palmer Drought Severity Index
USA	United States of America
ENSO	El Niño Southern Oscillation
AD	Anno Domini
ISM	Indian summer monsoon
IADFs	Intra-annual density fluctuations

DBH	Diameter at Breast Height
NNK	Nicotine-derived nitrosamine ketone
MAM	March-April-May
GEER	Gujarat Ecological Education and Research
km^2	Square Kilometer
Mm	Millimeter
Ft	Foot
Cm	Centimeter
ISFR	India State of Forest Report
SC	Site Code
Lat (^{o}N)	Latitude in degree North
SN	Site Name
Lon (^{o}E)	Longitude in degree North
SL	Slope of the site
Elev (m)	Sampling site elevation in meter
SFD	Source-to-Flim Distance
Km	Kilometer
DTO	District Transport Office
IAF	Indian Air Force
Lps	Lipopolysaccharide
WD	Water Displacement
STD	Standard Chronology

ARSTAN	Auto Regressive Standardization
MSE	Mean Square Error
MS Total	Mean Square Total
PCA	Principal Component Analysis
OPC	Orthogonal Principal Components
ºC	degrees Celsius
%	Percent
Viz	Namely/videlicet
e.g	For example
Kg	Kilogramme
MoEF & CC	Ministry of Environment, Forest and Climate Change

LIST OF PHOTO TEMPLATE

Chapter 1

Introduction

1.1 Climate change

Global warming has emphasized the importance of long-term climate information derived from tree rings and other paleoclimatic archives. This data is crucial for both scientific researchers and the general public. These records offer a way to assess current climate variations within a historical context spanning hundreds to thousands of years. This allows an evaluation of changes that predate any human-induced influences. (Mann ME et al., (2008). According to Cook ER et al., (2010) the access of large-scale paleoclimate records improves the robustness of assessments of regional weather transitions with regard to external factors and internal information loops.

Tree-ring records, owing to their sensitivity to climate and accurate dating, have been widely employed to extend short-term instrumental climate data from local to global scales, covering periods ranging from hundreds to millennia (IPCC, 2007; Climate Change, 2007). The recent global warming phenomenon has raised concerns about its devastating impact on Earth's ecosystems and species. In recent decades, the Earth has undergone its warmest period in the last 1000 years, and forecasts indicate a continuation of temperature increases in the time to come.

Human activities, such as deforestation and the burning of fossil fuels, are increasing levels of greenhouse gases, thereby intensifying the trapping of more heat. Climate change and the significant warming observed in recent decades are widely discussed topics among the public, governmental officials, and policymakers. From 1880 to 2012, the Earth's surface temperature has increased by an average of 0.85°C (IPCC, 2013). Various studies, including those from India and other regions (Jones and Briffa, 1992; Shrestha et al., 1999; Liu and Chen, 2000; Arora et al., 2005; Fowler and Archer, 2005; Brohan et al., 2006; Bhutiyani et al., 2007; Dash and Hunt, 2007; Immerzeel, 2008; Singh et al., 2008; Tyagi and Goswami, 2009; MoEF, 2010;

Kothawale et al., 2010; Shekhar et al., 2010; Shrestha and Aryal, 2011; Dash et al., 2012; Dimri and Dash, 2012; Ren et al., 2017; Qing-Long et al., 2017, Dimri et al., 2018a, 2018b), have reported on these temperature changes. The latest Intergovernmental Panel on Climate Change (IPCC) report (sixth assessment report) reveals that the last four decades have been consecutively warmer since the mid-19th century, with land temperatures rising more rapidly than ocean temperatures (IPCC, 2021). Temperatures are projected to continue rising throughout the 21st century, accompanied by an increase in extreme weather events such as heavy precipitation, droughts, and heatwaves (Dai, 2013; IPCC, 2014; Trenberth et al., 2014).

The warming, especially in higher mountain areas, has significant impact on ecosystems, leading to changes in plant phenology, biodiversity, and forest dynamics (Bertin, 2008; Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Gautam et al., 2013; Telwala et al., 2013; Upgupta et al., 2015). Tree species at high altitudes are more responsive to temperature changes, and shifts in ecosystem boundaries, plant species regeneration patterns, and tree line shifts are expected consequences (Dubey et al., 2003; Gaire et al., 2014).

1.2 Climate change in India

Numerous studies have examined climate trends in the Indian subcontinent (Shekhar et al., 2010; Dimri and Dash 2012; Jain and Kumar 2012; Punia et al., 2015; Rohini et al., 2016). They generally find that the warming trend in India over the past century aligns with global trends. However, a distinct feature is the substantial increase in maximum temperatures (Tmax) in India, leading to differences in diurnal temperature range (DTR) trends compared to other regions. Studies on rainfall patterns in India shows that there is no clear trend of increase or decrease in average rainfall across the country. However, significant regional variations in rainfall trends have been observed (Kumar et al., 2010; Joshi and Pandey 2011; Ghosh et al., 2016; Bisht et al., 2018). However, a decrease in the frequency of intense rainfall events has been reported in many Asian regions, accompanied by a reduction in rainy days and overall annual precipitation (Singh et al., 2014). The significance of greenhouse gases (GHGs) and water vapor in shaping climate variations, particularly in India (IPCC 2014). The geographical features of India, particularly the Himalayas, exert a significant influence on local and regional climates, and accurate modelling of their impact is essential (Bookhagen and Burbank 2010). Global climate models have improved over the years and are accepted by climate experts. These models consider GHG emissions, natural variability, and aerosols (IPCC 2014). Research on Indian climate focuses on understanding current climate characteristics across seasons and regions, predicting regional climate changes due to local and global factors, and addressing the complexities of temperature and precipitation trends (Krishnan et al., 2020). The Himalayan mountains, which are geologically young, play a crucial role in driving monsoon winds (Bookhagen and Burbank 2010). The dynamics of these winds, along with the heating of the Himalayan slopes, affect the monsoon flow and contribute to extreme precipitation events. Additionally, the dust from human activities like charcoal/wood burning and fossil fuel combustion influence the Indian climate. Aerosols can suppress cloud formation, impacting continuous rain but promoting occasional heavy precipitation (Choudhury et al., 2020).

In research conducted by the India Meteorological Department revealed a 0.56°C increase in the all-India mean annual temperature from 1901 to 2009 (Attri and Tyagi 2010). This warming trend was attributed to a 0.7°C rise in maximum temperature. In the past three decades, both maximum and minimum temperatures have played a role in the warming trend, exhibiting variations between the winter and post-monsoon seasons (Attri and Tyagi 2010).

1.3 Climate change in northeast India

Northeast India (NEI) is influenced by the southwest monsoon, receiving a substantial amount of rainfall. However, over the past three decades, the region has experienced alterations in rainfall patterns and frequencies (Saha et al., 2023), posing a significant threat to its biodiversity and the livelihoods of its inhabitants, who heavily depend on rain for agriculture. In such instances, the majority of rainfall is concentrated within a specific season, occasionally leading to moisture stresses during critical phases of the cropping season or contributing to hydrological disasters. Further, a substantial reduction in rainfall has been reported in the states of Northeast India, accompanied by a notable increase in both minimum and maximum temperatures (Mondal et al., 2014) Research on the impact of climate change on crop productivity suggested that many agricultural crops in the northeastern Indian region may experience a declining trend in yield, if adaptation strategies are not implemented (Kumar et al., 2011).

1.4 Climate change and Forest ecosystems

Forests have been a fundamental source of sustenance for humanity since time immemorial, intricately woven into the fabric of human civilization (Upadhyay et al., 2019; Jeanne-Lazya et al., 2022). In antiquity, this symbiotic relationship thrived in equilibrium, fostered by lower population density and conscientious forest stewardship by communities. However, contemporary challenges arise from rapid industrialization and an increasing global populace, exerting substantial pressure on forest ecosystems. This industrial surge not only expedites climate change processes (Marotzke et al., 2017) but also heightens the jeopardy facing specific forest species and ecosystems.

Globally observed shifts in precipitation patterns, encompassing rainfall and snowfall, coupled with escalating air temperatures, underscore the intricate responses of enduring terrestrial ecosystems to prolonged climate shifts (IPCC 2013; Bernier and Schöne 2009). While certain species in particular locales may glean positive impacts from climate change, such as prolonged growing seasons, heightened temperatures, and elevated CO_2 levels, the overarching projections lean predominantly negative (Keenan 2015).

Climate change is disrupting the flowering and fruiting times, altering regeneration patterns of plant species at high-altitude zones, and influencing the biodiversity (Dubey et al., 2003; Telwala et al., 2013). Escalating temperatures and changing precipitation patterns reshaping the natural ranges of numerous species, resulting in shifts in species distribution (Kelly and Goulden 2008; Coetzee et al., 2009; Lenoir et al., 2010; Anderegg et al., 2015). Species grappling with adaptation struggles and changing distributional ranges confront the peril of extinction due to drought and heat stresses (Allen et al., 2010). This predicament is further compounded by heightened ozone levels at lower altitudes, nitrogenous contaminant deposition, inadvertent introduction of exotic pests, habitat degradation, and additional disturbances like fires (Bernier and Schöne 2009).

The impact of climate change also extends to nutrient cycling in both natural and managed ecosystems (Spiecker 2002; Grimm et al., 2013). Forest productivity intimately correlates with climatic variations, where shifts in temperature and precipitation can attenuate growth rates and, under specific circumstances, culminate in tree mortality (e.g., suppressed trees in dense stands are susceptible to drought - Spiecker 1986, Spiecker 2002; Grimm et al., 2013). The influence of climate on tree growth exhibits variability based on tree species, provenance, competition for growth, and other site conditions (Williams et al., 2010). Growing seasons and site productivity hinge on variations in average climatic conditions, such as air temperature (Menzel and Fabian 1999; Lobell and Gourdji 2012).

As per the findings of "Climate Change and India: Adaptation Gap" (2015), about 36 districts in India, accounting for 5.5% of the land area and roughly 36 million people, are currently undergoing temperature patterns comparable to the Representative Concentration Pathway (RCP) 8.5, indicating a warming of 4°C or more. In India, the western and northeastern regions are experiencing more pronounced warming compared to other areas. It has been observed that the country, in general, aligns with the RCP 4.5 trajectory. However, specific regions like the northeastern, Madhya Pradesh, Rajasthan, and Jammu and Kashmir exhibited significant warming between 2006-2013, following the paths of RCP 6.0 and 8.5. The northeastern and western regions of India are witnessing an increase in the number of hot nights. A notable rise in the frequency of hot days (20-25 days per year) has been documented for the northeastern, northern, and southern regions in the near-term projected future climate. Larger increments in growing degree days are anticipated in RCP 8.5 for the northern and northeastern regions. These shifts in night-time temperature and growing degree days may lead to alterations in cropping periods and subsequently impact crop yields (Garg et al., 2015).

Recognizing the influence of climate change on forests, the development of adaptation and mitigation strategies has become a central focus for foresters and researchers (Schoene and Bernier 2012). Vital information about tree growth and forest productivity is crucial for achieving sustainable forest management objectives. This involves comprehensive inventory data, covering volume, production potential, dimensions, wood quality, and the responsiveness of these parameters to climate stimuli through tree-environment interactions. Dendrochronology, the study of tree rings, serves as an indispensable archive revealing historical climatic changes.

1.5 Dendrochronology

The research field of dendrochronology uses the annual rings of trees to deduce with high temporal resolution, information regarding the age, growth rate, historical occurrences of forest fires and insect pest outbreaks, wood quality (density), and the connections of different tree species with their previous environments (Upadhyay and Tripathi, 2019). Tree rings record the environmental conditions through changes in their growth pattern and later used as an archive for the past environment (Spiecker, 2002). Tree ring width measurement provides past information on growth over broad environmental gradients during time periods ranging from sub-annual to multi-centuries. This information plays vital role in realizing impact of global climate change on forests flora (Babst et al., 2018).

The science of dendrochronology dated annual the tree rings to the precise year of development in order to study historical, prehistoric, and contemporary behaviours and environmental factors. Trees are highly reliant on their environment for survival, as well as their development is impacted by both natural (viz. weather patterns and rainfall) and man-made (viz. air and water pollution) processes and events. These factors are repeatedly and reliably shown in the rings of the trees (Upadhyay et al., 2021; Balraju et al., 2022). Almost all of the world’s geographic regions experience annual variations in the amount of wood that trees grow, as well as in the physical and chemical features of the wood, like the widths within its rings. Environmental conditions may become more favourable for tree growth in some years, enabling the trees to produce large amounts of wood. However, in other years, climate conditions may be generally unfavourable for tree growth, leading to a reduction in the volume of wood produced (Irina, 2014).

Dendrochronology, delves into the annual rings of trees, provide insights into their age, growth rate, historical events such as forest fires and outbreaks of insect pests, wood quality (density), and the interaction of tree species with past environments, offering a high temporal resolution. The annual rings function as records of environmental conditions, reflecting changes in growth patterns and serving as an archive for past environments (Spiecker, 2002). Measurements of tree ring width offer retrospective growth information across extensive environmental gradients and various timescales, from sub-annual to multi-centennial. This information is pivotal for comprehending the impacts of global climate change on forest vegetation (Babst et al., 2018). Dendrochronology has played a crucial role in examining the effects of climate change on forest growth, recovery from climatic extremes, the relationship between growth and canopy dynamics, and indications of CO_2 fertilization (Babst et al., 2018). Other applications encompass quantifying aboveground biomass (Babst et al., 2014b), understanding the physiology of wood development (Rathgeber et al., 2016), and standardizing climate reconstruction models (Guiot et al., 2014).

Climate change has become a defining characteristic of the Anthropocene (Marotzke et al., 2017), necessitating the forecasting and quantification of its impact on natural ecosystems. Forests, serving as significant sinks for anthropogenic CO2 (Le Quéré et al., 2016), store it in their woody biomass for prolonged periods (Körner, 2017). Grasping the impact of biotic and abiotic changes on forest ecosystems can be accomplished at spatial and temporal scales by anticipating the consequences of heightened warming (Babst et al., 2018).

1.6 Tree Rings and Forest Growth

Tree rings serve as valuable records offering insights into the climate-tree growth relationship, playing a crucial role in understanding forest development at large spatial scales under the influence of climate change (Rohner et al., 2016). However, the availability of tree ring data remains insufficient for comprehensive insights into this complex relationship (Rohner et al., 2016). To enhance our understanding of forest dynamics, the integration of tree ring measurements with forest inventory data becomes essential (Evans et al., 2017). This combination allows for the improvement of models that capture forest growth responses to anthropogenic climate change, paving the way for more effective management strategies to safeguard ecosystems and their services. Forest inventory data, including measurements like diameter at breast height (DBH), can be effectively merged with tree ring data to reconstruct annual tree diameter (Bakker, 2005). The integration of these datasets enables the development of absolute estimates of tree growth, achieved through allometric equations (Babst et al., 2018; Forrester et al., 2017). These estimates, in turn, offer valuable insights into carbon sequestration and forest productivity (Babst et al., 2018; Klesse et al., 2018). Understanding demographic competition, which significantly influences individual growth, becomes crucial for carbon accounting work (Chen et al., 2016; Trotsiuk et al., 2016; Babst et al., 2018).

To gain insights into the impact of various factors on tree growth, such as climate, biophysical conditions, tree size, competition, canopy status, and forest management practices, Bayesian hierarchical models can be employed (Evans et al., 2017). As climate change continues, with projections indicating an increase in temperature-dependent extreme events like droughts or heatwaves (IPCC, 2013), understanding the ability trees to adapt to these changes becomes paramount (McKenney et al., 2014; Price et al., 2013). Predicting species behaviour under environmental changes involves assessing genetic and physiological responses to climate through time-series data based on tree rings (Alberto et al., 2013).

The understanding of wood anatomical traits related to climate adaptation poses a challenge, but dendroecologists have developed methods linking these traits with climate, enabling the quantification of climatic limits imposed on trees (Girardin et al., 2016; Hartmann and Trumbore, 2016; Housset et al., 2018). Hydraulic traits, such as xylem anatomy and wood density, act as indicators of a tree's response to environmental changes and its vulnerability to drought (Choat et al., 2008; Chave et al., 2009). These traits also play a role in the trade-off between xylem safety and efficiency, with wood density serving as a strong proxy for various hydraulic traits (Anderegg and Meinzer, 2015).

As atmospheric CO_2 concentrations rise, intrinsic water use efficiency (iWUE) in forests increases, allowing for enhanced carbon sequestration per unit of water (Keenan et al., 2013; Ponce Campos et al., 2013). However, the link between xylem anatomy, its functions, and the environment underscores the complexity of hydraulic traits as indicators of drought vulnerability (Nardini et al., 2013). Studies showed that a loss of 50% in hydraulic conductivity in gymnosperms and 80% in angiosperms can lead to plant death (Brodribb and Cochard, 2009; Urli et al., 2013). Climate change has also altered the occurrence and frequencies of forest disturbance events, including forest fires, insect outbreaks, floods, wind, avalanches, pathogen outbreaks, and drought (Speer, 2010). Dendrochronology serves as a tool to study the history of these disturbances, offering valuable information on their occurrence, frequency, and impact on tree growth (Speer, 2010).

Further, the integration of tree ring data with remote sensing data, such as NDVI, enables the monitoring of changes in vegetation structure and physiology (Wang et al., 2004a). The correlation of tree ring width data with NDVI helps refine estimates of forest productivity (Babst et al., 2014a). Overall, tree rings, with their high-resolution age estimates and long-term growth records, can play a crucial role in understanding tree population dynamics and developing sustainable forest management systems (Brienen and Zuidema, 2005).

1.7 Scope of the study

The current study focuses on using dendroclimatological observations to interpret tree ring growth patterns, reconstructing the past climatic patterns from the analysis of these tree rings and predicting response of selected tree species to upcoming changes in climate. Moreover, merging dendrochronological data with inventory and remote sensing data would benefit in predicting the changes in growth of selected tree and their carbon sequestration potential in different northeast Indian states under changing climate scenario.

1.8 Objectives

1. To develop tree ring database of key tree species from different states of northeast India
2. To determine tree growth- climate relationship using different parameters of tree ring data, such as ring width, latewood density, and early and latewood width etc.
3. To comprehend the effect of climate change on carbon sequestration potential of selected trees of northeast India.

Chapter 2

Review of Related Literature

Dendrochronology, the study that employs tree rings to date historical events and reconstruct past environmental conditions, has witnessed significant development over the past three decades. Initially confined to a narrow geographical range, dendrochronological analysis has evolved into a global phenomenon encompassing a wide range of topics. The core concept relies on cross-dating, the process of identifying contemporaneous rings in different trees by utilizing ring morphology features. Dendrochronology yields accurate dates up to the year and provides both qualitative and quantitative reconstructions of environmental variations on timescales ranging from seasons to centuries.

Despite its utility, dendroecological studies face challenges related to tree-ring production, particularly issues related to false and missing rings. Missing rings occur when the cell formation for a specific growth season is entirely halted or only occurs on a portion of the stem. This results in incomplete time series when sampling such trees. On the other hand, false rings stem from fluctuations in wood density within a single tree ring, resembling normal latewood but appearing as dark shadows parallel to ring boundaries (Stokes and Smiley, 1968). The use of skeleton plot procedures is considered an effective method to rectify errors associated with missing or false rings (Schweingruber, 1988; Cook and Kairiukstis, 1990). Skeleton plotting facilitates dating based on a visual assessment of relative ring widths, aiding in the identification of pointer years indicating positive or negative events.

Trees form rings through periodic growth, adding a layer of new wood cells between the older wood and the outermost layer (bark) along the stem's entire circumference. This growth is regulated by the cambium, a meristematic tissue responsible for rapid cell division to form new layers of tissue (Kaennel and Schweingruber, 1995). Trees in regions with seasonal precipitation and/or temperature variations, such as those in temperate climates, exhibit clear seasonal rings.

During the dormant season (spring), trees produce large cells or vessels with efficient water transport. As the growing season progresses and becomes drier, smaller cells with thicker walls are produced. Growth stops in late autumn, and in the following spring season, a new layer of large cells is formed, easily distinguishable from the small cells produced at the end of the previous growing season. Each annual ring in coniferous trees represents a year of growth, comprising light and dark bands representing growth in spring/early summer and summer/autumn. In broadleaf trees, the initial part of the annual ring often includes a large vessel visible to the naked eye, followed by smaller invisible vessels. The distinct borders of the rings allow for calculating the tree's age, while the width of each ring reflects the inherent properties of the tree and environmental conditions during a specific growing season.

Pressler borers are commonly used to extract samples (cores) from tree trunks, and sometimes discs are taken from stems and roots using saws. These samples are polished to provide a smooth surface for clear ring visibility. Electronic measuring systems aid in counting and measuring the rings, providing data with one-year precision and obtaining calendar dates of ring formation. Tree-ring width curves for individual trees are observed to identify mass movement events, often by comparing them with ring series from trees on a control slope. The control slope should have similar orientation, inclination, bedrock, and morphology, ensuring that it primarily gives tree rings under the influence of non-geomorphic factors.

Trees, as long-living organisms, record environmental information in their growth rings. Tree rings represent a record of survival, with trees acting as filters that react to changes in environmental conditions, leading to physiological and metabolic reactions resulting in ring structures of different qualities and widths (Smith, 2008; Fritts, 1976). Dendrochronology utilizes ring width as a predictor of tree performance in changing environments, with abrupt changes serving as valuable indicators for dating and analyzing the impact of incidents, such as extreme climatic events (Schöngart et al., 2004).

2.1 Dendrochronology Studies at Global level

Dendroclimatology at global level started with the early work of A. E. Douglass (Schweingruber, 1988) and researchers like H.C. Fritts (1976) who provided the basic knowledge of dendrochronological analysis through textbook. One of the earlier tree ring network analyses was done by Brubaker (1980), who examined the climate response across the Pacific Northwest using Principal Component Analysis. She created a 400-year chronology and discovered a consistent signal from the first eigenvector in response to summertime and springtime rainfall and the second eigenvector in response to warmer temperature and winter rainfall. Collection for tree-ring chronology climate network was started by LaMarche and Fritts (1917) for broad-scale drought reconstruction throughout the U.S. and Canada. A PDSI reconstruction from the network established the longstanding background for dust bowl drought of the 1930s in western USA (Stockton and Meko, 1975).

Climate, marked by extreme events like droughts and floods, poses significant challenges in the context of global warming. According to model projections, the likelihood of these events is expected to increase in the coming years (IPCC, 2013). The rise in temperature is anticipated to disperse and intensify drought conditions, leading to the drying of the land surface (IPCC, 2013). Additionally, warmer climates are projected to alter the amount, intensity, frequency, and type of precipitation worldwide (De et al., 2005; Goswami et al., 2006; Kumar et al., 2006; Rajeevan et al., 2008; IPCC, 2013).

Tree ring analysis has been used throughout the world to establish the linkages between tree growth and climate. The science of dendrochronology uses tree ring widths as an archive for the past climate of the area. Tree ring growth is affected by the climate of the area and its signal is preserved by the tree rings in the form of their width. Several studies based on the use of tree rings have been done in the different parts of the world.

In India, Analysis of the relationships between tree rings and climate was initiated with the pioneer work of Chowdhury (1939, 1940a, 1940b). Subsequently a preliminary report on simple correlation between climate and tree ring sequences was made for the Western Himalaya based on tree-ring data of a short time span (Pant, 1979), but systematic tree-ring research based on accurate dating of long sequences of growth rings had only been started since the end of the 1980s.

Pioneers like Fritts (1976) contributed a lot in establishing the science of dendrochronology and gave the most important principle of cross-dating. The tree analysis uses the field samples in the form of either increment cores or cross-sections of the tree. The coring process was described by Stokes and Smiley, (1968), gave the procedure for collecting the core sample depending on the nature of the study. The response function analysis is used to explain the relationship of both growth and climate (Schweingruber et al., 1978; LaMarche and Pittock, 1982).

The most commonly measured attribute of the growth rings after width is the early and late wood density (Polge, 1970). The latewood density showed the best relation to growing season climate than ring width. (Schweingruber et al., 1978). The climate phenomena seen through tree rings have spatial scales from a few hectares to a hemisphere, and temporal scales from the few hours of an ice-storm, through decades of drought, to centuries of change global atmospheric circulation (Hughes, 2002).

In North America, long tree ring records have been used for reconstruction of the past climate using the trees growing at the timberline (Norton et al., 1983a, 1985). In New Zealand, straight bole, tall and dominant tree canopy provided the most suitable tree cores for the chronology construction (Norton et al., 1983b, 1985). (Norton, et al., 1983c, 1985) In some case, the damages to the tree, viz. poor form, reaction wood etc. yield the most information about forest disturbances (i.e., avalanche events, flood etc.).

In African the ring boundaries of Acacia species are delimited by long calcium oxalate crystal change and often marginal parenchyma cells (Gourlay, 1995; Nicolini et al., 2010). X-ray density measurement of Acacia samples has not allowed or aided the identification of ring boundaries, due to high wood density, the presence of gums and a complex wood anatomy (Eshete and Stahl 1999; Gourlay, 1995). The number of growth rings per year depends on the number of wet seasons, and on the severity of the dry seasons experienced at the tree stand (Eshete and Stahl 1999; Gourlay 1995).

In the lowlands, the distinction between suitable and unsuitable samples could be attributed to plant-level access to water, the degree of human disturbance and the availability of stem discs rather than cores (Eshete and Stahl 1999; Gebrekirstos et al., 2008). In the upper lands, this distinction might be primarily attributed to differentiate in groundwater flow and precipitation regime. Denkoro and Doba forest are located at the border of two relatively dry rainfall regimes and experience not only low but also a highly erratic precipitation during the minor wet season. Doba forest, located at the top of a mountain ridge, is well-drained; hence, trees respond to multiple dry spells per year (Wils et al., 2009). On the other hand, Denkoro forest, located on a slope, receives groundwater flow more continuously; hence, ring formation occurs rarely (Wils, 2009). Additional variability may be caused by the incidence of mist and frost at night (Cherubini et al., 2003). Some individual cores could not be crossdated, because of the irregular radial growth of *Juniperus procera,* yielding many partial [either wedging or partially indistinct (Worbes, 1995) rings]. Note that the samples that could be crossdated contained multiple false and indistinct growth rings as well, but those could be identified as such during crossdating (Wils et al., 2010a).

In 2012, Ramirez and Del Valle gives a global and local climate signal from tree rings of *Parkinsonia praecox* from Colombian coast. In this the chronology made up of eighteen trees were develop that allowed for the reconstruction of global and local climate drivers spanning the previous sixty-three years. It gives strongly correlated chronology with wind data and rainfall as well as index of ENSO (El Nino Southern Oscillation)

According to the review of, Dendroclimatology in South America by (Boninsegna et al., 2009) the development of chronologies in humid subtropical or tropical climates remains a major challenge. Despite obvious advances in the last decades, the number of tree rings chronologies is weak in those regions. Whereas, the future of dendroclimatology in the tropical regions is thought to be extremely promising and the attempt to identify annual growth rings in tropical and sub-tropical species from South Africa and constantly increasing (cf. Ferrero et al., 2014)

In Central Africa, develop chronologies spanning up to 68 years for three deciduous Acacia species and for evergreen species from the rift valley in Ethiopia. During the wed season the tree growth has a strong correlated with precipitation (Gebrekirstos et al., 2008)

Teck in Southeast Asia was one of the species in subtropical and tropical regions which are used for dendroclimatology research. Teak has a large natural geographical distribution and growth in such country like India, Myanmar, Thailand and loas. Additionally, teak was brought to the Indonesia and Philippians. Berlage (1931) developed the first chronology and since then teak chronologies were continuously developed resulting in large compilations of teak tree-ring chronologies (e.g. Cook et al., 2010).

Australia develop a *Toona ciliata* chronology with a length up to 146 years, ranging from 1854 to 2000. In this the tree ring width gives a significant positive correlation with precipitation and significant negative correlation with temperature over a period of time from 1900 to 2000, enabling reconstruction of rainfall back to 1860. Since *Toona ciliata* has a very wide rages of natural distribution, so the *Toona ciliata* has a potential candidate for setting up tree ring network.

In Subtropical regions developed chronologies from montane tree using *Cderela lilloi* and *Juglans australis* species which grown on the eastern slope of the Andes (Villalba et al., 1992, 1998). These chronologies spanning from 1804 to 1994 for *Cderela lilloi* and from 1897 to 1994 for *Juglans australi,* it gives related temperature variation and rainfall distribution on the tree growth, which allowed the reconstruction of seasonal and annual variations in precipitation. In Northwestern Argentina which is the subtropical low land forest, Ferrero and Villalba 2009 were able to develop a chronology from *Schinopsis lerentii* from a period of 1829 to 2004 giving that the tree growth was positively corelated with precipitation.

Seasonality induces cambial dormancy of trees, particularly if these belong to deciduous species (Brienen and Zuidema, 2005). Annual tree rings provide growth information for the entire life of trees and their analysis has become more popular in tropical forest regions over the past decades (SolizGamboa et al., 2010). It is demonstrated that tree-ring studies is a powerful tool to develop high resolution and exactly dated proxies for biomass accumulation over time in individual trees (Mbow et al., 2013). Lopatin et al., (2006) found significant correlation coefficient between tree-rings and cumulated NDVI values from June to August months indicate that integrated NDVI values could be used in the Komi Republic as a proxy for estimation of forest growth trends on the scale of the whole region.

2.2 Dendroclimatic studies in India

The basic necessity for the successful used of tropical dendroclimatology is the presence of the annual ring structure in the wood. All over the world the tree face periodically unfavourable growing conditions and consequential respond for the behaviour and the variation of annual low temperature, precipitation or flooding. Hereby the radial growth is slowdown or interrupted for a days or months. This gives the result of different anatomical wood structures that appear as rings boundaries in the cross section of the stem. These rings are annual if the triggering climate factors, such as a dry or rainless period (in most parts of the tropics), occur once a year (Worbes, 1995).

In addition to temperate zone, only few applications have used to developed for tropical regions (e.g. Schongart et al., 2004, 2006; Brienen and Zuidema 2006a, 2006b; Pumijumnong and Eckstein, 2011). This is due to the limited of financial resource and technical facilities in tropical countries Additionally, less sampling replication can also be a problem because of the enormous diversity of species which come along with low abundances of individual particular species in most of the tropical forest. The method of non-destructive standard like coring are not possible for most of the tropical broad-leafed species, in which anatomical wood inspection and reliable tree ring detection are require a certain wood surface over those of standard tree core.

Except pioneer work on climatic reconstruction by Hughes and Davies (1987), most of the early tree-ring studies in the western part of the Himalaya were involved in the selection of sampling sites and the evaluation of tree species suitable for dendroclimatic analysis. Bhattacharyya et al., (1988) evaluated the potential of six conifers, *viz.*, *Abies pindrow*, *Cedrus deodara*, *Picea smithiana*, *Pinus gerardiana*, *P. roxburghii* and *P. wallichiana* in the Jammu and Kashmir region. They showed that two conifers, *Pinus gerardiana* and *Cedrus deodara*, growing in the dry inner valley of the Pir Panjal Range, south of Kashmir which is in the lower elevation it exhibited high age (which is up to 500 years) and the chronology of the tree were suggestive to drought response. Climatic reconstructions of spring and summer mean temperature and precipitation based on well-replicated samples of *Abies pindrow* and *Picea smithiana* were conducted in the Kashmir valley (Hughes & Davies, 1987). Later, Hughes (1992) did detailed reconstructions of mean temperature for spring (April-May), late summer (August-September) and the growing season (April-September) precipitation since AD 1780 based on ring-width and density chronologies of *Abies pindrow* at Srinagar, Jammu and Kashmir. Bhattacharyya and Yadav (1989b) reported that *Cedrus deodara* growing in Joshimath, Uttaranchal attains great age and its growth is inversely related to pre-monsoon temperature and positively related to precipitation during both summer and winter. Subsequently, there were a considerable number of studies on the reconstruction of the pre-monsoon temperature based on tree-ring data of *Cedrus deodara* either individually (Borgaonkar et al., 1996; Yadav et al., 1999; Yadav & Singh, 2002a) or in combination with *Pinus wallichiana* and *Picea smithiana* (Yadav et al., 1997).

Many tropical trees are known to produce growth rings since long back (Gamble, 1902; Chowdhury 1939, 1940a, 1940b) but their application in dendrochronology has not been much explored due to the problem of cross-dating and difficulties to obtain samples. Bhattacharyya and Yadav (1989a) discussed the cross-dating problems associated with tropical and subtropical tree species in the Indian subcontinent and identified several dendroclimatically potential taxa. Two taxa, teak (*Tectona grandis*) and toon (*Cedrela toona*) were found suitable.

Tree-ring studies in Kashmir Valley, northwest Himalaya were started with the revolutionary works on ring-width and wood densities of two taxa *Abies pindrow* and *Piceasmithiana* (Hughes and Davies, 1987). These were further analysed in various studies (Hughes, 1992, 2001; Ram, 2012; Ram and Borgaonkar, 2013, 2014). Climate reconstructions carried out in Kashmir Valley include temperature (Hughes, 1992, 2001), precipitation (Borgaonkar et al., 1994) and Palmer drought severity index (PDSI) (Ram, 2012). There are several records of tree-ring-based precipitation reconstructions from the western Himalaya and adjoining regions (Bhattacharyya and Shah, 2009; Gaire et al., 2017). Most of the earlier records (Hughes and Davies, 1987; Bhattacharyya et al., 1988; Hughes, 1992, 2001; Borgaonkar et al., 1994; Ram, 2012; Ram and Borgaonkar, 2013) were based on tree-ring chronologies composed of a small number (4–25) of tree cores.

The forest of *Pinus roxburghii* are found throughout the Western Himalaya from west Bhutan to Sikkims and central Afghanistan. In which the geographical distribution is influence by the southwest monsoon. In *Pinus Roxburghii* the growth rings studies have showed that several droughts of years had been mark by low index value of the growth rings.it is important to understand the pass monsoon behaviour in which the tree ring chronology of *P. roxburghii* growing in limited moisture areas with water supply through summer precipitation. However, the availability of longer tree ring chronology in India is limited due to heavy exploitation for resin extraction and thus the old trees are difficult to get for studies (Yadav, 1992)

Tree rings study of *Pinus gerardiana* from Shashu and Kistwar in Jammu and Kashmir (Bhattacharyya, et al., 1988) has indicated high mean sensitivity, high common variance and low first order auto-correlation. The dendroclimatic potential are clearly brought out the important parameters. The 300 to 400 years old trees are commonly components in natural forest as given and observed by the author. In the northwest Himalaya *pinus gerardiana* are grown in dry season beyond the reach of the monsoon and the tree ring chronological studies are helpful in the reconstruction of the winter precipitation and temperature.

In Hoshangabad, Central India were made to explore a dendroclimatic potential of teak for the reconstruction of climate (Shah et a., 2007). This tree species has been found in al limited growing by the low monsoon precipitation. The reconstruction of mean monsoon precipitation of June to September back to AD 1835 was based on ring width data of teak. In this reconstruction of climate record have shown several alternative periods of low and high monsoon episodes. Bhattacharyya et al., (2007) studied early wood vessels of teak through image analysis of dated tree rings at Perambikulam, Kerala, and found that rainfall during October and November (northeast monsoon) of the previous year and April of the current year is the most important climatic variable limiting the early wood vessel area.

The Indian summer monsoon (ISM) carries a large amount of summer precipitation to the Indian continent, and thus has a key influence on economic activity and society in this densely colonized region (Webster et al., 1998). The research on the ISM was mainly conducted with the study of inter decadal and inter annual variations by using climate models and meteorological data. El Niño–Southern Oscillation (ENSO) has great influence on ISM at inter annual timescales, and El Niño events (warm phase of ENSO) have usually produced ISM failure (Webster et al., 1998). Available tree-ring records are broadly distributed in the Indian monsoon region (Yadav et al., 2011). Southern Himalaya climate was dominated by the change in the Indian summer monsoon. Therefore, this region is suitable for the research study of Indian monsoon variations.

The tree ring studies in the Eastern part of the Himalaya in comparison with the western Himalaya are limited in number. Chaudhary et al., (1999) evaluated the dendroclimatic potentiality of seven conifer species, *viz.*, *Abies densa, Juniperus indica, Larix griffithiana, Pinus roxburghii, P. wallichiana, Taxus baccata* and *Tsuga dumosa*, growing at diverse ecological sites. Moreover, all these texa found datable and site chronology of all the texa have been prepared. Larix griffithiana, which is sub alpine deciduous conifer growing in Sange, Arunachal Pradesh, have been record for suitable temperature reconstruction in the month of May using ring width data. However, the chronology is not long enough to reconstruct climate beyond the existing meteorological records (Chaudhary & Bhattacharyya, 2000). In Shillong Plateau *Pinus kesiya* are grown on and around which is in Northeast part of India, have been reconstruct to evaluate for its suitable tree rings analysis. Five well-replicated, 80 to 142 years long site chronologies were developed and correlated with climate records of Shillong; but there is no common response of the growth of *Pinus kesiya* to climate (Chaudhary & Bhattacharyya, 2002). *P. kesiya* features moderately hard wood with a high resin content, ranging in color from light brown to red. The yearly rings are distinctly visible and can be applied for dendrochronological purposes. By Conventry, E. M.'s ring counting has shown that at elevations between 1371.6 m to 1676.4 m, there is a higher growth rate (mean yearly grith increase of 1.57 inches), but at higher elevations, it is lower (1.26 inches). At forty to fifty years old, the tree can reach an over bark girth of 6 feet at this pace of development (Troup RS, 1921).

Cedrus deodara grows between 1200-3300 meters above sea level in the Western Himalaya, which extends from Afghanistan to Garhwal. Its longevity and wide range of ecological requirements make it most suitable species for dendroclimatic studies in India (Bhattacharrya et al., 1988; Bhattacharrya & Yadav, 1989, 1990). A study of the growth-climate link using chronology from Joshimath, Uttarakhand has revealed that growth is generally favourable by cold, rainy summers and warmer winters.

Recently, a comparative analysis of tree-ring data of both northeast and northwest Himalayan trees was conducted to evaluate the suitability of sites for tree-ring studies and climate reconstruction and to understand the changes in climate in a regional as well as global perspective (Shah, 2007).

Bhattacharyya et al., (2007) studied earlywood vessels of teak through image analysis of dated tree rings at Perambikulam, Kerala, and found that rainfall during

October and November (northeast monsoon) of the previous year and April of the current year is the most important climatic variable limiting the earlywood vessel area. Based on the mean vessel area of earlywood, this region's northeast rainfall was recreated for the years AD 1743 to 1986. The practise of dendrochronology is developing a field of application of tree-rings for assessing biomass and tracking the growth of individual trees. The method is based on the formation of annual rings in many tropical trees in areas with one distinct dry season (Worbes, 2002).

2.3 Dendrochronology studies in northeast regions

Singh et al., (2016) developed the first *P. kesiya* tree-ring chronology from Manipur in Northeast India and evaluated the ecological significance of intra-annual density fluctuations (IADFs) in earlywood and latewood. They found that the IADFs that take place in the earlywood of *P. kesiya* were created by dry circumstances during April and June, whereas IADFs in latewood were created by increased the rain during August and September. The average temperature from April-June was also discovered a severely restricts tree growth. Their research provides a means of identifying intra-seasonal moisture variability and exposes the growth flexibility of *P.kesiya* in response to moisture variations.

In India, Chaudhury and Bhattacharyya, (2002) initiated dendrochronological investigation on this species in the Northeastern region. They collected 281 tree core samples from 143 living trees of *P. kesiya* and developed five new tree-ring chronologies. An important inverse relationship between the maximum temperature for June and the mean temperature for the previous December and the current May was found for LPF site chronology. LPF found a strong positive association with the amount of rainfall in December and April of this year, the latter of which was also found in the SRF chronologies. An important direct connection with rainfall and a significant inverse correlation with the mean temperature of March were noted in the USF chronology, March and April rainfall was similarly noteworthy and positively connected with the RKF chronology.

Another new *P. kesiya* tree-ring width chronology from Northeast India was developed from Mizoram by Upadhyay et al., (2019). Using *P. kesiya*'s raw ring width chronologies to differentiating between event years (or pointer years) that are positive and negative. They discovered correlations between drought and negative pointer years in their research.

Earlier efforts to utilized digital image of tree rings for anatomical analysis and to explore the facility of using reflected visible light instead of X-ray densitometry were conducted by Yanosky and Robinove in 1986, followed by Yanosky and colleagues in 1987. These studies were also pioneers in recognizing the possibility of using reflectance as an alternative to maximum wood density. Another approach involved analysing light transmited thin wood microsection, as demonstrated by Park and Telewski in 1993. However, this method necessitated the use of a microtone to create the thin sections of the samples.

2.4 Studies on tree rings chronology development

The chronology statistics (mean sensitivity and inter-series correlation) found in the present research fall within the range of those reported for the deferent conifer and broadleaved species from Nepal (Gaire et al., 2011; Gaire et al., 2014; Gaire et al., 2017a, b; Aryal et al., 2018; Liang et al., 2014; Thapa et al., 2015; Kharal et al., 2017). However, the measurement of the chronology created in the present research is incredibly short compared to that of previously prepared chronologies from Nepal (Gaire et al., 2011; Gaire et al., 2014; Gaire et al., 2017a, b; Aryal et al., 2018; Liang et al., 2014; Thapa et al., 2015; Kharal et al., 2017). According to research by Cook and Kairiukstis (Cook et al., 1990), the relationship between height and DBH with growth discovered that DBH is a poor predictor of tree age.

The rings of each sample were dated to the calendar year of its formation after using cross-matching technique of skeleton-plot method (Stokes and Smiley, 1968). The ring-widths were measured to the closest 0.01 mm using a Leica stereozoom microscope equipped with a Velmex linear stage interface with a computer system to record the measurements. These measurements and dates were re checked using the computer program COFECHA (Holmes, 1983) for any error in the measurement or dating of the samples. The age-related trend of the average raw ring-width in teak samples from both locations

Cross-dating of the species *Juniperus hochst* (African Pincle Cedar) was found complicated due to the irregular shape of the stem. The growth rings formation was found sensitive to local conditions due variation in precipitation regime (Conway et al., 1997, 1998; Wils et al., 2009)

In the South Island of New Zealand, 32 tree rings chronologies were developed from the three tree species and used for dendroclimatological reconstruction for the first time. The variation pattern of ring width within the tree has also been investigated (Norton and Ogden, 1986) In a palynological survey, Hatanaka and Miyashi (1980) reported that *C. japonica* was superior throughout the Holocene to give suggestion about constructing long tree ring chronology of buried tree

One of the first dendrochronological investigations was carried out in America by Andrew E. Douglass, who found a clear dependence between the width of growth rings in pine species from the southwestern part of United States of America (USA) and precipitation (A.E. Douglass, 1914). This research along with others stimulated the birth and development of dendrochronology, which promoted the realization of new studies mainly applied to reconstruct climate (dendroclimatology) (M.K. Hughes, 2002)

When discussing studies that use yearly tree growth rings it’s important to differentiate between research that use strict dendrochronological approaches such as cross dating, and those that only use ring counts to age trees or date events. Strict dendrochronological methods are extremely valuable to ecologists, because they provide tree-ring dates an absolute chronological foundation. In this review we have focused on research that have employed the strict dendrochronological technique, however, we also address other uses of tree-ring measurements, as we think that they can gain from a more accurate dendrochronological approach fritts (1976).

In addition to the robust mean weighting used in conventional methods, the ensemble weighting chronologies consist of two weighting algorithms (Cook ER, 1985). This weighting technique could be more effective at modifying the chronologies for samples having both living and sub-fossil cores. This is due to the fact that living and fossil cores generally have fewer periods that overlap and frequently show greater variances in mean chronology values. The weighting process can better retain low-frequency variations and tends to raise (lower) the chronology indices during times of high (low) climatic signals.

According to (Fang K, 2012, et al., 2012), this is due to the tree rings may integrate the monthly rainfall of successive months in the growth season and the precipitation from the dormant season can “compensate” for monthly water shortages. This phenomenon is more noticeable in areas with deep soil, which may hold onto water during the winter (the non-growing season) and promote tree development the following year. Sites with extremely shallow soil, such Xiaolong Mountain to (Fang K, et al., 2012) and the Guiqing Mountain regions Mountain (Fang K et al., 2010), likely to have tree development that is more responsive only to growing season hydroclimate conditions.

Meko et al., (1993) analysed the statistical properties and drought signal of climatically screened tree-ring chronologies network developed especially from the eastern USA and other parts. This network was further expanded by Cook et al., (1999) and used to examine tree-rings-PDSI relationship for drought reconstructions (1700- 1978) in continental U.S. Korner (1998) reviewed tree-line positions using data for worldwide tree-line position and described the reasons of tree-line formation in a global perspective.

Multiple climate proxies have been used by Mann et al., (1998) to rebuild the variations in climate for past six centuries and demonstrated that abrupt increases in temperature are connected with industrial development. 250 years chronology of Scots pine (Pinus sylvestris) based on height increment was developed by Pensa et al., (2005) and linked with summer season temperature for whole region at the northern timberline in Finland and Sweden. One of the major developments in tree ring studies was the publication of Monsoon Asia Drought Atlas (MADA), a tree-ring based atlas of variability in drought covering most of monsoon Asia for the past millennium.

One of the earliest tree-ring studies of *P. kesiya* was carried out in Thailand by Buckley et al., (1995). They created three chronologies of *P. kesiya* the most extensive of which had 45 series and came from the NNK site (1789-1994). The climate reacting the relationship of the NNK chronology showed a strong beneficial correlation between monthly rainfall, November mean and minimum temperature. Their work was later expanded by D'Arrigo et al., (1997) by developing two new chronologies. They also collected additional samples from the previous sites and improved the chronologies developed earlier by Buckley et al., (1995). An association between drought years and suppressed tree growth was noted by comparing the ring width indices with annual rainfall (D'Arrigo et al., 1997).

Ring width and density chronologies of *Abies pindrow* from sub-alpine forests in Kashmir Valley have been studied by Hughes and Davies (1987). Some of the chronologies date back to the seventeenth century, but good relationship with climate could only be inferred from early 18th century records. These chronologies had been discovered to be appropriate for recreating spring and early summer temperatures. Stable isotope ratios of hydrogen, oxygen and carbon in the annual rings of this species from Kashmir Valley have also shown good common variability (Ramesh et al., 1985, 1986). The isotope ratios are found to be significantly related to the climatic parameters of the growing season (Ramesh et al., 1986).

2.5 Tree rings studies with climate reconstruction

Other high-resolution records that can be employed as proxies for climate reconstruction (e.g. ice cores and historical documents) are also exceptionally scarce in sub- Saharan Africa (Verschuren, 2004) and the need to improve this situation has been noted by various authors (Gasse, 2000; Olago and Odada, 2004; Umer et al., 2004; Verschuren, 2004). Ethiopia, one of the world's least developed economies and the location of the major Nile River source, which supplies over 90% of Egypt's freshwater, makes the situation there especially dire. At the same time, research on climate change and its economic consequences in Ethiopia has been limited and fragmentary so far (Conway and Schipper, 2010).

Trees that thrive in regions with pronounced seasonality hold onto signs of historical mass migration that have a yearly or perhaps even monthly resolution. Tree-ring records could be among the most accurate natural archives available for recreating historical mass-movements and consequently, comprehending their historical context. Most dendrochronological studies concentrate on the reconstruction of the spatial and temporal distribution of different types of mass movements such as rock falls (Stoffel et al., 2005; Stoffel and Perret, 2006; Perret et al., 2006), landslides (Shroder, 1978; Fantucci and Sorriso-Valvo, 1999; Gers et al., 2001; Stefanini, 2004; Migoń et al., 2010), debris flows (Baumann and Kaiser, 1999; Boll-schweiler et al., 2007; Bollschweiler et al., 2008; Malik and Owczarek, 2009; Zielonka and Dubaj, 2009; Arbellay et al., 2010) and others (Denneler and Schweingruber, 1993).7

Bhattacharyya et al., (1988) evaluated the potential of six conifers, viz., *Abies pindrow,Cedrus deodara, Picea smithiana, Pinus gerardiana, P. roxburghii and P. wallichiana* in the region of Jammu and Kashmir. They verified that two conifers, *Pinus gerardiana and Cedrus deodara*, which were growing in the arid inner valley at lower elevations of the Pir Panjal Range, south of Kashmir, had tree-ring chronologies that indicated a drought response, along with high ages (up to 500 years). Climatic reconstructions of spring and summer mean temperature and precipitation based on well-replicated samples of *Abies pindrow* and *Picea smithiana* were conducted in the Kashmir valley (Hughes and Davies, 1987).

Hughes (1992) did detailed reconstructions of mean temperature for spring (April-May), late summer (August-September) and the growing season (April-September) precipitation since AD 1780 based on ring-width and density chronologies of *Abies pindrow* at Srinagar, Jammu and Kashmir. Significantly cool springs, early summers, and wet growing seasons were identified in this reconstruction, but no long-tern trend was evident. Bhattacharyya and Yadav (1989) reported that *Cedrus deodara* growing in Joshimath, Uttaranchal attains great age and its growth is inversely related to pre-monsoon temperature and positively related to precipitation during both summer and winter. Subsequently, there were a considerable number of studies on the reconstruction of the pre-monsoon temperature based on tree-ring data of *Cedrus deodara* either individually (Borgaonkar et al., 1996; Yadav et al., 1999; Yadav and Singh, 2002) or in combination with *Pinus wallichiana* and *Picea smithiana* (Yadav et al., 1997). A recent tree-ring study on *Cedrus deodara* growing at five moisturestressed sites in river basins of the western Himalaya revealed that extreme cool/wet climate conditions are acting more basin-specific whereas extreme hot/dry climate conditions are operating more on a larger scale (Yadav, 2007).

However, the majority of climatic reconstructions focused on temperature, a few studied investigated the hydrological conditions. The wettest and the driest non-monsoon months took place in 14th an 13th decade, respectively, based on the reconstruction of rainfall from AD 1171 during the non-monsoon months (October prior to May current). Both wet and dry spring years were noted during the Little Ice Age (Yadav and Park, 2000; Singh and Yadav, 2005; Singh et al., 2006).

Studies of Taxus baccata in the Gharwal Himalaya showed that the tree-ring sequences among different trees cross-dated well and were sensitive to the pre-monsoon temperature (March-June) (Yadav and Singh, 2002). Tree species, Abies spectabilis, was studied at four distantly located treeline sites in the Uttarkashi district by Yadav et al., (2004), they demonstrated a strong correlation among the site chronologies and strong responses of tree growth to changes of temperature. Pant et al., (2000) suggested that density parameters, viz., earlywood, latewood, minimum, maximum, and mean densities, as well as total ring width may be useful for dendroclimatic studies. Bhattacharyya and Yadav (1989) discussed the cross-dating problems associated with tropical and subtropical tree species in the Indian subcontinent and identified several dendroclimatically potential taxa. Two species, teak (*Tectona grandis*) and toon (*Cedrela toona*) were deemed appropriate.

2.6 Dendrochronology studies on tree growth climate relationship

Dendrochronology provides a useful tool for understanding the relationship between climate and trees (Fritts, 1976), as shown by several research studies as well as other projects currently underway worldwide (Hughes et al., 2011). Many of these studies have documented how climate influence the distribution of forests. Additionally, several recent studies based on tree rings have demonstrated that the response to climate varies with stand age (e.g., Esper et al., 2008; Yu et al., 2008; Rozas et al., 2009; Vieira et al., 2009; Zhang et al., 2009; Copenheaver et al., 2011; Hadad et al., 2015).

A strong positive correlation was found between the growth and precipitation in April and the spring (March-April-May, MAM) as well as the summer (June-September) period and the overall year precipitation. According to the growth-climate response study, it is clear that precipitation in the spring season is the primary restricting factor for the growth of *S. robusta*. The negative correlated of growth with temperature in May suggests that temperature-induced moisture stress in the late spring is essential for the development of the species. During the spring season, the temperature rises quickly, and trees that are stressed from dryness are unable to develop as much. The significance of the precipitation shown in the current study is likewise documented in research conducted in Nepal's middle to high mountains (Aryal et al., 2018; Sano, et al., 2005; Bhattacharyya et al., 2007) and some species in tropical areas of the Indian sub-continent (Deepak et al., 2010; Bhattacharyya et al., 2007; Shah et al., 2007) and Thailand (Borgaonkar et al., 2001). Temperature-induced moisture stress has been observed with a decreasing growth trend in the last several years in both standard and signal-free chronologies. This might be the result of temperature-induced moisture stress or drought stress in the region, as there is an ongoing increase in temperature and the declining trend in precipitation recorded in the research region in recent years. A comparable favourable correlation between yearly rainfall and the development of tropical teak trees was also discovered in Western Ghat (Deepak et al., 2010).

The science of reconstructing past climate by use of tree-rings is known as dendroclimatology which is a branch of the more general discipline of dendrochronology (Fritts, 1976). After Chow dhury's initial work on growth ring formation in relation to climate, limited work has been carried out in teak from the point of view of dendroclimatology at several sites of India viz., from moist deciduous forest in Thane, Maharashtra (Pant and Borgaonkar,1983; Ramesh et al.,1989; Bhattacharyya et al.,1992), dry deciduous forest in Korzi, Andhra Pradesh (Yadav and Bhattacharyya, 1996), Western ghats of Kerala (Bhattacharyya et al., 2007; Borgaonkar et al., 2010), upper Narmada river basin in Central India (Wood, 1996) and dry deciduous forests of Madhya Pradesh (Shah et al., 2007; Somaru et al., 2008) and outside India viz., from Thailand (Pumijumnong and Park, 1999; Buckley et al., 2007) and Indonesia (D’Arrigo et al., 1989; D’Arrigo et al., 2006). These investigations research demonstrated that teak tree rings might provide useful proxy information for dendroclimatic research, particularly for monsoon precipitation.

The study of dendroclimatology focuses on tree rings organic records of previous climates. The field of dendroclimatology has grown and developed over the last forty years since the inaugural international workshop on dendroclimatology in 1974, moving from a potentially fascinating technical method of high-resolution paleoclimatology to a significant source of evidence for decision-making (Hughes, 2002). The IPCC makes extensive references to the work on proxy records (Houghton et al., 2001), including tree rings, and the field of dendroclimatology has experienced a huge increase in interest regarding discussions on climate change. Furthermore, within the field of dendroclimatology itself, the issue of climate change has drawn attention.

It is a significant location for the dendroclimatic study because the monsoon rainfall in this area varies geographically. Some areas to the north in Western Ghats while receiving heavier rainfall are followed by long dry spells, while regions closer to the equator receiving less annual rainfall, have rain spells lasting almost the entire year (Ranjit, 2007).

Temperatures and precipitation are the two primary determinants of tree growth. To get insight into its function in tree growth, the standardized ring-width-index chronologies of two sites was linked with the yearly rainfall of matching sampling sites. The teak's narrow growth rings have been discovered to correspond with the little rainfall years. Earlier tree ring studies of teak from central Java region showed that rainfall of the previous year's rainy season and during the usual onset month of the current year's rainy season has significant relation to teak growth (Jacoby and D'Arrigo, 1989). This suggests that the moisture level of the soil before to the start of the following year's growing season is crucial for the growth of teak. Similar observation was also found by Ramesh et al., (1989) by using the stable isotope ratio of annual rings contains considerable potential for rainfall reconstruction.

The meteorological data (yearly rainfall) that is closest to the tree ring sample location, as provided from the meteorological stations in Dandeli and Shimoga, has been conducted for the ring-width study of teak. This record runs from AD 1941 to 1999 and from AD 1947 to 2007 for the Dandeli and Shimoga areas respectively.

Dendroclimatology basically studies at the link between climate and tree growth based on determined yearly increments. Through the measurement of yearly growth rings of many individuals with in a tree species, to create continuous growth chronologies. Whenever tree growth is restricted, either directly or indirectly, by climatic factors that can be measured and dated, the dendroclimatological methods may be used to recreate previous environmental circumstances. Tree rings have unique advantages compared to other proxies (i.e. ice core, lake sediments, etc.) as tree have a wide geographical distribution, their rings preserve a continuous record with an annual resolution and can consequentially be dated by ring counting (Managave and Ramesh, 2012).

Besides precipitation or temperature, other aspects of environmental issues were also addresses in certain tree-ring research. Ring widths in both *Cedrus deodara* and *Pinus gerardiana* were narrow mostly during years of deficient rainfall and also in years of an El-Niño event, which suggested that these two taxa have excellent potential to reconstruct long records of droughts (Bhattacharyya et al., 1992).

Divergent conclusions have been drawn from earlier research on how forests react to climate change as they mature. Some authors (e.g., Szeicz and MacDonald, 1994; Carrer and Urbinati, 2004; Linderholm and Linderholm, 2004; Esper et al., 2008; Rozas et al., 2009; Vieira et al., 2009; Hadad et al., 2015) contend that stand age influences the climate signals that can be seen in plants, but other research (e.g., Fritts, 1976; Linares et al., 2013; Sun and Liu, 2015) demonstrate that climate responses to growth are age independent. According to the current research, *P. cooperi* trees from the Sierra Madre Occidental in northern Mexico are more susceptible to the effects of climate than older trees, especially if they are younger than 80 years old. This effect could favour earlier leaf emergence or budburst (Lebourgeois et al., 2012), thus resulting in better growth in the early growing season. Given that tree growth has no independent effect to precipitation and temperatures, warm nights and wet winters can promote radial development in trees, but hot winter days have the opposite effect on tree growth.

Thus, winter rainfall combined with warmer *Tmin* ensures moisture availability and increases carbohydrate reserves for early wood during the early spring (March), when pines typically start to increase tree-radial growth (Stahle et al., 1998). If soil moisture is sufficient to maintain foliage water potential and minimize vapour pressure deficits, a proper moisture budget allows optimal tree growth for the next growth season (Dang et al., 1998).

The different temperature responses of trees imply that the stem contracts during the day, due to transpiration and photosynthesis and expands during the night when water reserves are gradually replenished, which translates in a better overnight hydration (Vieira et al., 2013). Thus, warmer days prevent development by causing moisture loss, whereas warmer nights promote growth. We discovered that for *P. cooperi*, the impacts of the preceding winter’s rising temperatures are age-dependent; that is, whereas warmer winter maximum temperatures have detrimental impacts on radial development that are stronger in younger trees.

The climatic sensitivity of trees may also be associated with hydraulic limitations (Carrer and Urbinati, 2004; Yu et al., 2008). Numerous researches have demonstrated that in trees with comparable environmental circumstances, hydraulic resistance rises with age and tree size. In addition, the rate of photosynthesis generally decreases with tree age; this may occur because old trees have greater access to water, and this occurs because their roots penetrate to greater depths (Bond, 2000). Furthermore, it was noted that precipitation has a similar influence on radial tree development in both age groups when comparing monthly precipitation with tree-ring chronology. This negative association may be explained as the result of a water deficit indirectly influencing the yearly growth of young trees. The elevated temperatures may produce an imbalance in soil water due to an increase in evapotranspiration. Hence, evapotranspiration and temperatures can become final determinant of the water balance and the functioning of younger trees in drought-prone ecosystems.

In *Nothofagus menziesii* and *N. solandri* significant relationships occur between ring-width in subalpine trees and temperature during the growing season (Norton, 1984) and between ring-width in lower altitude trees and growing season rainfall (Norton, unpubl.) also obtained positive correlations between current growing season temperature and ring-width in *N. solandri*. Changes in growth-climate relations in *N. solandri* along an altitudinal gradient have also been investigated (Norton, 1985).

The process of reconstructing historical climates begins with response function analysis. Knowledge of previous climates is important both for determining the likelihood of future climate changes (e.g. due to rising CO_2 levels) and understanding historical climate changes and their potential effect on current systems. Though palaeoclimate reconstructions have certain limits, they may produce a wealth of useful data, especially about the frequency of certain climate conditions or events.

A number of different climatic and related parameters have been reconstructed using tree-rings including temperature (e.g. Briffa et al., 1983; Hughes et al., 1984), rainfall (e.g. Cook and Jacoby, 1977), river flow (Jones, Briffa and Pilcher, 1984), sea ice conditions (Jacoby and Ulan, 1982) and synoptic pressure patterns (e.g. Fritts et al., 1979). Reconstructions of the summer temperature in New Zealand dating back to 1760 AD and precipitation and river flow in Canterbury dating to 1879 AD (Norton, unpubl), have been developed and demonstrated the kind of information that may be gathered. According to the temperature reconstruction, there was a noticeable period of below-average temperatures in the 1780s and above-averages temperatures in the 1830s.

Currently, dendrochronology's applicability has been primarily restricted to the temperate and boreal regions, because of the strong seasonality of the climate, which causes trees to periodically generate growth rings with distinct wood-anatomical borders. Strong annual cycles in temperature and light availability in temperate and boreal regions force trees into dormancy (no cambial activity) during winter, causing the formation of distinct annual rings (Fritts, 1976).

2.7 Dendroclimatic studies with related to carbon

Devall and Parresol (2003) during their dendrochronological investigation of teak and mahoe (*Hibiscus elatus*) found that July and November were the best growth period of teak species at Rio Abajo. The growth literally decreases during occurrence of several hurricanes but it increases following year. They conclude that teak is a suitable species for subtropical wet forest as it grows better than native species, mahoe. Kohl et al., (2017) studies the diameter growth-annual Carbon accumulation in 61 trees of Cedrela odorata, Hymenaea courbaril and Goupia glabra which resulted to have positive trends of diameter growth and carbon accumulation ultimately. Averages of 39% to 50% of carbon stock were accumulated by Carbon. Thus, old trees not only contribute to stoking of carbon but sustain increase rates of Carbon accumulation at subsequent stages of their lifespan. Eguakun and Adesoye, (2015) assess the potential of carbon sequester by *Pinus caribaea* and *Tectona grandis* under climatic variations which shows that average Carbon stock is 994.4 ± 188.3 kg and 1350±180.6 kg. Therefore, choice of species is important for adapting mitigation strategies under climatic variations since different species differs in Carbon stocking rate.

Pompa et al., (2018) revealed the potential of species-specific ring data in providing better estimation of Carbon accumulation given that tree ring showed individual tree and annual resolution thus minimizing doubt in forest carbon budgets. They reported that Carbon accumulation was not significant across different sites where representative pines species were growing. However, Carbon accumulation varies with responds to different specific functional features of species, hydroclimate drivers, site conditions. Annual Carbon accumulation was more sensitive to precipitation during cold season and early spring for both *P. arizona* and *P. cembroids*. Overall, Carbon accumulation was less sensitive to climate variable than ring width and wood density. Gedalof and Berg, (2010) reported that increased growth of trees is directly corresponded to CO_2 fertilization effect. The growth increased trend were not species specific except for Douglas fir and Ponderosa pine and the results showed that offset emission is rarely affected by the CO_2 fertilization.

Sanogo et al., (2016) studied the possibility of dendrochronology in determining growth dynamics with regard to climate change and estimation of Carbon stock and sequestration of Vitellaria paradox and the result showed that distinct tree rings were well visible. The result also clearly showed the potential of dendrochronology as a means of extracting growth and Carbon sequestration and that with change in climate conditions, rate of growth and Carbon sequestration were affected. It calls for researcher’s attention to evaluate Carbon sequestration on other tree species using dendrochronological investigation.

Gujarat Ecological Education and Research (GEER) reported teak as one of the most potential trees to sequestrate Carbon, about 3.70 lakh tonnes of CO_2 can be taken up by teak having a girth of 10-30cm during its lifespan. Pichhode and Nikhil, (2017) depending upon plantation techniques, silvicultural practice and maintenance, teak as a great potential for carbon sequestration and mitigation strategies for climate change and so thus enhance forest ecosystem in terms of growth and biomass. Jones et al., (2015) developed species-specific model of *Pinus kesiya* and other tree compartments which totals to 16 models. The best fitted models for total above biomass are TAGB=0.067 D and TAGB= 0.0000003855 (DH)+ 0.023(DH) +3.496, having high r and adjusted r values of 0.087 to 0.99 yielding more accurate biomass for *Pinus kesiya* than mixed species models developed by Brown and Schroeder, (1999); and Chave et al., (2005). Thereby, they recommended these models for estimating biomass and Carbon sequestration of *Pinus kesiya*.

Chapter 3

Material and Methods

The study area is situated in the northeastern region of India, covering four states viz. Nagaland, Arunachal Pradesh, Meghalaya, and Mizoram. Positioned between latitudes 22°N and 29.5°N and longitudes 88.00°E and 97.3°E, the North Eastern Region shares international borders with Bhutan, China, Myanmar, and Bangladesh. Mizoram marks the southern boundary as the Tropic of Cancer passes through it. Covering an area of 262,179 km^2, Northeast India shares its international borders with Bhutan to the northwest and is divided into two distinct biogeographic zones: North East India and the Eastern Himalaya. This classification is based on the floral diversity, authenticity, and local climate, as defined by Rodgers and Panwar in 1988. The region is connected to the rest of India through a narrow corridor in North Bengal, measuring just 30 km in the west and 20 km in the east.

Characterized by predominantly mountainous terrain, covering nearly two-thirds of the area, the region also features the Brahmaputra and Barak plains, along with the Meghalaya plateau. The relief is diverse, ranging from near-sea level elevations in the Brahmaputra valley to heights as tall as 7,000 meters above sea level in the Eastern Himalaya. Arunachal Pradesh and Sikkim, located in the Eastern Himalaya, experience a cooler mesic climate due to high rainfall levels, resulting from the direct force of monsoon winds merging as they approach from the Bay of Bengal and colliding with the sharply rising hills.

The major rivers, including the Brahmaputra and Barak, along with numerous tributaries, drain the entire northeast region.

Nagaland, Mizoram, Assam, Manipur, Meghalaya, and Tripura collectively constitute the highly significant biogeographic zone known as North East India. As highlighted by Rao in 1994, this region serves as a crucial convergence point between the Himalayan mountains and Peninsular India. Additionally, it functions as a transitional zone connecting the biogeographic areas of India, Indo-Malayan, and Indo-Chinese.

The chosen sites are predominantly situated on hilly terrains and exhibit a wide range of climates, spanning from sub-tropical to temperate and even alpine conditions. This region is significantly influenced by the southwest monsoon, resulting in substantial rainfall, with an average annual precipitation of 2,000 mm. Temperature levels fluctuate according to altitude, and areas situated above 2,000 meters (6,562 ft) experience snowfall during the winter months. The study will involve the collection of tree core samples from diverse locations, with a focus on specific tree species.

To identify potential sites for tree-related studies, a thorough understanding of the regional climate and vegetation is essential. This will provide an overview of the climate and natural vegetation in the region.

3.1 Natural vegetation

The Northeastern region of India boasts a diverse terrain, varying elevations, and a wide range of climatic conditions, all of which contribute to its abundant and diverse flora and fauna. This region stands out for its high concentration of unique and endemic species and falls within the Indo-Burma biodiversity hotspot. Despite covering only, a fraction of the country's total land area, the forest cover in Northeast India makes a substantial contribution, accounting for nearly a quarter (about 24%) of the country's total forested area (Forest Survey of India, 2019). In the following sections, we will provide a brief overview of the various forest types found in the region, as described by Chauhan, (1996).

a. Tropical moist and dry deciduous forests

These forests thrive at altitudes of up to 900 meters above sea level and are typically found in regions with an annual rainfall ranging from 1500 to 2000 mm, featuring a dry period during winter (December to March). They can be located in various areas, including parts of Goalpara, Nowgong, Darrang, and Kocharigaon in

Assam. Additionally, these forests are present in the northern and northwestern regions of the Garo hills in Meghalaya, parts of Tripura, Northwestern Mizoram, and the forests of Moreh, Jiribam, and Tamenglong in Manipur. Among the tree species in these tropical moist and dry deciduous forests, the Sal tree (*Shorea robusta*) stands out as the most prominent and covers significant portions of the forested areas.

Moist deciduous forests are a critical habitat type in India, with previous studies primarily focused on regions like the Western Ghats, Eastern Ghats, and Andaman Island. However, there is limited data is known about the demographic makeup and composition of lowland moist deciduous forests. Given that the remaining fragmented forests are rapidly diminishing or undergoing modifications due to various human-made influences, there is an urgent need to collect quantitative inventories to better understand the tree diversity and stand structure in these fragmented lowland forests and their nature and dynamics. (Sundarapandian and swamy, 1997). Other important tree species found in these forests include *Acacia catechu, Artocarpus hetreophyllus, Bombax ceiba, Bauhinia purpurea,Lagerstroemia parviflora,* and *Tectona grandis, Dalbergia sissoo, Phyllanthus emblica, Schleichera oleosa, Madhuca longifolia, Santalum album,* etc.

b. Tropical evergreen and semi evergreen forests

Tropical evergreen and semi-evergreen forests thrive at altitudes up to 1200 meters above sea level, receiving a substantial annual rainfall ranging from 3000 to 5000 mm, accompanied by high relative humidity. These lush forests are typically located in the foothills and along river banks in all the states of the region. The uppermost canopy of these forests features an array of majestic trees, including *Laurus nobilis, Dalbergia latifolia, Mesua Ferrea,* thorny bamboo – Western Ghats, *Thuja occidentalis, Aesculus indica, Magnolia champaca, Mangifera indica,Ailanthus integrifolia, Dipterocarpus retusus, Elaeocarpus aristatus,* among others. In the middle canopy, you can find trees such as *Alstonia scholaris, Castanopsis indica, Dillenia indica, Ficus racemosa*, and more. These forests are characterized by their vibrant and diverse ecosystem, which plays a crucial role in the region's biodiversity.

c. Tropical grassland

Grasslands can be found in various landscapes, both in plains and at higher elevations. These grasslands are sustained through different mechanisms, including recurrent annual fires at higher altitudes and extensive grazing at lower altitudes. It grows in warm or hot climates where the yearly rainfall ranges from 50.8 to 127 cm (20-50 inches) and the annually precipitation in savannas is 76.2-101.6 cm (30-40 inches). The presence of tropical grasslands is typically attributed to a combination of natural and anthropogenic factors. These factors include floods, landslides, forest fires, widespread logging, the clearing of forests, and overgrazing. Within these grasslands, you can find some noteworthy tall grasses that can reach heights of about 5 meters, such as *Arundinella decempedalis, Imperata cylindrica,* and *Saccharum griffithii.*

These grasslands are also home to various important tree species, including *Albizia* species, *Dalbergia* species, *Dillenia indica*, and Lagerstroemia speciosa, among others. These trees contribute to the overall biodiversity and ecological balance of the grassland ecosystems.

d. Sub-tropical mixed forests

These forests are characterized by their evergreen and dense nature, harboring a wide variety of species. Within these lush ecosystems, you can find climbers, orchids, and ferns, adding to their biodiversity. These particular forests thrive at altitudes ranging from 1000 to 1600 meters above sea level, receiving annual rainfall between 1500 and 4000 mm. They are spread across several states in Northeast India, including hilly regions in Assam, Meghalaya, Koubru and Nongmaiching hills in Manipur, and areas along the border with Burma (Myanmar) in Manipur and Mizoram. You can also find them in the Patkai ranges of Nagaland. Among the many tree species in these forests, you'll encounter *Duabanga grandiflora, Castanopsis purpurella, Pinus kesiya, Myristica spp, Quercus acutissima, Phoebe goalparensis, Podocarpus neriifolia, Prunus cerasoides, Alnus nepalensis, Albizia chinensis, Betula alnoides, Cryptocarya amygdalina, Quercus gambleana, Rhus semialata,* and more. The second stratum of these forests includes trees like *Acer oblongum, Brucea mollis, Dysoxylum gobara, Itea chinensis, Litsea khasyana, Neolitsea umbrosa, Rhus semialata, Syzygium praecox*, and others, contributing to the rich biodiversity of the region.

e. Sub- tropical pine forests

These forests thrive at altitudes ranging from 900 to 1800 meters above sea level, with conditions characterized by moderate rainfall. *P. kesiya* is typically found in isolated patches, often accompanied by various broad-leaved species. These may include, but are not limited to, *Eupatorium adenophorum, Daphne papyracea, Lyonia ovalifolia, Rubus ellipticus, and Viburnum* species. During the rainy season, certain species like *Agrimonia nepalensis, Artemisia nilagirica, Ranunculus cantoniensis*, and more, occasionally emerge in clear patches on the forest floor, which is typically covered with pine needles.

f. Temperate forests

Temperate forests thrive at altitudes ranging from 1400 to 2500 meters above sea level. These evergreen forests are characterized by their substantial and aged tree trunks, which are adorned with mosses, ferns, and other epiphytic growths. These forests are pristine, impenetrable, and composed of virgin primary growth, making them distinct from the characteristic temperature forests in the eastern Himalaya region. The most common tree species in these forests are *Rhododendron arboreum, Litsea salicifolia, Michelia spp., Betula alnoides, Pinus kesiya, Elaeocarpus serratus, Garcinia anomala, Myrica esculenta, Alnus nepalensis, Castanopsis armata, Echinocarpus dasycarpus, Exbucklandia populnea, Ilex excelsa, Prunus cerasoides, Quercus griffithii, Schima khasiana,* and more.

g. Bamboo forests

Bamboos usually make up the underneath of tropical evergreen and subtropical mixed-deciduous forests, However, Melocanna baccifera bamboo can be found in pure stands in some parts of the state. These bamboos typically thrive within an elevation range of 40 meters to 1520 meters in regions that are tropical or subtropical, with only a few kinds occurring in temperate regions like Phawngpui and Mount Chalfilh. Alongside the bamboo, you can find predominant species such as *Litsea monopetala, Emblica officinalis, Pterospermum acerifolium, Terminalia myriocarpa, Caryota mitis, Artocartus chama, Duabanga grandiflora, Albizia procera, Gmelina arborea,* and various *Syzygium species (*Singh et al., 2002*).*

h. Sub alpine forests

This type of vegetation is typically located at higher altitudes, ranging from around 2800 to 4500 meters above sea level, and is characterized by a dense growth of small, crooked, and stunted trees. Among these forests, Sikkim fir (*Abies densa*) stands out as one of the dominant tall tree species. Additionally, important shrubby vegetation in these areas includes *Astragalus membranaceus, Berberis, Cassiope lycopodioides, Junipers, Pyrus communis, Rhododendron arboreum, Salix, Taxus,* and more.

i. Jhum land

Jhumlands refer to forest areas utilized for shifting cultivation, a method involving the clearing of land by slashing and burning existing vegetation to grow agricultural crops. These forest areas are classified into three categories based on their current use status: current jhumland, old jhumland, and abandoned jhumland.

3.2 BIOGEOGRAPHY OF THE STUDY SITES

A. NAGALAND

Nagaland has an extensive forest cover, encompassing 134,464 km², which constitutes a remarkable 81.2% of the state's geographical expanse. Within this verdant landscape, approximately 10% of Nagaland, equivalent to 1,274 km², is enveloped by dense forests.

The forest composition reveals that 36% of the cover is moderately dense, spanning an area of 4,897 km², while open forests account for 54%, totalling 7,293 km². Village forests sprawl over 12,455.77 km², and additional segments include national parks (20.02 km²), reserved forests (85.83 km²), purchased forests (192.46 km²), protected forests (507.56 km²), and wildlife sanctuaries (20.35 km²). Notably, an extraordinary 92.51% of Nagaland's expanse is privately owned.

Situated in one of the top 25th biodiversity hotspots globally, Nagaland hosts a rich tapestry of flora. The state embraces around 2,431 species of angiosperms from 963 genera and 186 families. Gymnosperms contribute 9 species from 6 genera and 5 families. Nagaland thrives on the cultivation and commercial utilization of various species of bamboo, cane, and orchids. Additionally, the state is a haven for medicinal plants, boasting 20 species of high commercial value, including *Valeriana wallichii, Tagetes minuta, Aconitum heterophyllum, ginseng, lemon grass, Smilax china, Taxuz bacata* and *Conitum ferox.*

The Fauna variety of Nagaland is equally impressive, featuring uncommon birds and animals. The state hosts 32 species of mammals, 65 species of avian, 42 species of fish spanning 10 families and 24 genera, and 9 reptilian species. Some pristine areas of Nagaland harbor a plethora of endemic species across plants, animals, and microorganisms, contributing to the richness of the state's ecological tapestry.

Forest types

Nagaland is blessed with diverse forest types owing to its wide range of elevations, from few 100 meters to around 4000 meters within the tropical region. According to the Champion and Seth Classification, Nagaland's forests can be categorized into Northern Sub-Tropical Pine Forests, Northern Tropical Semi-Evergreen Forests, Northern Montane Wet-Temperate Forest, Northern Tropical Wet Evergreen Forests, and Northern Sub-Tropical Broad-leaved Wet Hill Forest.

Climate

Nagaland has a distinctive monsoon climate with variances ranging from tropical to temperate climates. The longest monsoon season lasts five months, from

May to September with peaks occur in May, June and July. Different areas have annual rainfall ranging from 1000 mm to over 3000 mm, averaging around 2000 mm due to diverse topography and relief. Summer temperatures can fluctuate between 15 to 30 degrees Celsius, while winter temperatures range from below 5 to 25 degrees Celsius.

Site description

Kohima Botanical Garden is a stunning and diverse horticultural oasis situated in Kohima, the city of Nagaland, India. Located in the New Ministers' Hill Ward of Kohima, this garden is meticulously cared for by the Nagaland Forest Department, its latitudes 25.649343°N and longitudes 94.0992154°E, and it has an average elevation of 1261 meters. Kohima Botanical Garden gives an extensive array of native and exotic plant species, including trees, shrubs, blooming plants, and medicinal flora, the garden provides a tranquil escape just outside the city. Beyond its aesthetic appeal, the garden stands as a crucial hub for botanical research and education. Kohima Botanical Garden seamlessly blends natural beauty, research, education, and recreational opportunities, making it a multifaceted gem for both locals and tourists.

The weather is not too hot nor too clod during the summer season from March to June which is 20°C to 30°C. but after the rainfall the climate change it get hot and humid, whereas, in the monsoon i.e. from July to October the temperature ranges from 25°C to 30 ° C, in winter season i.e. the month of January, February, November and December is the coldest month in which the temperature ranging from 5°C to 19°C as shown in the (figure 3.1), whereas frost occur at the higher altitudes. Where as in the month of May to September the average temperature 25°C to 29°C. The rainfall mostly starts in the month of May to September which also has a maximum precipitation (figure 3.1). And the root zone moisture has mostly effective in the month of September which has the highest i.e. 0.77cm (figure 3.1).

The climograph in Figure 3.1 illustrates the average monthly climatic variables during the analysis period. It indicates that the maximum temperature reaches 28°C, while the minimum temperature fluctuates between 5°C and 19°C. The peak precipitation occurs from May to September, with July experiencing the highest precipitation levels. Regarding root zone moisture, its influence is relatively low during the early growth season. The moisture content starts at 0.61 cm in April and extends through October. September records the highest root zone moisture for the month at 0.76 cm.

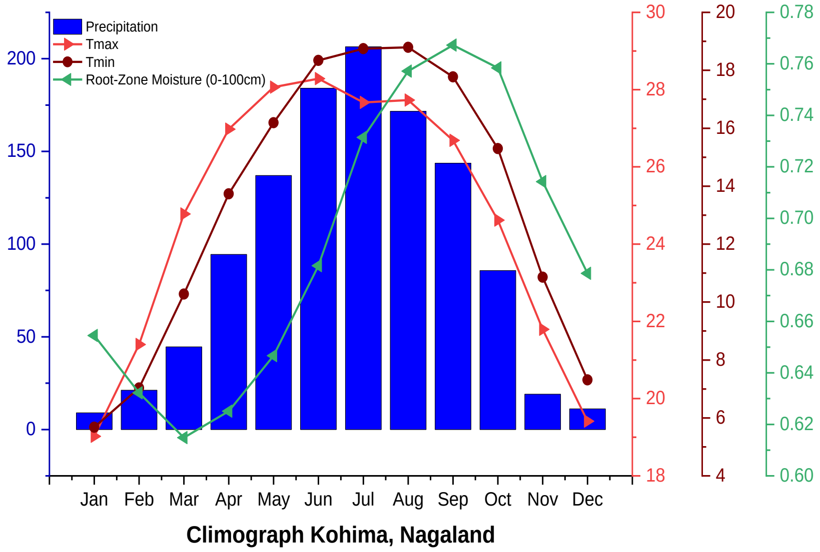


Figure 3.1. Climograph of Kohima, Nagaland.

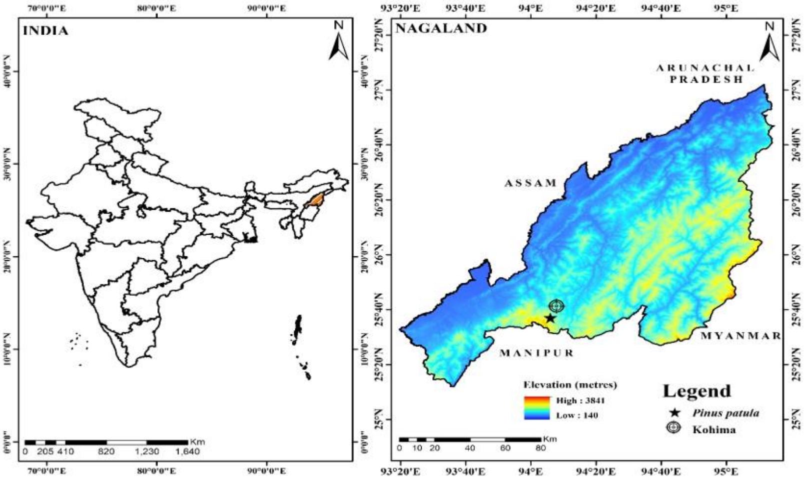


Figure 3.2. Map showing the location of tree core sampling site of *Pinus patula* at Nagaland, Northeast India.

Table 3.1. Details of tree core sampling site of *Pinus patula* at Nagaland, Northeast India.

Species name	***Pinus patula***
Site name	Kohima Botanical Garden, New Ministers’ Hill Ward of Kohima
Lat (^{0}N)	25^{0}38.943’
Lon (^{0}E)	094^{0}05.971’
Elev (m)	1417
SL	Moderate
NT/NC	30/60

SN= site Name; SC=site code; Lat (^{0}N) = latitude in degree north; Lon (^{0}E) = longitude in degree north; Elev (m) = sampling site elevation in meter; SL = Slope of the site; NT/NC = number of tree/ number of cores.

B. ARUNACHAL PRADESH

Forests stand as a vital resource in the state of Arunachal Pradesh, where mainly sizeable tribal people live in close connection with and is heavily dependent on them. Serving as the backbone of the Arunachal Pradesh population, these forests represent the eastern Himalayan zone’s richest biogeographical region. The state is home to 20% of all the fauna species in the nation, in addition to 20 species of canes, 52 species of rhododendron, 4500 species of flowering plants, 23 species of conifers, 400 species of pteridophytes, 35 species of bamboo, and more than 500 species of orchids. Recognized as one of the world’s 12 mega diversity "Hot Spots", these forests play a pivotal role in generating employment and stand as the single largest source of revenue for the state.

Arunachal Pradesh holds the distinction of being the largest in term of area among the states of the North-Eastern and ranks as the second-largest state in term of forest cover, surpassed only by Madhya Pradesh inside the nation. Known as the "Prabhu mountains” in the writing of Mahabharata and Kalika Purana, Arunachal Pradesh boasts incredibly gorgeous hilly forest ranges, spanning from Alpine to

Tropical rainforest, adorned with silvery fir trees, abundant climbers, and luscious grass.

Forest area

Covering 51,540 km^2, the state's forest area constitutes 61.55% of the total land area. Among the documented forest area, respectively, together with protected forests and unclassified woods make up 20.46%, 18.49% and 61.05%. Private individuals own just 15,500 ha of the total forest area, while the state possesses 5.138 million ha. In accordance to the Forest Survey of India (FSI)'s release of the India State of Forest Report 2021 on the 13th of January, Arunachal Pradesh, which has a geographical area of 83,743 km^2 and 16 hills districts (out of 25; the newly divided one is not shown separately), has experienced 257 km^2 decline in forest cover since the 2019 evaluation.

The state is home to eleven Wildlife Sanctuaries and two National Parks, with respective areas of 0.23 million and 0.5 million hectares. The percentage of the state's total land area that is protected is 11.68%. The state of Arunachal Pradesh is home to two 2,847 km^2 Tiger Reserves: Namdapha and Pakhui. In addition, a Biosphere Reserve has been established for the area of 5,112 km^2 Dehang-Dibhang valley.

According to ISFR 2021, the geographical area comprises 79.33% of total forest cover, which includes both inside and outside the reported forest area, totaling 66,430.67 sq km. This includes 15,196.74 sq km (18.15%) of open forest, 21,058.37 sq km (25.15%) of very dense forest, and 30,175.56 sq km (36.03%) of moderately dense forest. The area of scrub, which is not part of the total, is 796.98 square kilometers (0.95%).

Forest types:

According to the Champion and Seth Classification, the state encompasses 16 forest types, organized into 10 forest type groups. These groping consist of Sub-Alpine Forest, Himalayan Dry Temperate, Subtropical Pine, Dry Alpine Scrub, Tropical Wet Evergreen, Tropical Semi-Evergreen, Himalayan Moist Temperate, Tropical Moist Deciduous, Subtropical Broadleaved Hill and Moist Alpine Scrub.

Climate

The state experiences a humid, hot, and subtropical climate in the foothills, characterized by a windy, cool, and pleasant climate at lower altitudes, transitioning to a cold climate in the higher snow-covered mountains. The heavy monsoon rainfall often leads to floods and landslides, particularly in the evergreen regions of Lohit and Tirap.

The climate in Arunachal Pradesh varies with elevation. The Upper Himalayas, situated at a very high elevation near the Tibetan border, experience an alpine or Tundra climate. Moving below to the Middle Himalayas, the climate transitions to a temperate one. Areas at sub-Himalayan and sea-level elevations generally encounter a moist, sub-tropical environment characterized by scorching summers and mild winters. The region receives substantial rainfall, ranging from 80 to 160 inches.

Site description

The Tawang district covers an approximate area of 2172 sq. km., sharing borders with Bhutan to the south and west, West Kameng district to the east, and Lower Tibet to the north. Situated about 180 km. from Bomdila, the district is characterized by latitudes 27°52′N to 27°28N and longitudes 91°32’E to 92°23’E. With a population of 38,924 residing in 181 villages (as per the 2001 census), Tawang district spans an elevation from 6,000 to 22,000 feet, with inhabitants predominantly found in lower altitudes, enjoying a cool temperate climate.

Comprising three subdivisions, three blocks, and nine circles, Tawang district's administrative hub is located in Tawang town. The district's river network was part of the Brahmaputra River basin, featuring notable rivers such as Tawang-Chu and Nyamjang-Chu, both flowing in a south-westerly direction. The drainage pattern is predominantly dendritic to sub-parallel, aligning with the geomorphological trends of the hills and mountains. Most streams and rivers in the district are perennial, winding through narrow, deep gorges in the hilly terrain, eventually contributing to the Manas River.

In the district, annual rainfall typically ranges from 1500 mm to 2000 mm, with the Tawang area receiving around 1600 mm annually. The primary period of rainfall occurs from the end of May to September (Figure 3.3), aligning with the monsoon season. During this period, heavy rains characterize the summer months, while winters experience intermittent snowfall and rain. The driest months are December, January, and February (Figure 3.3). Summer precipitation is influenced by the South-West monsoon, usually commencing around the end of May or the first week of June and concluding by the end of September or the beginning of October (Figure 3.3). The local topography significantly shapes the district's climate, resulting in bitterly cold winters and mild summers. Despite the moderate temperatures, the mountain peaks retain snow throughout the year, and winter temperatures often drop below freezing.

The climograph in Figure 3.3 presents the average monthly climatic variables for the analysis period. It indicates that the maximum temperature is 20°C, while the minimum temperature ranges from -8°C to 10°C. However, during December, January, and February, which are the coldest months, temperatures can sometimes drop below freezing. The peak precipitation occurs between June and September, with July experiencing the highest levels. The average root zone moisture has a minimal impact in the early growth season, especially in January and February. In September, the root moisture reaches its highest point at 0.78 cm.

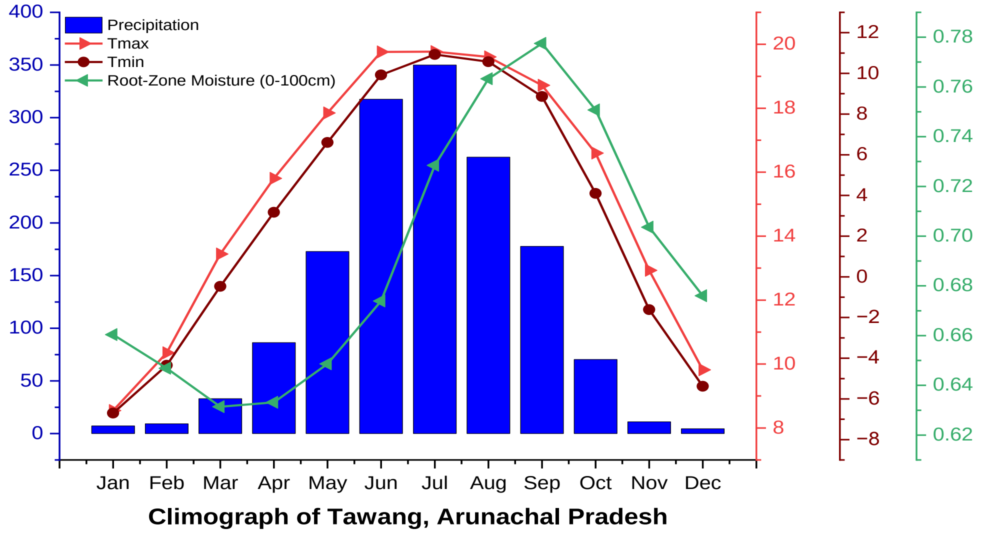


Figure 3.3. Climograph of Tawang, Arunachal Pradesh

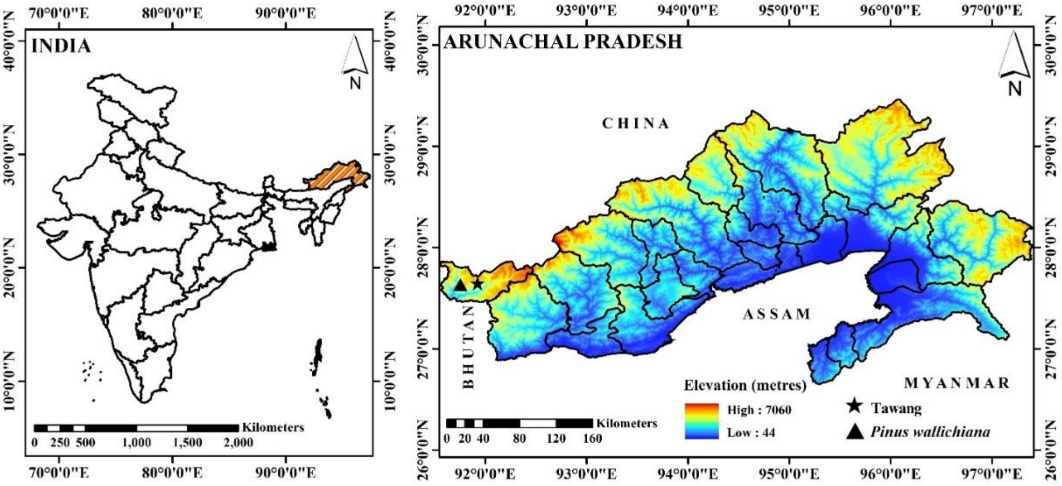


Figure 3.4. Map showing the location of tree core sampling site of *Pinus wallichiana* at Arunachal Pradesh, Northeast India.

Table 3.2: Details of tree core sampling site of *Pinus wallichiana* at Arunachal Pradesh, Northeast India.

Species name	***Pinus wallichiana***
Site Name	Tawang area
Lat (^{o}N)	27^{o}34.527’
Lon (^{o}E)	091^{o}51.684’
Elev (m)	2756
SL	Moderate
NT/NC	16/32

NT/NC = the number of trees divided by the number of cores; SC = site code; Lat (^{o}N) = latitude in degree north; SN= site Name; Lon (^{o}E) = longitude in degree north; SL = Slope of the site; Elev (m) Sampling site elevation in meter.

C. MEGHALAYA

Meghalaya is located in the North Eastern region of India, Meghalaya occupies 22,429 sq. km, or 0.68% of the nation’s total land area. Bangladesh borders the state on the south and west, while Assam borders it on the north and east. It is situated between latitudes 24°58'N and 26°07'N and between longitudes 89°48'E and 92°51'E. Three distinct regions comprise the state: Khasi Hills, Jaintia Hills and Garo Hills. It lies in the region with heavy rainfall, with an average of yearly rainfall ranges from 4,000 mm to roughly 11,500 mm. Mawsynram the wettest spot-on Earth. With average temperature varying from 12°C to 33°C, the Western portion of the State experiences higher temperature. The mean temperature in the central uplands ranges from 2°C to 24°C, which is relatively colder. Several rivers drain the State including the Sanda, Simsang, Umngot and Myndu. There are 13 districts in the State, all of which are hills and tribal districts Meghalaya has a population of 2.96 million, making up 0.24% of all Indians according to the 2011 census. The urban and rural population constitute 79.93% and 20.07% respectively. The State has a far lower population density than the national average-132 people per sq. km.

It is one of the few states in the union which can be proud in having a wealth of natural trees that cover almost all of its territory and was far greater than the national average. Its location physiographical features, altitude variation, copious amount of rainfall, temperature climate, and rich soil all contribute to a high degree of species diversity, and encourages different types of forests. Types of vegetation includes tropical rain forest, cold deserts and alpine meadows located in foothill regions. As the name suggests, "Meghalaya" is an abode of clouds, therefore it has a lot of moisture in the air. In the north, the hills rise gradually, but in the south, they rise unexpectedly. The altitudinal deviation, which takes place from 50 to 1950 meters with the Shillong plateau at the peak. There are many rivers and rivulets that cut through and drain the hills to the north and south. There are two distinct warm-wet and cold-dry seasons in the monsoonal weather. The Southern part of the State contains the wettest places in the world, Sohra (Cherrapunjee) and Mawsynram, due to their extreme rainfall. A beautiful landscape is created by the plateau's rolling hills, streams, deep ravines, waterfalls, and hills covered in a rich vegetation, all of which are nourished by rain water. A unique and rare animals and plants can also be seen in the forests. In terms of botany, the preserved primary forests are extremely rich and well-known.

Forests of Meghalaya

Forests of the State are the home to approximately 800 medicinal plant resources, 40 bamboo species, 352 orchid and more than 3500 flowering plants. The state is a part of the Indo Burma Biodiversity Hotspot on a global scale. Meghalaya is home to over 40 endemic species and 75 Threatened plant species. Among its endangered species are the insect eating Pitcher plant (*Nepenthes khasiana),* Wild citrus *(Citrus indica)* and Pygmy Lily *(Nymphaea tetragona)*. The Rhododendron Forest near Shillong Peak is a well-liked tourist site during the flowering season, which spans from February to April.

Meghalaya is a state rich in forests. Being a predominately tribal State, rural resident's lives depend heavily on forests in both sociocultural and socioeconomic aspects. In contrast to other States, the private sector and the local people own the majority of Meghalaya's forests. The three Autonomies District Councils viz Khasi Hills, Jaintia Hills and Garo Hills was in charge of managing both public and private Forests. Shifting cultivation was still common in the State. The official communication received from the State, throughout the previous five years, namely from 2014-2015 to 2018-2019, 178.7 hectares of forest land have been redirected for non-forestry purposes per the FC Act, 1980. SFD has grown 2,982 ha of plantations in the same time. In 2012, the State announce an Act that provided definitions for forest The state's network of protected areas, which makes up 2.22% of its total land area, is comprised of 65 Community Reserves, four Wildlife Sanctuaries, and two National Parks.

The Forest Survey of India's State of Forest Report, 2017 states that the state has 17,146 sq. km (76.44% of Geographical area) of forest cover and 657 sq. km (2.92% of Geographical area) of tree cover. As opposed to the National Goal of keeping two-thirds of the country's land area in hilly and mountainous areas, the State has 79.37% forest and tree cover, and making up 2.26% of India's Forest and Tree Cover. The State was ranked fourth in the country in terms of the percentage of forest cover. However, due to the existing land tenure structure, the State Forest Department only has direct jurisdiction over 1145.19 sq. km of forest areas, or 5.10% of the overall geographic area and are referred to as Reserve Forest, Protected Forest, National Park, Wildlife Sanctury, Parks and Garden and the remaining forest areas belong to District councils, clans, private people and communities.

Meghalaya's Forest Types

In the State, Sub-Tropical, Semi Evergreen and Sub- Tropical Pine, Deciduous and Evergreen Tropical Forests are all thriving. The wide variety of flora ranging from Temperate, Sub-Tropical and Tropical types are a result of the varied topography and variation in precipitation.

Climate

The height and distribution of physical relief have an impact on the Meghalaya plateau's temperature. Depending on weather conditions, the Meghalaya plateau has 4 distinct seasons: these are

May to the start of October is the rainy season.

Early October through November is the cool season.

December to February is the chilly season.

From March to April is the warm or hot season.

During this time, the whole plateau observed strong winds. This was due to the creation of low pressure on the Tibetan plateau at this time of year and the migration of jet streams northward from the Gangetic plain to the Tibetan plateau.

In comparison to the Khasi and Jaintia hills, the western part of the Garo hills is slightly lower in elevation. Garo hills saw greater temperatures and more humidity between February and October. January is the coldest month, as well as April and May are the warmest. The distribution of rainfall has also been impacted by the nature of elevation and slope. Rainfall is highest in the South-eastern Garo hills and lessens in the North and Central areas. Because of their higher elevation, the Khasi and Jaintia hills experience a temperate climate. The foothill regions in the south, the sub-montane region in the north, and the central uplands is known for their warm and humid weather.

The Mawsynram and Cherrapunji area is located in the southern part of the plateau. With an average yearly rainfall of 12670 mm, it has the highest amount of rainfall. It is located near the head of the Bangladesh plains, which explain why. As it abruptly emerges from the plains, the south-west monsoon meets these borders. A lot of precipitation falls in the escarpment area due to the vertical movement of this moist monsoon. This type of rainfall refers as orographic rainfall.

Site description

The Riat Laban Reserve Forest in Motinagar, covering an area of 2.05 sq. km, is located in the East Khasi Hills District, near Shillong, the capital of Meghalaya. It falls under the supervision of DTO (T) East Khasi Hills District, Shillong, and has a history spanning over a century, marked by dedicated security and management efforts. In 1874, during a visit by the Viceroy of India to Shillong, specific areas were earmarked for timber production and water conservation for the city (Lyngwa, 1997).

Situated in hilly terrain, the reserve forest is surrounded by some of the highest points of the Meghalaya plateau, including the prominent Laitkor and Shillong peaks. The capital city of Meghalaya is named after Shillong Peak. In the late 20th century, the renowned British botanist L. M. Bor acknowledged the Shillong Peak forests, considering them a traditional grove. The forest vegetation in Upper Shillong, specifically in Riat Laban and Laitkor, is characterized as sub-tropical Pine and Broadleaf types.

Within the Pine Forest, *Pinus kesiya*, also known as Khasi pine, is the sole species present. In the Broadleaf areas, prominent trees such as *Pyrus paschia*, *Rhododendron formosum*, and *R. arborea* continue to thrive.

At the Riat Laban, Motinagar, the temperatures range between 20°C to 23°C in summers and 4°C to 13°C in winter.

The climograph in Figure 3.5 presents the average monthly climatic variables for the analysis period. It indicates that the maximum temperature is 27°C, while the minimum temperature ranges from 6°C to 21°C. The coldest months are January, February, November, and December. The maximum precipitation occurs during the late months of April to September, with June and July experiencing the highest levels. In contrast, the average root zone moisture has a minimal impact in the early growth season, particularly in January and February. September records the highest root moisture content at 0.95 cm.

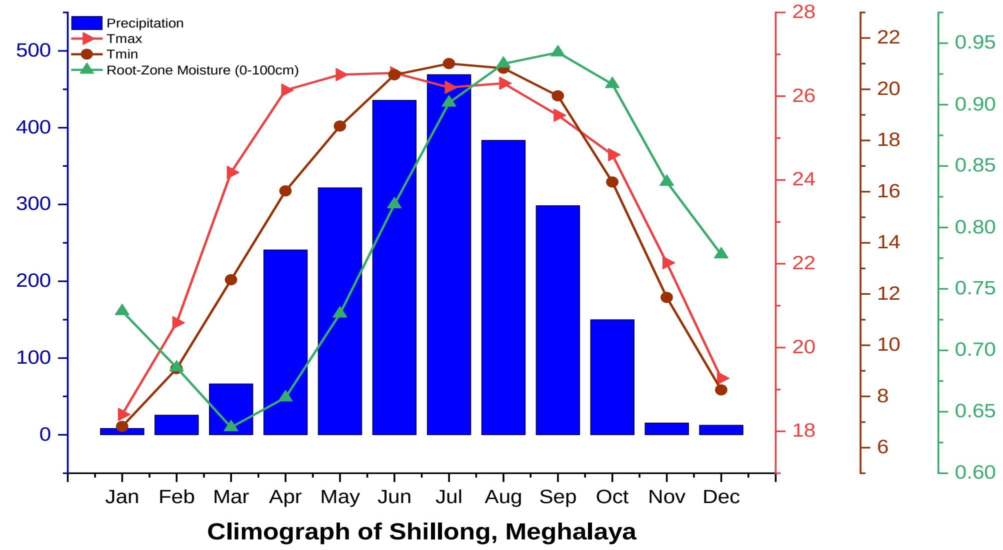


Figure 3.5. Climograph of Motinagar forest, Shillong, Meghalaya.

The samples were collected from Motinagar, within the Riat Laban Reserve Forest, situated approximately 3.5 km from the main city. Core samples were collected from 30 trees, with two cores obtained from each tree. Defect-free trees were selected randomly.

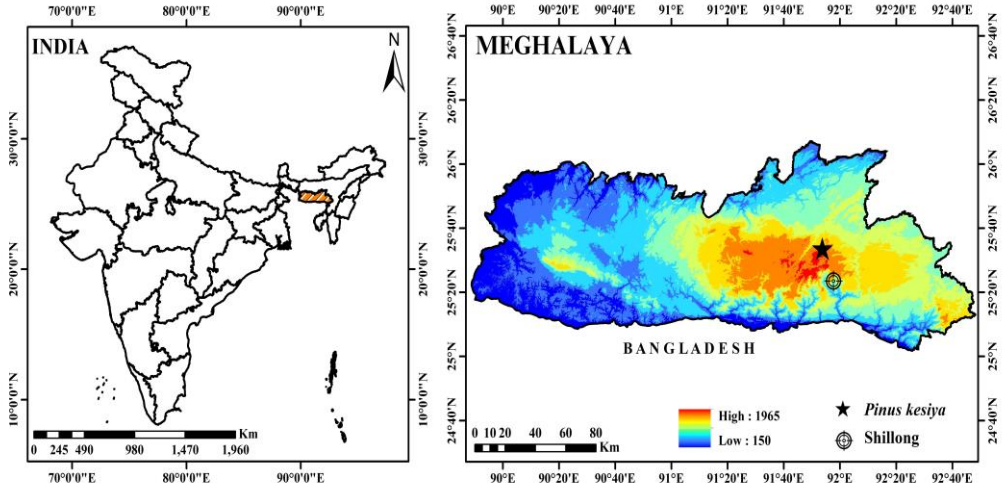


Figure 3.6. The map displays the *Pinus kesiya* tree core sampling site located in Meghalaya, Northeast India.

Table 3.3. Details of tree core sampling site of *Pinus kesiya* at Meghalaya, Northeast India.

Species name	***Pinus kesiya***
Site name	The Riat Laban reserve Forest
Lat (ºN)	25º33’35.82”
Lon (ºE)	091º53’47.54”
Elev (m)	1687
SL	Moderate
NT/NC	30/60

SN= site Name; SC=site code; Lat (ºN) = latitude in degree north; Lon (ºE) = longitude in degree north; Elev (m) = sampling site elevation in meter; SL = Slope of the site; NT/NC = number of trees/ number of cores.

D. MIZORAM

The state is known for its rich flora and Fauna, with many rare and endemic plant and animal species. Mizoram, among all the states, claims the highest proportion of geographical area covered by forests. The state’s forests are managed through a three-tier system, involving the village councils, state and district councils.

The forests of Mizoram are classified into six Forest Types and four Type Groups in accordance with the 1968 Champion & Seth Classification of Forest Types. In the state, importance top canopy species may be found in the tropical wet-evergreen forests like Mesua ferrea, *Amoora wallichii, Michelia champaca, Dipterocarpus turbinatus, Artocarpus chaplasha* and *Terminalia myriocarpa*. Abundant bamboo species occupy the middle and lower levels of the evergreen forest, along with variety of canes. Mizoram is home to 27 reported bamboo species.

Forest area

The state’s Recorded Forest Area is 5,641 sq. km, including 1,158 sq. km of Unclassed Forests and 4,483 sq. km of Reserved Forest. From January 1, 2015, to

February 5, 2019, a total of 0.24 hectares of forest land in Mizoram was diverted for non-forestry purposes under the Forest Conservation Act, 1980 (MoEF & CC, 2019).

Mizoram boasts 8 Wildlife Sanctuaries and 2 National Parks, encompassing a total area of 1241 square kilometers, which constitutes 5.89% of the geographical area. Among these, the Dampa Tiger Reserve is situated in the state, covering an expanse of 500 square kilometers.

Forest cover

The latest assessment from the Forest Survey of India, Dehradun, reveals that Mizoram has a forest cover estimated at 18,005.51 square kilometers, accounting for over 85.41% of the state's total land area (India State of the Forest Report, 2019). According to the National Forest Policy of 1988, the national objective is to attain a tree or forest cover of at least one-fourth of the total land area. Specifically, in hilly and mountainous regions, the goal is to maintain vegetation covering approximately two-thirds of the land. This approach aims to prevent soil erosion and degradation while preserving the stability of the sensitive ecosystem.

Types of forests

There are reportedly six major forest types in the state i.e. Cachar Tropical Semi-Evergreen Forest, Secondary Moist Bamboo Brakes, Pioneer Euphorbiaceous Scrub, East Himalayan Moist Mixed Deciduous Forest, East Himalayan Subtropical Wet Hill Forest and Assam Subtropical Pine Forest.

Climate

Mizoram experiences a moderate climate throughout the year, characterized by neither extreme heat nor cold. The entire state falls under the direct influence of the southwest monsoon, ensuring an ample supply of rainfall. With an extended summer, brief winter, and abundant precipitation, the climate is humid-tropical. Temperature fluctuations are minimal, with peak temperatures recorded from May to July, dropping with the onset of the monsoon. The lowest temperatures occur in

December and January. Autumn temperatures range between 18°C and 30°C, while winter temperatures vary from 11°C to 25°C, indicating a relatively mild climate.

The higher elevations of the hills endure predictable frigid temperatures, especially during the summer, while the lower sections remain warm and humid. Storms typically occur in March-May, preceding or around the beginning of summer. In Mizoram, the winter season spans the four months from November to February, followed by spring. The rainy season extends over the three months from June to August. September and October are considered autumnal months, characterized by a favorable and moderate climate, with temperatures ranging between 19 to 24 degrees Celsius.

Over the past two decades, there has been a noticeable increase in the average temperature, likely attributed to global warming. This phenomenon is primarily a result of the unsustainable development model and environmental mismanagement. A significant rise of 1.8°C in the mean maximum temperature occurred in just five years, from 2000 to 2006, contributing to the unpredictable and non-periodic nature of rainfall. The irregular rainfall patterns and the increase in mean maximum and mean minimum temperatures may be linked to a sharp decline in forest cover, attributed to various activities such as road construction, insufficient implementation of forest acts, and the absence of a monitoring body.

Site Description

The tree cores were collected from the forest division of Mizoram state which is a division of Champhai Forests. Champhai Forest Division occupied almost all of the area of the district. Becaused of its highest elevation among eight District of the state and it was famous for having the largest plain areas of the state which is mostly used for cultivation. According to Koppen’s climatic classification, the state is divided into humid subtropical climate and subtropical climate respectively. Champhai experience a lot of rainfall and are influenced by the southwest monsoon. Champhai receive an average yearly precipitation of 2062 mm and temperature ranges from 13.5°C to 21.3°C.

The climograph in Figure 3.7 displays the average monthly climatic variables for the analysis period. It reveals that the maximum temperature is 33°C, while the minimum temperature ranges from 4°C to 18°C. The coldest months are January, February, and December. The maximum precipitation is observed during the months of June to September, with these months experiencing the highest levels. In contrast, the average root zone moisture has a limited impact during the early growth season, particularly in January, February, and December. From June to September, the root zone moisture content is most effective.

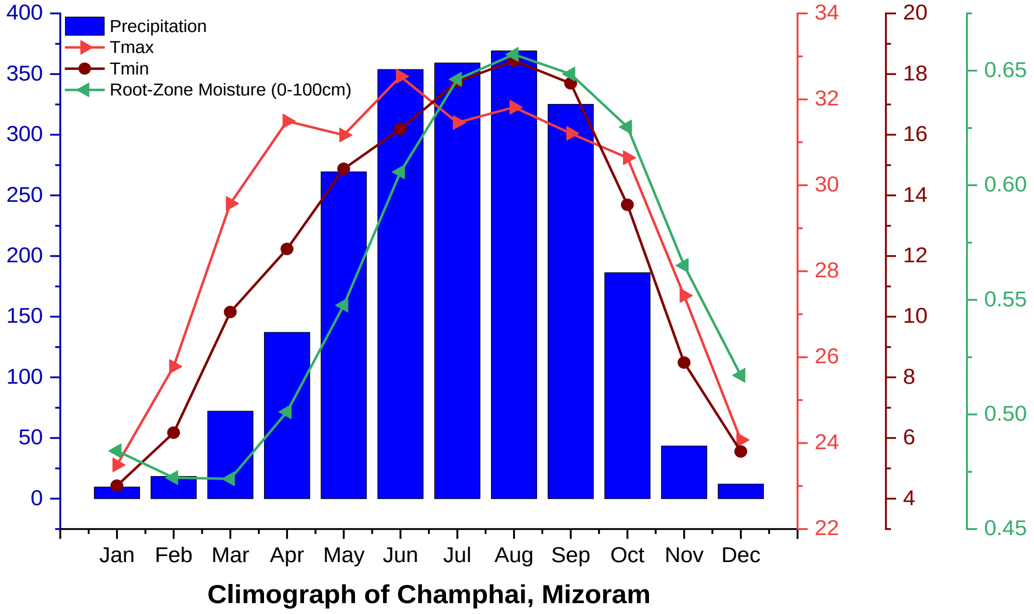


Figure 3.7. Climograph of Champhai, Mizoram.

The sample were collected from Vengther village of Champhai forest division. Vengther village is located at 3 km towards East from the District Head Quarters Champhai

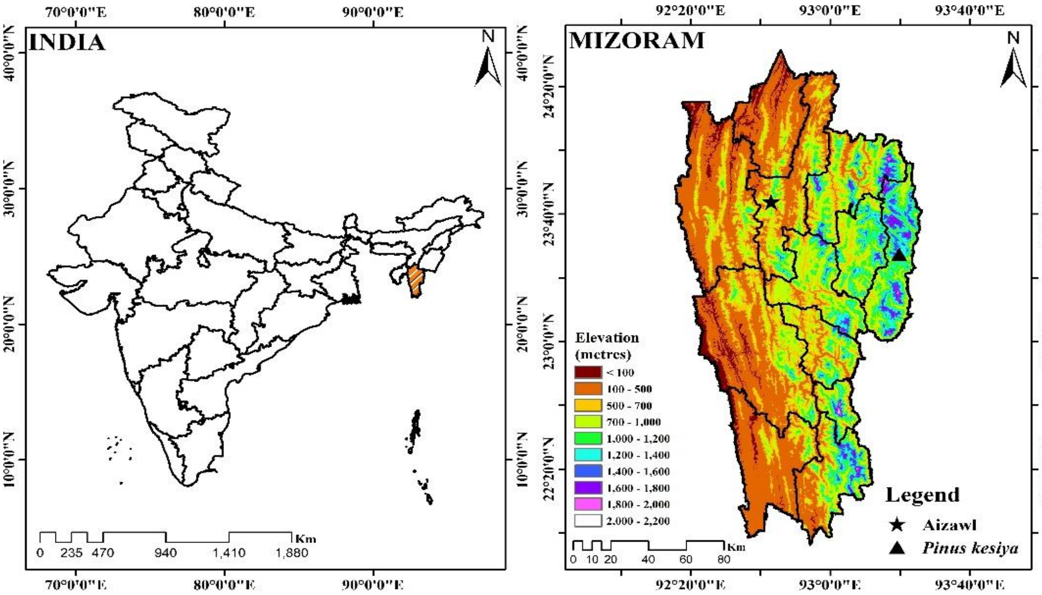


Figure 3.8. Map displaying the location of the *Pinus kesiya* tree core sampling site in Mizoram, Northeast India.

Table 3.4. Details of tree core sampling site of *Pinus kesiya* at Mizoram, Northeast India.

Species name	***Pinus kesiya***
Site name	Vengther Village
Lat (^{0}N)	23^{0}32’ 19.33”
Lon (^{0}E)	93^{0}22’ 24.67”
Elev (m)	1566
SL	Moderate
NT/NC	20/40

NT/NC = the number of trees divided by the number of cores; SC = site code; Lat (^{0}N) = latitude in degree north; SN= site Name; Lon (^{0}E) = longitude in degree north; SL = Slope of the site; Elev (m) Sampling site elevation in meter.

3.3 SPECIES DESCRIPTION

A. *Pinus wallichiana*

Class: Pinopsida

Order: Pinales

Family: Pinaceae

Genus: Pinus

Common name: Blue pine

Local names: The following words is used in French: pin de Himalaya, pin peuleur; English: Bhutan pine, Himalayan blue pine, Himalayan white pine; Germany: traneniefer; Pakistan: biar, kali; India: biae, chil, kail, lion; Italy: pino dell, iamlaia, pino excelsa.

Botanic Description*:* *Pinus wallichiana* is a tree that can reach up to a height of 50 m, featuring a straight trunk and short, downcurved branches. In solitary trees, branches tend to be longer, forming a crown shaped like a dome. Young trees' bark is smooth at first, but as they become older, it develops fissures. Branching patterns consists of smooth, uniformly spaced whorls. Glaucous young shoots eventually turn a light grey-green color as they mature, and they remain smooth, ribbed, and darken with age. The winter buds are grey with an orange tinge, ovoid-conic, and pointed.

The leaves are arranged in fascicles of 5, and basal sheaths are deciduous, measuring 15-20 cm long, often curved at the base. They are slender and flexible, with the abaxial side being green and the adaxial side featuring multiple bluish-white stomatal lines. Usually pendant, in some trees, they may spread.

On lower branches, male strobili are typically seen in dense groups on younger twigs. Cones that are female are 20-30 cm long and occur in clusters of one-six, they are initially youthfully erect but later becomes pendant as they mature. The cones are bluish-green in their youth, maturing to light brown with pale brown apophyses.

Biology: Seed production typically starts between the ages of 15 and 20 years. These types of trees exhibit strong tendency to outbreed, and self-fertilized seeds typically display poor growth. As they remain on the tree, cones open to release their seeds. However, the number of plants that may flourish beneath the trees is restricted because leaf secretions prevent these seeds from germinating.

Depending on the region, new leaves appear in March or early April and mature to maximum size by August or September. Needle shedding happens from June through August. Before the female cone develops, male flowers at different heights bloom on the lower branches of the trees in April and May. By June, the male flowers have released pollen. In the majority of places within their natural range, cones mature between early September and November. About 16-18 months pass between the first development of female flowers and the ripening of cones.

Ecological: In Nepal, this species thrives at altitudes ranging from 1800 to 3600 m, occasionally reaching up to 4400 m. It frequently forms mixed stands with *P. roxburghii*. Typically, it exhibits a distinctive presence in abandoned fields and grazing lands, extending from Afghanistan in the west to Bhutan in the east, originating from Nepal. This tree has a high affinity for light, often demonstrating invasive tendencies under favorable circumstances.

Limits of Biophysics: Height ranges from 1500 to 3600 m, mean annual temperature from 12 to 17°C, mean annual rainfall from 250 to 2000 mm, rainfall regime of summer; winter; bimodal, soil type: the plant grows best in well-drained, porous soils with sufficient soil depth above the rock. It can also adapt to limestone.

Tree management: A hardy yet relatively short-lived tree in cultivation, its seedlings exhibit frost hardiness. Young trees that have been burned by fire may sometimes emerge from the base, although they are less fire-resistant. Drought conditions may affect small seedlings following the monsoon season. Though dense matted grass is hazard, they may tolerate competition from shrubby growth. The seedlings are readily harmed by browsing. When the tree is young, it grows quickly, producing new shoots that can reach up to one meter annually. By the age of 30, trees attain a height of 20 meters. Growth in height diminishes rapidly after reaching 25 meters, likely due to their aversion to exposure at that height.

Traditionally managed under selection systems, there is a gradual shift toward a systematic system of shelterwood with periodic blocks that are fixed. Rotation times range from 120 to 200 years for various forests. In new blue pine crops, cleaning and weeding are usually unneeded. Even though thinning is preferable, most people don't do it for financial gain.

Management of Germplasm: According to the research on seeds obtained from eight locations in northern Pakistan also indicate that cold, dry conditions are best for storing seeds, making up for years with low yields. The most favorable propagation outcomes were noted after 120 days of stratification in moist sand and nursery planting at a temperature of 15-20°C for the soil. Ideally, the seeds should be sown in individual pots in a cold frame as soon as they ripen or, alternatively, in late winter. A brief 6-week stratification at 4 degrees Celsius can enhance the germination of seed that have been kept.

Diseases and Pests: The species is prone to a number of diseases and pests. In the North Western Himalayan region of India, *Dioryctria abietella* causes significant damage to the cones and seeds of *P. wallichiana*. In 1975, a large-scale pine mortality occurred in Western Bhutan, and was ascribed to bark beetles known to be lps stebbingi. Additionally, in 1980, Pakistani blue pine forests saw a serious Biston regalis epidemic for the first time ever.

B. ***Pinus patula***

Class: Pinopsida

Order: Pinales

Family: Pinaceae

Genus: Pinus

Common name: Mexican weeping pine

Local common name: Spanish (ocote, pino patula, pino chino), French (pin argenate), English (spreading leaved pine, patula pine), Brazil (pinheiro), Germany (kiefer, mexikanische), Maxico (ocote), Nepali (patula salla).

Botanical description: *Pinus patula* may grow to a height of thirty meters or more with a diameter of up to 1.2 meters at breast height. The bole is cylindrical and straight, with occasional forking, giving rise to two or more stems. In wider spacing conditions, the crown tends to spread, displaying a rounded or spirelike shape. Young bark exhibits a distinctive reddish-orange color with a scaly texture, while mature bark takes on a grey-brown hue with vertical ridges.

The leaves, arranged in fascicles of 3 (occasionally 4, rarely 5), are slender, pendent, measuring 15-25 cm in length, and display a light green to yellowish-green color. Margins are sharply serrate, and both the dorsal and ventral surfaces have stomata.

Cones are hard, strong, serotinous, generally slightly curved and reflexed, measuring 7-10 cm long, incredibly tenacious, sessile, and show a glossy brown or yellowish-brown in color. They continue to remain on the tree and are carried in 3-6 groupings, displaying considerable variability in dimensions and form.

The seeds are tiny, measuring just 5 mm in length, and have a pale brown wing that is about 17 mm long and has a somewhat thicker base where it connects the seed. The seeds themselves are dark brown to nearly black.

The name 'Pinus' is originating from the Greek word 'pinos,' which means pine tree, and probably from the Celtic word 'pin' or 'pyn,' signifying rock or mountain, in reference to the pine's natural environment.

Biology: *P. patula* is a monoecious plant, meaning that female flowers are usually carried in the upper crown and male flowers are usually found in lower crown.

Ecological: Commonly found in densely populated stands, *P. patula* displays a fragmented distribution, predominantly thriving in areas that are challenging for cultivation. Throughout its range, *P. patula* is frequently associated with *P. gregorii* and *P. teocote*, and there are reports of hybridization. Along with *Abies religiosa*, *Taxus Mexicana*, and hardwood species including Acer, Cercis, Fagus, Tilia, and Liquidambar, it also coexists with *P. montizumae* and *P. rudis*.

Biophysical boundaries: Height: 1,000-3,000 m, mean annual rainfall: 1,000-2,000 mm, mean annual temperature: -10-28°C.

Type of soil: Common properties of soil are both acidity and ad abundance of moisture. On the highlands of East Africa, it flourishes on recently formed, in young, rich volcanic soils, as well as in mature, leached, and infertile soils derived from the basement complex in other locations across South Africa and East Africa.

Management of Tree: In most regions, *P. patula* initial spacing normally varies between approximately 2.4 and 2.75 meters. In general, closer spacing is advisable for saw logs, especially to encourage knot-free wood. On poorer sites, wider spacing is recommended. Current saw log schedules aim for approximately 250 trees per hectare with a mean diameter at breast height (DBH) of 45 centimeters during a 45-year rotation. Rotations for pulp projects differ; 15 years in Swaziland and 25 years in South Africa is the suggested period.

Management of Germplasm: *P. patula* exhibits orthodox seed storage behavior, retaining viability in open storage for a minimum of three years. After 21 years of hermetic storage at 5°C, a few seeds can survive. Viability may be maintained in hermetic storage for several years at 3°C with a moisture content of 7-10% and for 6 months at room temperature. The amount of seeds per kilogram varies on the origin and environmental circumstances of the ripening year, averaging about 143,000 seeds per kilogram. It is possible to reach 98% purity.

Diseases and Insect Pests: Most insect pests that harm *P. patula* are defoliators, mostly from the order Lepidoptera. *Saturniidae, Noctuidae, Lasiocampidae,* and *Arctiidae* are notable families. During the nursery stage, defoliators, different leaf rollers, and cutworms cause damage. Pest seen in plantation environments include adult bark beetles (such as the mottled pine bark weevil), leaf-eating beetles, and sucking insects like the pine woolly aphid. *P. patula* is susceptible to diseases such as armillaria root rot, branch tip die-back, and foliage leaf cast.

C. *Pinus kesiya*

Class: Pinopsida

Order: Pinales

Family: Pinaceae

Genus: Pinus

Common name: Khasi pine

Local Name: Hindi (Saral, fir, dingsa, dingse, dieng-kysi), Burmese (tinyu), Filipino (khasya pine, tapulao), English (Khasya pine, Benguet pine, Khasi pine), French (pin a trois feuilles), Thai (chuang), Trade name (khasi pine).

Botanical Description: *Pinus kesiya* is an imposing tree with the capability to reach heights of up to 45 m. It has a branch-free bole that extends 15-20 m and can achieve a diameter of up to 100 cm. The bark is notably thick, featuring a reticulated pattern and deep fissures, varying in thickness from 25.4 mm to 45.72 mm. Its branchlets often showcase a pruinose texture with a waxy bloom. *P. kesiya* stands as an evergreen tree with nearly whorled branches, creating an oval crown in young trees and a rounded one in mature ones. Usually every year, the tree develops two whorls of branches, the spring internodes being longer than the summer internodes. The wood, which is frequently used for building in the Khasi hills, is resinous, somewhat hard, and has a pale brown to red color. This species holds promise for resin and turpentine oil production (Troup RS 1921). The needles, arranged in bundles of 3, are extremely slender and flexible, measuring 12-21 cm in length and has a vibrant grass-green hue.

Mature cones, usually occurring in clusters of up to three, hang pendulously and adopt an ovoid to ovoid-conical shape, varying from 5-8 cm in length. These cones can be either subsessile or positioned atop a short stalk, measuring up to 10 mm long, with apophysis that may be either beaked or flattened, displaying a short, blunt, deciduous umbo.

The seeds are small, each accompanied by a short wing measuring 1.5-2.5 cm in length. Ongoing debate surrounds the potential amalgamation of *P. khasya* and *P. insularis* into *P. kesiya*, driven by variations in field features and goods. According to some authors, *P.kesiya* has not been fully characterized.

Biological: The tree sheds old needles from April to May, coinciding with the complete or almost full size of fresh needles, which last for one year and one-three months. In February and March, fresh branches appear and begin to yield blooms. *P. kesiya* is a light-demanding tree although it can withstand some shadow in its early years the extent of which depends on aspect and situation. It is a wind-firm species characterized by an extensive taproot system. According to Troup RS 1921) the tree is prone to fire injuries and is particularly susceptible during its young stage, often leading to tree mortality.

Ecology: Among all the tropical pines found in Asia, the Khasi pine has the broadest natural geographic distribution. It mainly occurs in the Naga hills of Nagaland and Manipur, the Mizo hills of Mizoram, and the Khasi hills of Meghalaya in India. It is distributed in an altitudinal range of 762 to 1950 meters in India, with optimal performance observed at elevations between 1220 and 1372 meters. While it often forms pure or nearly pure stands, it occasionally associates with broadleaved vegetation, particularly along riverbanks. Beyond India, it can be found in Myanmar, Thailand, China, Laos, Vietnam, and the Philippines. Under favorable conditions, the tree can reach a height of 30 meters or more and a girth exceeding 300 cm (Troup RS 1921).

Limits of Biophysics: Height: 300-2700 meters; average yearly temperature: 17-22°C; average yearly rainfall: 700-1800 mm, with a noticeable dry season.

Management of Germplasm: The seeds can be preserved for a number of years, when stored in a cool, dry atmosphere and sealed tightly in a container. The weight of one thousand *P.kesiya* seeds weigh 16-18 grams

Diseases and Pests: In the Philippines, Pine shoot moths (*Dioryctria rubella*) can cause problems in *P. kesiya* stands, whereas bark beetles (*Ips calligraphus*) may cause issues in *P. kesiya* plantings. The insecticides fenitrothion (0.1%) and fenvalerate (0.2%) are effective against the pine shoot moth. In northern Sumatra, the primary pests include shoot and stem boring Pyralids, local squirrels, and members of the Psychid and Geometrid families (e.g., *Milionia basalis*).

3.4 Basic concept of the principle of dendrochronology

Dendrochronologists adhere to fundamental principles and ideas that outline sample procedures, model the integration of environmental elements on tree growth, and establish essential procedures for dating tree rings and constructing chronologies. The signal-to-noise ratio plays a crucial role in measuring the extent of required data that is documented in the chronology compared to the unneeded data and random variance were discovered in the tree-ring collection. Sound can originate from environmental elements that are not the focus of the research. Calibration is a pivotal process involving the comparison of a known document of an environmental variable with the tree-ring chronology, aiming to determine how tree growth responds to that variable. Meteorological data, such as monthly temperature, precipitation, or the Palmer Drought Severity Index, serves as a calibration dataset for climate reconstruction (Fritts, 1976; Speer, 2010).

3.4.1 Principle of uniformitarianism

The principle of uniformitarianism is the key to the pass from the present structure, or in another word means that what processes that are happened in day today are same with the processes that occurred in the past. This was given originated from James Hutton in 1785 as “uniformity is the order of nature” which mean “the present is the key to the past”. Uniformitarianism is the key of starting point for the analysis of the past climates and environments variability.

3.4.2 Principle of cross dating

This is the basic requirements of dendrochronology; cross dating is the primary method in the precise year of growth rings of each yearly rings is determined. This help to identify the error of a basic ring count which is probably going to yield an error because of the absence or false rings. When the annual rings are not dating exactly, an accurate calibration is impossible due to misdate in chronology by one or more years. Cross dating involves aligning the patterns of a tree’s broad and small rings to pinpoint the precise position of the ring borders by examining the anatomical wood structure. This process serves as a validation method, verifying the precise date of a specimen. Through cross dating, accurate dates are established for each individual ring in the tree-ring record.

3.4.3 Principle of limiting factors

According to Liebig’s Law of the Minimum, the majority of the limiting factor is controlling the tree rings chronology, which is documented in the tree rings width.

3.4.4 Concept of Autocorrelation

This is due to the community and unidirectional flow of the development of time and the progression of growth by all biological organism are subjected to autocorrelation, it can also due to the problem of the statistical analysis in which the data are not autocorrelated due to its artificial increases in correlation statistic. Tree growth often exhibits autocorrelation, a statistical feature indicating that the present year’s growth is impacted by the prior year’s growth. This phenomenon is cause by the biological activities of the tree, wherein the climate of the present year affects the factors like heat, rainfall and influencing the growth. Additionally, autocorrelation extends to the subsequent year's growth through the development of new buds, sugars, and hormones.

3.4.5 Concept of ecological amplitude

As we know that the microclimate of each site is influence by its aspect, topography and slope which is laterally the dispersion of the species. So ecological amplitude is the pattern in which the vegetation on each landscape is controlled by the range of climate in which a species responds (Lomolino, et al., 2006). Accordingly, the tree species are less stress in the middle of its range and more stress near the borders of its range in which the species may be subject to harsher climate condition. So, it is better to gather the sample species near the edge of its range for the climate research related because it likely to record of the climate variable of that specific interest.

3.4.6 Sensitivity principle

Trees growing in extremely restrictive environments exhibit more variances in there ring widths. The variability in these ring widths is referred to as sensitivity. The concept suggests that narrower rings play a crucial role in dating the limiting climatic factors.

3.4.7 Site selection principle

Site selection is one of the extremely considered for the dendrochronological sampling, whereas the sampling of sample should be collected from the place where most likely to stress by the climate variable in which most of the chronology is done for dendroclimatological reconstructions, like temperature, precipitation, rainfall etc is recorded in the tree rings which are grown at high elevation or latitudinal zone.

3.4.8 Principle of replication and sample size

Collection of sufficient number of sample (replicate) from the same tree will help to develop an accurate chronology, it also helps to provide the basis for cross dating and contributes to the environmental reconstruction. Mostly from one tree 2 core sampling should be taken which are advised in order to obtain a mean tree rings chronology for ring width analysis.

3.4.9 Tree species selection

Tree species which a visible annual ring and which long chronology is suitable for dendroclimatic studies (Cook and Kairiukstis, 1990). Whereas the species which is grown under disturbed condition or the species which have a defect on the tree should be avoided.

3.5 Site selection

The study encompassed regions in Northeast India, specifically Nagaland, Meghalaya, Arunachal Pradesh, and Mizoram states. In Meghalaya, samples were gathered from the Riat Laban Reserved Forests under the Motinagar Beat Forest, located in the Shillong East Khasi Hills District. In Arunachal Pradesh, the samples were obtained from Tawang District. In Nagaland, the collection took place at the botanical garden in Kohima, situated in the New Ministers' Hill Ward of Kohima, Kohima District. This garden is maintained by the Nagaland Forest Department. Lastly, in Mizoram, samples were collected from Champhai District.

3.6 Sample collection

Samples are collected from four states in Northeast India i.e., Nagaland, Arunachal Pradesh, Meghalaya and Mizoram.

The tree sample were collected mostly in the winter season during the month of January to march, the first sample was collected in the year of 2019 and the last sampling in 2022. The sample collection was done by using an increment coring method, an instrument call Haglof increment borer were coring from standing trees by extract the core sample. Although this procedure is destructive method but it has no effect on the health of the trees or the quality of their wood due to self-healing mechanism of the trees.

The tree core was obtained from a standing tree, with two core samples taken at a 90° angle and another at a 270° angle to the slope direction from the stem of the tree. Sampling at breast height was chosen for greater maneuverability and the ability to build momentum for coring. Ideally, tree coring aims to reach the central portion or pit of the tree. However, this may not always be achievable, particularly when the pit is situated away from the geometric center, as is often the case with leaning trees.

It is crucial to avoid sampling trees with defects like knots or fire-damaged stems, as these can lead to cores with confusing twisted and pinch ring patterns. Following coring, beeswax was applied to the increment corer barrels.

Prior to coring, the corer was placed with one hand at the midpoint of the tree stem and the other at the center of the borer handle to push and rotate the cutting tip in the same direction and the other hand is to keep the drill from shaking and to maintain an angle at 90° with the stem, after the borer was inserted atleast 2-3 centimeters into the wood, we don’t need to push anymore except rotating the corer in clockwise. To know that the coring of the sample has reach the center of the tree the spoon of the increment borer was used to measure.

Taking and packing a core, after coring the tree the core sample was collected with the spoon by inserting into the shaft of the increment borer carefully, after the spoon were inserting inside the shaft of the increment borer in which the tip of the spoon is force to pinch into the end of the core, then the increment borer was turned in opposite direction to cut the tip of the core sample from the tree, after the core is broken off inside the tree was collected by removing the spoon from the borer shaft. Then the core was placed at the paper straw or plastic straw to keep it safe from breakage. While packing the core inside the straw the spoon is just removing enough from the shaft to slide the expose core into the straw. Then the straw was sealed with a masking tape. Then the straw was labelled with the number of the tree, species name, the portion of the tree in which the core was extracted from like core A or B is used as a code name and the name of the site from which the sample was collected. When the core is store inside the straw the straw was placed inside the map tube to protected from the breakage or getting lost.

After the core was collected from the increment borer the borer was remove by turning the borer in anti-clockwise direction, whereas if the borer remains in the tree for an extended period of time the wood which are pushed out will relax back onto the borer's shaft, the rope was applied at the handle of the borer and then by pulling backward force along the rope at the same time while turning the borer in anti-clockwise direction was help in taking out the borer from the tree.

After the borer is removed from the tree, the increase corer was cleaned to preserve the tool's durability. The increment borer was cleansed using ethanol and dewatering agent (WD-40 oil). The point of cutting is crucial for obtaining good straight core free from breaks or twists, the borer's tip section was being regularly checked to ensure its condition. Sharpening tools was used to sharp the tip of the borer using the Haglof's kits.

3.7 Sample processing

The core was brought to the department from the field in the paper straw or plastic straw. When the core was still inside the straw, air dried was done to avoid shrinkage problem, once the core sample was drying, the tree core was removed from the straw and pasted in the wooden mount. (stoke and Smiley, 1968)

Before mounted the core all the information that has written in the straw was transfer to the core mount starting from pit to bark (speer, 2010), like sample ID, tree species name, etc, after all the information were transfer, a line of glue was filled in a strip groove with a sufficient amount of glue and the core were carefully mounted in the groove. A cross sectional view must face upward so that the clear rings will be seen. Once the core is carefully mounted on the mounting strip, masking tape were used to hold the core in a place as the glue dried to prevent from bending of the core.

Low steam pressure was used to a twisted core sample (tea kittle) to wet and warm the core so that it can be untangling. A gently compressed was functional to the core sample counter in the direction that was twisting as it moved from side to side due to the steam's heat.

After the glue dried, the mounted cores was flattening with a razor blade and subsequent sanding with sandpapers of various grits (80, 100, 120, 180, 200, 300, 400, 600, 1200) to achieve a smooth surface on the core sample. The process began with a lower grit such as 80 or 100 and progressed to higher grits like 600 or 1200 if necessary. This continued until the ring boundaries in the core sample became visible under the stereo-zoom microscope.

3.8 Cross dating of the tree core sample.

The aim of cross dating is to assign the calendar date to each annual ring, the tree rings ware counted from pit to bark end in which the marking was done by starting from pit portion, core was marked with a single dot to assign the decade year or ten years, two dots for 50 years and 3 dots for one hundred years. The Skeleton plot method of cross dating (developed by A. E Douglass during early 1900s) was used to cross date the tree cores (Stokes and Smiley, 1968). The cross-dating method relies on the principle that the trees in certain regions has comparable large and tight ring growth patterns. Although individual trees may have different absolute growth rates, the overall growth patterns remain consistent among trees exposed to similar micro-climatic conditions. The method involves creating a graphical representation of these growth patterns, plotting wide and narrow rings on a graph, facilitating easy comparison between two or more specimens, The method entails matching the widths of relatively narrow and wide rings using graph paper as a standard scale. Each vertical line on the graph paper represents a calendar year. The Samples collected during the dormant season (winter) yield a complete annual ring next to the bark, assignable to the most recent growing season. A basic structure for every series is created to be contrasted to another paired species to identify which rings is absent or incorrect. A composite layout for every tree is generated by duplicating patterns from paired layout. The main layout aligns all skeleton plots to share the same time axis, averaging consistently marked rings onto the master skeleton plot.

Ring circumference measurements for every dated ring were conducted with the use of the WinDendro Density 2019 software. The Measure J2X computer software was utilized for precise measurements (0.001 mm precision), performed from pith to bark end and attempted perpendicularly to the current ring boundary. A conservative optical criterion was adopted for Early Width and Late Width measurements, considering the first thin-walled cells with wide lumens to the final row of cell before the cell wall thickening as Early Width (inclusive of any false rings). Late Width included the initial row of narrow lumens and thick-walled cell up to the final row, excluding any false rings. In cases of gradual Early Width to Late Width transitions, the bands of true Early Width and true Late Width were identified, and the halfway point between them was used to measure the two components.

3.9 Chronology development of tree rings

After measuring the tree rings widths, the computer program COFECHA was used to check for any dating error in the measured ring width series. (Holmes, 1983; Grissino Mayer, 2001). The samples displaying dating errors were either corrected or removed. Subsequently, the tree-ring series underwent standardization to eliminate biological growth trends and stand dynamics arising from factors such as age, size, and competition among trees, thereby preserving common climatic signals (Cook & Kairiukstis, 1990). Power transformation was initially applied before detrending to stabilize the variance in the raw ring width series (Cook & Peters, 1997). For detrending, the Friedman super smoother was chosen, with sensitivity set to moderate flexibility (alpha value = 5) (Friedman, 1984). This method retains low frequency variance in the chronology indices, minimizing disturbances not related to climate. The detrending process transforms raw ring width series into dimensionless indices with a mean of one and uniform variance. The indices from all series were averaged using the bi-weight robust mean method, which reduces the impact of outliers, resulting in the standardized tree-ring chronology known as the standard chronology (STD) (Cook & Kairiukstis, 1990). This method mitigates the effect of the year before growth vitality on the present year's growth. Due to a decline in sample size in the early portion of a tree-ring chronology, stemming from variations in tree age, the variance stabilization method was applied after detrending to account for this disparity (Osborn et al., 1997). Chronology statistics were computed for the STD of the site (Fritts, 1976; Speer, 2010).

All individual tree ring series undergoes standardization to eliminate age dependent growth trends and fluctuations in forest stand, while retaining changes likely related to climate (Cook, 1985; Cook and Kairiukstis, 1990). The standardization process utilized the ARSTAN computer program.

In the standardization procedure, each series' raw measurements were first power-transformed, followed by the application of the 1st Friedman super smoother and alpha curve (Friedman, 1984). Autoregressive modelling was then applied to remove any existing first-order auto-correlation. The detrended series were averaged using the bi-weight robust mean function (Cook, 1985; Cook & Kairiukstis, 1990) to generate the tree-ring indices.

Typically, a decline in sample size is observed in the early part of a tree-ring time series. The subsample signal strength (SSS) criteria were applied (Wigley et al., 1984) with a limit value of 0.85 to determine the most dependable period of the chronology. Additionally, the level of linkage between site chronologies was determined using Pearson correlation method for a single time.

3.10 Ring density and maximum latewood density measurement

For the measurement of ring density (RD) and maximum latewood density (MXD), the samples were sliced into thin laths of 2 mm and underwent a 48-hour ethanol (≥99.5%) treatment in a Soxhlet apparatus to remove extractives. Subsequently, these samples were thoroughly washed in boiling deionized water, air-dried, sanded, and then scanned. The scanned samples were measured using WinDendro Density 2019 software.

3.11 Tree-ring width-climate relationship

To assess the influence of climatic variables [temperature (Tmax and Tmin), precipitation, and root-zone soil moisture (0-100cm)] on tree-ring growth, the relationship between tree-ring width and climate was examined using established statistical methods, i.e., Pearson’s correlation (Fritts 1976).

Within the correlation function, a series of coefficients were computed between the monthly climatic parameters and tree-ring chronology, organized over a timeframe spanning from the previous year's growth season to the current year. These coefficients represent univariate approximations of Pearson’s product moment correlation (Fritts 1976).

3.12 Climate Data

In this study, climate data from various sources were acquired for different sites, considering the length of the analysis period and data availability. For Nagaland and Meghalaya, climate data from MERRA-2 (National Aeronautics and Space Administration (NASA) Power Project) at a spatial resolution of 0.5° x 0.625° was utilized for climate growth analysis (refer to Figures 3.1 and 3.5). In the case of Arunachal Pradesh, CRU TS 4.07 (land) data, including Tmax, Tmin, and Precipitation, with a spatial resolution of 0.5° x 0.5°, along with root zone soil moisture (0-100cm) from MERRA-2, was employed for the analysis (see Figure 3.3). As for Champhai, we employed Tmax, Tmin, and Precipitation data from the local weather station, complemented by root zone soil moisture (0-100cm) from MERRA-2 (see Figure 3.7).

3.13 Development of statistical growth model

A statistical growth model was developed for all three species using climatic data as predictors and actual growth as predictand. Estimated values were computed by applying predictor data to model coefficients, and the resulting values were compared with those of the predictand. The fit regression model, utilizing the normal least squares method, defined the connection between predictors (climate variables) and predictand. Stepwise multiple linear regression, an automated statistical approach, was employed to identify the most essential variables influencing vegetation growth in the study area. This technique added or eliminated variables based on specific criteria (F-statistic threshold for entry: 0.05; F-statistic threshold for removal: 0.1) at each phase. The multivariate regression model was developed using following equation:

$$\hat{Y} = a0 + a1X1 + \ldots + aiXi \qquad \text{(Eberly, 2007).}$$

In the regression model, Ŷ denotes the dependent parameter to be predicted, where a0 stands for the intercept, i represents the number of independent variables, and a1…i and X1…i signify the regression coefficients and values for the independent abiotic variables, respectively. In this model, Tree-ring Width Index was used as dependent variable and abiotic parameters as independent variables. The capability of model to describe the growth-climate relationship was determined by *p*-value, R^2, adjusted R^2, and predicted R^2 values. Akaike information criterion (AIC) and bayesian information criterion (BIC) were used to evaluate model fits, considering log-likelihood, number of parameters (k), and sample size (n). Models were validated using 10-fold validation, where higher 10-fold R^2 values indicated efficient model performance.

3.14 Estimation of aboveground woody biomass (AWB) and carbon

Annual tree-ring width (TRW) values, representing radial growth, were employed to reconstruct historical tree diameters and their basal area increment. These, along with mean wood density (WD), were utilized to estimate biomass and, consequently, carbon accumulation. The allometric equation by Návar (2009) was applied for this purpose, previously employed successfully by Pompa-García et al., (2018) for estimating yearly aboveground woody biomass from tree ring widths:

$$AWB = 0.0752 \times D^{2.4448} \times 2.0331^{p} \qquad \text{(Návar, 2009).}$$

where AWB = aboveground woody biomass; D =DBH (cm); and *p* = WD (g cm^{-3}).

Tree-ring width annual values were multiplied by 2 to determine the diameter at breast height, following the suggestions of Peters et al., (2017).

The wood carbon content for all three species varied between 47% and 50% (Choudhary et al., 2014; Ramírez-Martínez et al., 2021). To prevent potential overestimation, the annual carbon accumulation was derived by multiplying the aboveground woody biomass of each year by 0.46. To compare the estimated carbon accumulation, we used the allometric equations proposed by Brahma et al., (2021) for *P. patula* and *P. kesiya*, and by Brown and Schroeder (1999) for *P. wallichiana*.

Allometric equation given by Brahma et al., (2021):

$AGB = (0.18D^{2.16}) \times 1.32$

Where, AGB = aboveground biomass; D = diameter at breast height

Allometric equation given by Brown and Schroeder (1999):

$Y = 0.887 + [\{10486 \times (DBH)^{2.84}\}/ \{(DBH)^{2.84} + 376907\}]$

Where, Y = above ground biomass (AGB); DBH = diameter at breast height, cm;

3.15 Relationship of accumulated carbon with climate

To further validate the climate-growth analysis results of radial growth, the accumulated annual carbon values of each species were correlated with monthly climate data using Pearson’s correlation. Here, a series of coefficients were computed between the monthly climatic parameters and accumulated carbon, organized over a timeframe spanning from the previous year's growth season to the current year. These coefficients represented univariate approximations of Pearson’s product moment correlation (Fritts 1976).

Chapter 4

Results and discussion

4.1 Tree ring analysis

The wood and tree ring characteristics of the selected tree species were thoroughly examined using high-resolution scanned images from an Epson professional scanner (Figure 4.1). Each of the three species displayed well-defined growth rings. In the case of *P. patula* and *P. kesiya*, a distinct zonation was noticed between early and latewood. However, in *P. wallichiana*, the clear zonation of early and latewood width was observed in the sapwood portion, but it was less pronounced in older rings. The earlywood color of *P. wallichiana* varied from brownish yellow in recent years' rings to almost brown in older rings, transitioning into a very dark brown shade in the latewood portion.

For both *P. patula* and *P. kesiya*, the wood color underwent a gradual change from yellowish white in earlywood to dark brown in latewood. However, there was no clear distinction between sapwood and heartwood. The wood exhibited a straight grain with a medium texture.

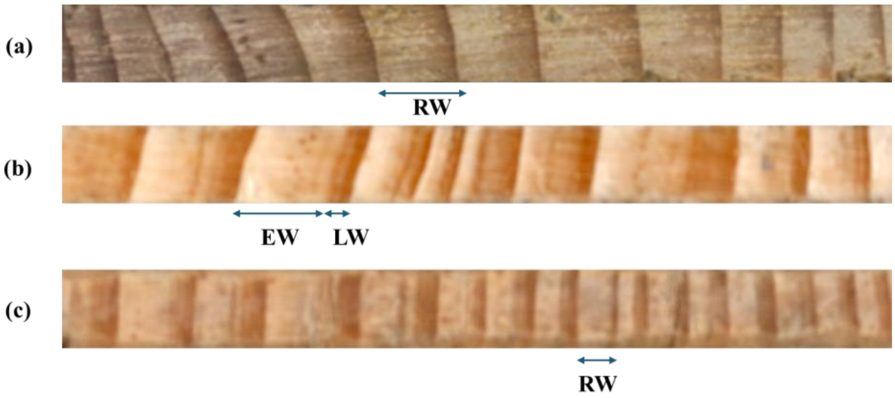


Figure 4.1. Growth ring features of (a) *Pinus walliciaha*, (b) *Pinus kesiya* and (c) *Pinus patula* studied from Arunachal Pradesh, Meghalaya, Mizoram and Nagaland, Northeast India. The abbreviations are: RW = ring width; EW = earlywood; LW = latewood; FR = False ring or false band.

4.2 Tree-ring Width Chronology

A total of 4 tree ring width (TRW) chronologies including one of *P. wallichiana* from Arunachal Pradesh, *P. patula* from Nagaland, and *P. kesiya* from Meghalaya and Mizoram were developed. Additionally, the corresponding partial ring width chronologies (EW and LW) for TRW were also developed for each site.

4.2.1 Cross-dating accuracy

The cross-dating accuracy of each measured tree ring series was assessed using computer program COFECHA (Holmes 1983; Grissino-Mayer 2001). The individual tree ring series of each species were correlated with that master chronology and recorded for their mean series intercorrelation. Tree ring series having high correlation with master series were included in the final dataset. The poorly dated tree ring series having low correlation with master series were removed from analysis.

The mean inter-correlation among series for *P. wallichiana* (0.329, Arunachal Pradesh), *P. kesiya* (Meghalaya, 0.338; Mizoram, 0.396), and *P. patula* (0.443, Nagaland) indicates a degree of commonality among the samples included in their respective four chronologies (Table 4.1, 4.2, 4.3, 4.4). This commonality in the discrete series contributes to the overall site chronology (Table 4.1, 4.2, 4.3, 4.4). The mean inter-correlation among the series of *P. wallichiana* was slightly above the threshold level. This could be attributed to lower sample depth caused by limited availability of good-quality samples, primarily due to the higher amount of resin in older annual rings, making it challenging to delineate the ring boundaries. Further, the low to moderate values of series mean inter-correlation observed at all the sites could also be connected to the prevailing moist climatic conditions in the states of Arunachal Pradesh, Nagaland, and Mizoram in Northeast India.

4.2.2 Tree ring chronologies development

After successfully cross-dating, four tree ring width chronologies, along with their corresponding partial chronologies for earlywood and latewood width were developed from Nagaland, Arunachal Pradesh, Meghalaya and Mizoram. The tree ring chronologies for ring width (RW), earlywood width (EW), and latewood width (LW) of *P. patula* from Kohima, Nagaland, spanned from 1983 to 2021, covering a total period of 39 years. The tree ring chronologies (RW, EW, and LW) of *P. wallichiana* from Tawang, Arunachal Pradesh, covered a period of 121 years (1901-2021 CE). The tree ring width and partial chronologies of *P. kesiya* varied in length due to the series included in the final chronology development after COFECHA, covering a period of 124 years (1896-2019 CE) for RW, 118 years (1902-2019 CE) for EW, and 124 years (1896-2019 CE) for LW in Shillong, Meghalaya. Similarly, the tree ring chronologies of *P. kesiya* from Champhai, Mizoram, also varied in length, with 40 years (1978–2017 CE) for RW, 40 years (1978–2017 CE) for EW, and 38 years (1980–2017 CE) for LW. The descriptive statistics of the developed tree ring chronologies of RW, EW, and LW for each species and site are discussed below.

4.2.2.1 Nagaland

The tree ring chronologies of *P. patula* spanned from 1983 to 2021, incorporating 61 series from 31 trees in the Tree Ring Width (TRW) Index, 59 series from 31 trees in the Earlywood Width (EW) Index, and 54 series from 30 trees in the Latewood Width (LW) Index (Figure 4.2 a, b & c). The developed chronologies demonstrated a robust mean series inter-correlation of 0.443 (TRW), 0.431 (EW), and 0.340 (LW). Mean sensitivity, a metric reflecting the year-to-year variability in tree-ring width (Fritts, 1976), exhibited moderate values of 0.134 (TRW), 0.141 (EW), and 0.163 (LW). The standard deviation, measuring changes in both lower and higher frequency variances (Fritts, 1976), showcased moderate values of 0.130 (TRW), 0.142 (EW), and 0.183 (LW). Autocorrelation, indicating the degree of correlation between a particular year's growth and the previous year's growth, revealed moderate values (0.310, TRW; 0.319, EW; 0.428, LW), suggesting that current climatic factors play a significant role in the species' growth in this region. Subsample Signal Strength (SSS), a measure of the signal captured by a subset of cores from a master chronology (Wigley et al., 1984, Briffa and Jones, 1990), allows researchers to quantify the variance common between a subset of samples and the master chronology. The tree-ring chronologies achieved the threshold level of 0.85 in the years 1985 (0.876, TRW), 1985 (0.860, EW), and 1986 (0.919, LW) (Table 4.1).

Table 4.1. Statistical details of tree-ring chronologies developed from Nagaland, Northeast India

	TRW	***EW***	***LW***
TS (YRS)	1983-2021 (39)	1983-2021 (39)	1983-2021 (39)
SIC	0.443	0.431	0.340
MSL	34.0	35.0	34.0
NT/NC	31 (61)	31 (59)	30 (54)
MS	0.134	0.141	0.163
SD	0.130	0.142	0.183
AC-1	0.310	0.319	0.428
Common Period Analysis			
TS (YRS)	1995-2021 (27)	1995-2021 (27)	1995-2021 (27)
NT/NC	31 (61)	31 (59)	30 (54)

Common variance (PC-1)	28.9%	26.7%	22.5%
SNR	13.215	10.752	10.992
Year with SSS ≥ 0.85	0.876 (1985)	0.860 (1985)	0.919 (1986)
EPS	0.930	0.915	0.917
TRW = tree ring width; EW = Earlywood Width; LW = latewood width; TS (YRS) = time span (years); SIC = series inter-correlation; MSL = mean segment length; NT/NC = number of trees/numbers of tree cores; MS = mean sensitivity; SD = standard deviation; AC-1 = first order autocorrelation; SNR = signal to noise ratio; SSS = sub sample strength; EPS = Expressed population signal			

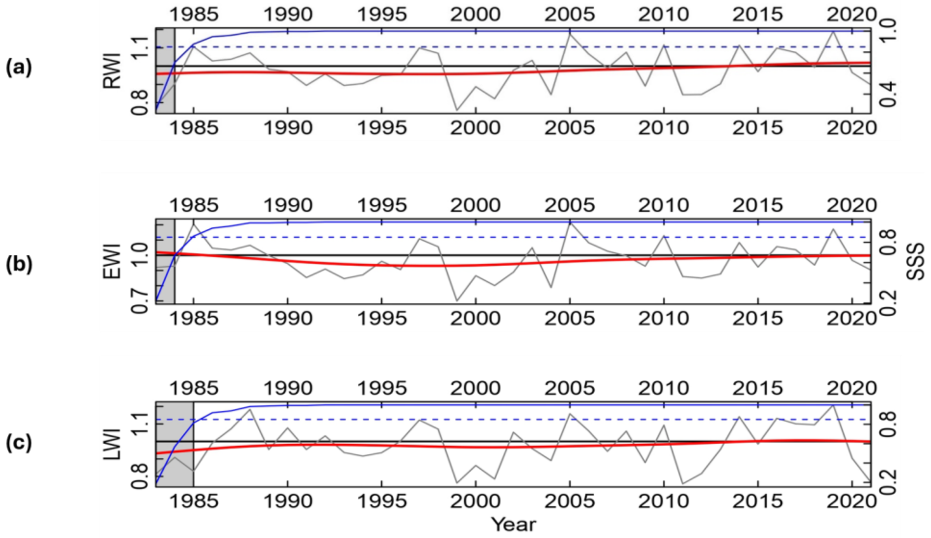


Figure 4.2. Tree ring chronologies of *P. patula* from Nagaland (a) TRW, (b) EW and (c) LW. The red curve represents a 10-year spline-smoothing curve and a blue curve denotes the sub-sample signal strength (SSS).

4.2.2.2 Arunachal Pradesh

The tree ring chronologies of *P. wallichiana* extended from 1901 to 2021, encompassing 20 series from 14 trees in the RWI, 18 series from 13 trees in the EWI, and 15 series from 11 trees in the LWI (Figure 4.3 a, b & c). The developed chronologies exhibited a robust mean series inter-correlation of 0.329 for RWI, but this dropped to 0.282 and 0.192 for EW and LW, respectively. This decrease may be attributed to a low sample size and high moisture levels at the site. Mean sensitivity, a metric of year-to-year variability in tree-ring widths showed moderate values of 0.140 (TRW), 0.173 (EW), and 0.225 (LW). The standard deviation, a measure of changes in both lower and higher frequency variances displayed moderate values of 0.135 (TRW), 0.173 (EW), and 0.206 (LW). Autocorrelation shows degree of correlation between a current and previous year's growth revealed moderate values (0.222, TRW; 0.254, EW; 0.129, LW), suggesting the significant role of current climatic factors on the growth of species in the region. Subsample Signal Strength (SSS), which suggests the suitable time span of chronology for dendroclimatic analysis (Wigley et al., 1984, Briffa and Jones, 1990), crossed the threshold level of 0.85 in the years 1952 (0.851, TRW), 1952 (0.852, EW), and 1979 (0.872, LW) (Table 4.2).

Table 4.2. Statistical details of tree-ring chronologies developed from Arunachal Pradesh, Northeast India

	TRW	***EW***	***LW***
TS (YRS)	1901-2021 (121)	1901-2021 (121)	1901-2021 (121)
SIC	0.329	0.282	0.192
MSL	82.0	84.0	85.0

NT/NC	14 (20)	13 (18)	11 (15)
MS	0.140	0.173	0.225
SD	0.135	0.173	0.206
AC-1	0.222	0.254	0.129
Common Period Analysis			
TS (YRS)	1988-2021 (34)	1988-2021 (34)	1988-2021 (34)
NT/NC	14 (20)	13 (18)	11 (15)
Common variance (PC-1)	19.8%	18.7%	16.5%
SNR	2.886	2.551	0.703
Year with SSS ≥ 0.85	0.851 (1952)	0.852 (1952)	0.872 (1979)
EPS	0.743	0.718	0.413

TRW = tree ring width; EW = Earlywood Width; LW = latewood width; TS (YRS) = time span (years); SIC = series inter-correlation; MSL = mean segment length; NT/NC = number of trees/numbers of tree cores; MS = mean sensitivity; SD = standard deviation; AC-1 = first order autocorrelation; SNR = signal to noise ratio; SSS = sub sample strength; EPS = Expressed population signal

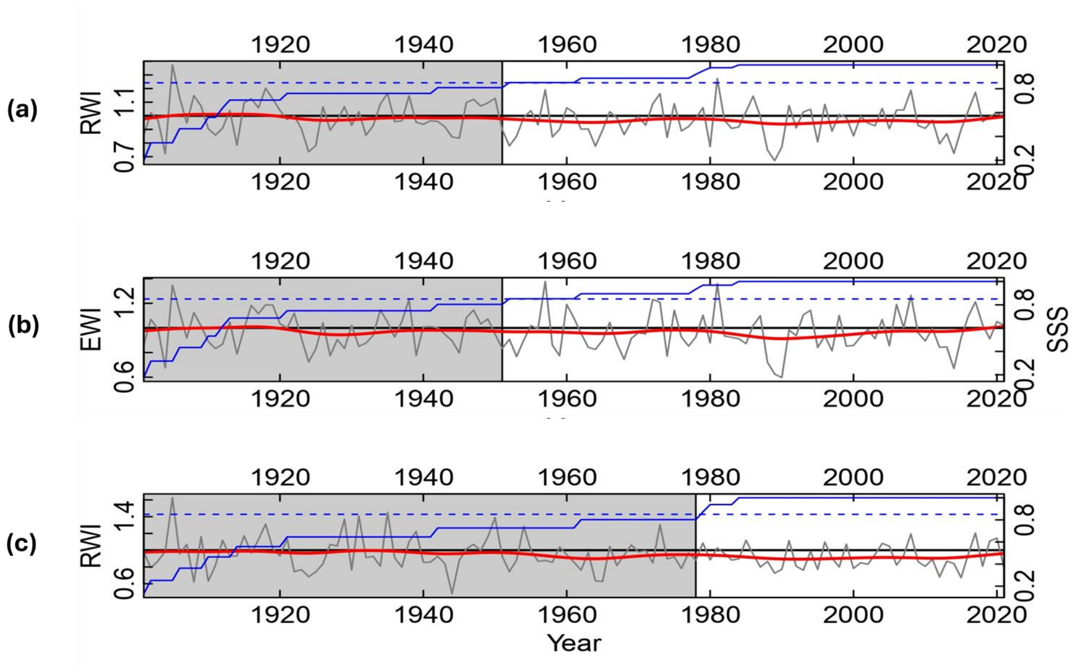


Figure 4.3 Tree ring chronologies of *P. wallichiana* from Arunachal Pradesh (a) TRW, (b) EW and (c) LW. The red curve represents a 10-year spline-smoothing curve and a blue curve denotes the sub-sample signal strength (SSS).

4.2.2.3 Meghalaya

The TRW and LW chronologies of *P. kesiya* originating from Shillong, Meghalaya, spanned a considerable temporal expanse of 124 years, encompassing the period from 1896 to 2019 (Figure 4.4 a & c). In contrast, the EW chronology covered a slightly shorter duration of 118 years (1902-2019 CE) (Figure 4.4 b). These chronologies incorporated 39 series derived from 24 trees for TRW, 32 series from 21 trees for EW, and 36 series from 22 trees for LW. The developed chronologies revealed a robust mean series inter-correlation of 0.338 for TRW and 0.332 for EW. However, the mean series inter-correlation experienced a decline to 0.206 in the case of LW. The metric of mean sensitivity, representing the year-to-year variability in tree-ring widths, demonstrated moderate to high values of 0.177 (TRW), 0.271 (EW), and 0.314 (LW). Similarly, the standard deviation, a measure capturing changes in both lower and higher frequency variances, displayed moderate to high values of 0.170 (TRW), 0.286 (EW), and 0.310 (LW). Autocorrelation, reflecting the degree of correlation between the current and previous years' growth, manifested moderate values (0.113, TRW; 0.179, EW; 0.133, LW), underscoring the significant influence of current climatic factors on species growth in the region. Subsample Signal Strength (SSS), indicative of the reliable time span of the chronology for dendroclimatic analysis (Wigley et al., 1984, Briffa and Jones, 1990), surpassed the threshold level of 0.85 in the years 1971 (0.850, TRW), 1974 (0.887, EW), and 1974 (0.854, LW) (Table 4.3). The TRWI statistics exhibited consistency with other *Pinus kesiya* chronologies established in Shyrwat Reserved Forest, Short Round Protected Forest, Riat Khwan Reserved Forest, Laitkor Protected Forest, and Upper Shillong Reserved Forest in Shillong, Meghalaya (Chaudhary and Bhattacharyya, 2002).

Table 4.3. Statistical details of tree-ring chronologies developed from Meghalaya, Northeast India

	TRW	***EW***	***LW***
TS (YRS)	1896 2019 (124)	1902-2019 (118)	1896-2019 (124)
SIC	0.338	0.332	0.206
MSL	53.0	49.0	52.0
NT/NC	24 (39)	21 (32)	22 (36)
MS	0.177	0.271	0.314
SD	0.170	0.286	0.310
AC-1	0.113	0.179	0.133
Common Period Analysis			

TS (YRS)	1999-2019 (21)	1999-2019 (21)	1999-2019 (21)
NT/NC	24 (39)	21 (32)	22 (34)
Common variance (PC-1)	21.6%	20.7%	19.1%
SNR	6.037	4.399	4.366
Year with SSS ≥ 0.85	0.850 (1971)	0.887 (1974)	0.854 (1974)
EPS	0.858	0.815	0.814

TRW = tree ring width; EW = Earlywood Width; LW = latewood width; TS (YRS) = time span (years); SIC = series inter-correlation; MSL = mean segment length; NT/NC = number of trees/numbers of tree cores; MS = mean sensitivity; SD = standard deviation; AC-1 = first order autocorrelation; SNR = signal to noise ratio; SSS = sub sample strength; EPS = Expressed population signal

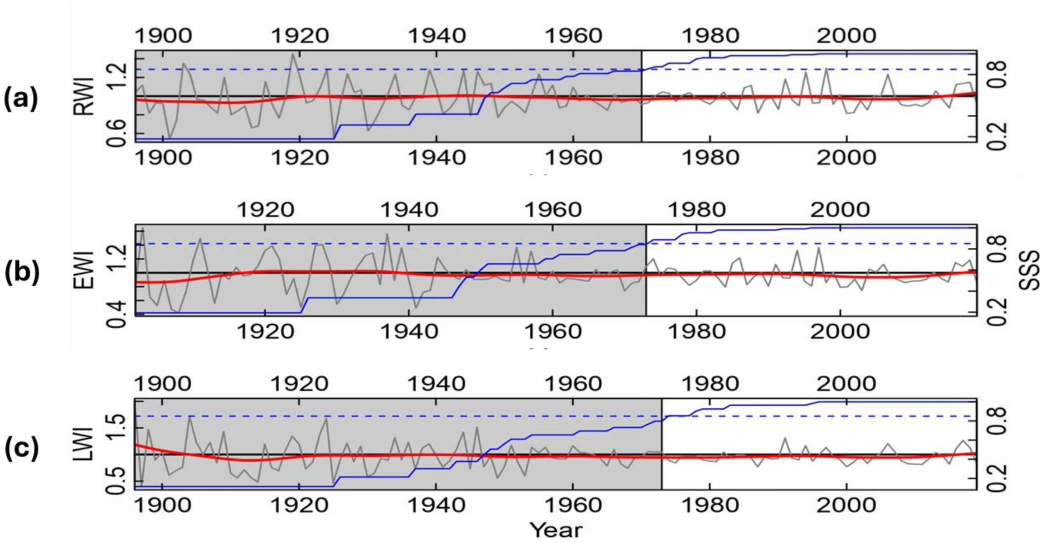


Figure 4.4 Tree ring chronologies of *P. kesiya* from Meghalaya (a) TRW, (b) EW and (c) LW. The red curve represents a 10-year spline-smoothing curve and a blue curve denotes the sub-sample signal strength (SSS).

4.2.2.4 Mizoram

The TRW and EW chronologies of *P. kesiya*, derived from Champhai, Mizoram, spanned over 40 years, covering a period from 1978 to 2017 (Figure 4.5 a & b). However, the LW chronology covered a slightly shorter duration of 38 years (1980-2017 CE) (Figure 4.5 c). These chronologies incorporated 36 series obtained from 19 trees for TRW, 36 series from 19 trees for EW, and 30 series from 18 trees for LW. The developed chronologies unveiled a robust mean series inter-correlation of 0.396 for TRW, 0.365 for EW, and 0.337 for LW. The metric of mean sensitivity, reflecting the year-to-year variability in tree-ring widths, exhibited moderate values of 0.235 (TRW), 0.235 (EW), and 0.152 (LW). Similarly, the standard deviation, a measure capturing changes in both lower and higher frequency variances, demonstrated moderate values of 0.193 (TRW), 0.193 (EW), and 0.145 (LW). Autocorrelation, illustrating the degree of correlation between the current and previous years' growth, manifested moderate values (0.032, TRW; 0.032, EW; 0.070, LW), underscoring the significant influence of current climatic factors on species growth in the region. Subsample Signal Strength (SSS), indicative of the reliable time span of the chronology for dendroclimatic analysis (Wigley et al., 1984, Briffa and Jones, 1990), surpassed the threshold level of 0.85 in the years 1987 (0.875, TRW), 1988 (0.854, EW), and 1988 (0.854, LW) (Table 4.4).

Table 4.4. Statistical details of tree-ring chronologies developed from Mizoram, Northeast India

	TRW	***EW***	***LW***
TS (YRS)	1978-2017 (40)	1978-2017 (40)	1980-2017 (38)
SIC	0.396	0.365	0.337
MSL	28.6	28.6	28.1
NT/NC	19 (36)	19 (36)	18 (30)
MS	0.235	0.235	0.152
SD	0.193	0.193	0.145
AC-1	0.032	0.032	0.070
Common Period Analysis			
TS (YRS)	1991-2014 (24)	1991-2014 (24)	1991-2014 (24)
NT/NC	12 (22)	12 (22)	12 (16)
Common	20.2%	20.2%	23.2%

variance (PC-1)			
SNR	3.306	3.306	2.823
Year with SSS ≥ 0.85	0.875 (1987)	0.854 (1988)	0.854 (1988)
EPS	0.768	0.768	0.738
TRW = tree ring width; EW = Earlywood Width; LW = latewood width; TS (YRS) = time span (years); SIC = series inter-correlation; MSL = mean segment length; NT/NC = number of trees/numbers of tree cores; MS = mean sensitivity; SD = standard deviation; AC-1 = first order autocorrelation; SNR = signal to noise ratio; SSS = sub sample strength; EPS = Expressed population signal			

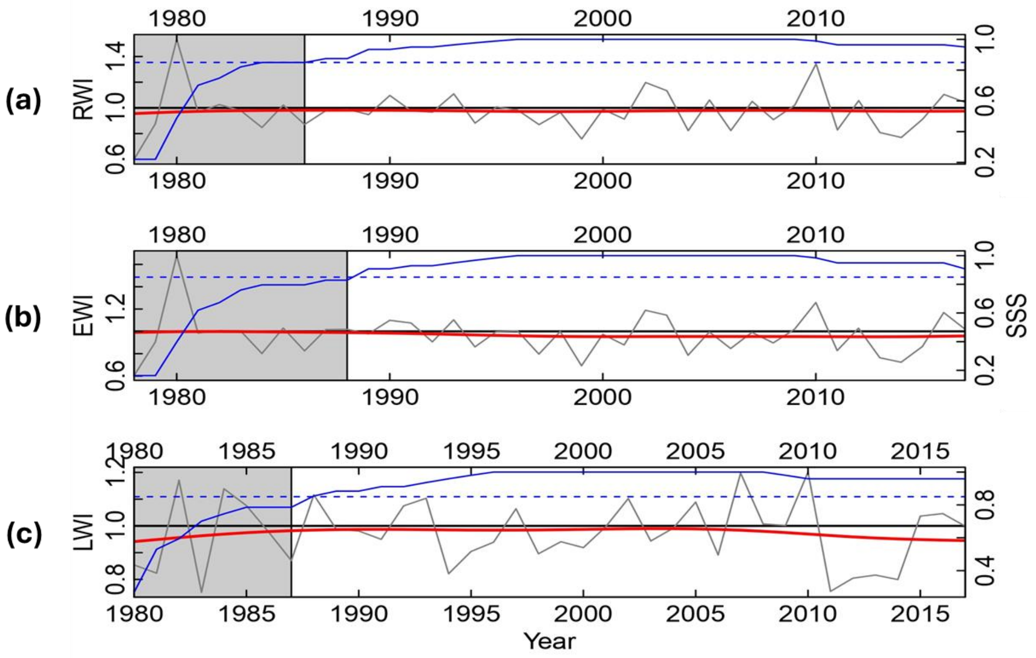


Figure 4.5 Tree ring chronologies of *P. kesiya* from Mizoram (a) TRW, (b) EW and (c) LW. The red curve represents a 10-year spline-smoothing curve and a blue curve denotes the sub-sample signal strength (SSS).

4.2.3 Ring-width density (RD) and maximum latewood density (MXD)

The RD and MXD of all three species from four different sites were estimated using WinDendro Density software (Table 4.5). The RD values of *P. patula* ranged from 0.345 gm cm^{-3} (Min) to 0.474 gm cm^{-3} (Max) with a mean value of 0.383 gm cm^{-3}, which showed similarity to results obtained by Fry and Chalk (1957) from Kenya. The MXD of *P. patula* was in between 0.484 gm cm^{-3} (Min) to 0.582 gm cm^{-3} (Max), with a mean value of 0.517 gm cm^{-3}. Kamala et al., (2014) also reported the *P. patula* wood density range from 0.33 to 0.69 gm cm^{-3}. Further, the global wood density database (Zanne et al., 2009) reported the wood density value for *P. patula* at 0.450 gm cm^{-3} from tropical and 0.387 gm cm^{-3} from subtropical regions of south America.

In case of *P. wallichiana*, the RD values ranged from 0.250 gm cm^{-3} to 0.360 gm cm^{-3} with a mean value of 0.305 gm cm^{-3} (Table 4.5). Similarly, the MXD was observed in between 0.326 gm cm^{-3} to 0.422 gm cm^{-3}, with a mean value of 0.377 gm cm^{-3}. The obtained values are in conjecture with Zanne et al., (2009), who reported an average wood density value of 0.34 gm cm^{-3} from China and 0.43 gm cm^{-3} from India for *P. wallichiana*.

For *P. kesiya*, the RD ranged from 0.299 to 0.388 gm cm^{-3}, with mean value of 0.370 gm cm^{-3} at Shillong site, whereas from 0.231 to 0.424 gm cm^{-3}, with mean value of 0.329 gm cm^{-3} at Champhai site (Table 4.5). In case of MXD, the values ranged from 0.417 to 0.511 gm cm^{-3}, with a mean of 0.491 gm cm^{-3} at Shillong site, and from 0.405 to 0.534 gm cm^{-3}, with a mean of 0.487 gm cm^{-3} at Champhai site. As per global wood density database (Zanne et al., 2009), the average wood density values are reported in between 0.420 to 0.511 gm cm^{-3} from different parts of China.

Table 4.5. Ring Density and maximum latewood density				
	Parameter	**Mean (raw)**	**Min (raw)**	**Max (raw)**
P. patula Wood density (gm cm^{-3})	RD	0.383	0.345	0.474
	MXD	0.517	0.484	0.582
P. wallichiana Wood density (gm cm^{-3})	RD	0.305	0.250	0.360
	MXD	0.377	0.326	0.422
P. kesiya (Shillong) Wood density (gm cm^{-3})	RD	0.370	0.299	0.388
	MXD	0.491	0.417	0.511
P. kesiya (Champhai) Wood density (gm cm^{-3})	RD	0.329	0.231	0.424
	MXD	0.487	0.405	0.534
RD = Ring Density, MXD = Maximum Latewood Density				

4.3 Tree radial growth and climate relationship

4.3.1 Relationship of *P. patula* radial growth with climate

The tree-ring width (TRW), earlywood width (EW), latewood width (LW) and latewood maximum density (MXD-raw) time series of *P. patula* were plotted against climate data obtained from MERRA-2 dataset of National Aeronautics and Space Administration (NASA).

4.3.1.1 Relationship with mean monthly maximum temperature

The analysis revealed an insignificantly positive relationship between TRW and EW in the months of the previous year's December-January, June, and August (Figure 4.6 a & b). Further, it demonstrated a slight positive influence of Tmax on LW during the previous year's December-January and November (Figure 4.6 c). As for MXD-raw, a positive response was observed only in the months of May-June (Figure 4.6 d), while a consistently negative relationship prevailed for the remaining months, with significant impacts during the previous year's November-December (*p*<0.05; *p*<0.1), February (*p*<0.1), September (*p*<0.1), and November (*p*<0.1).

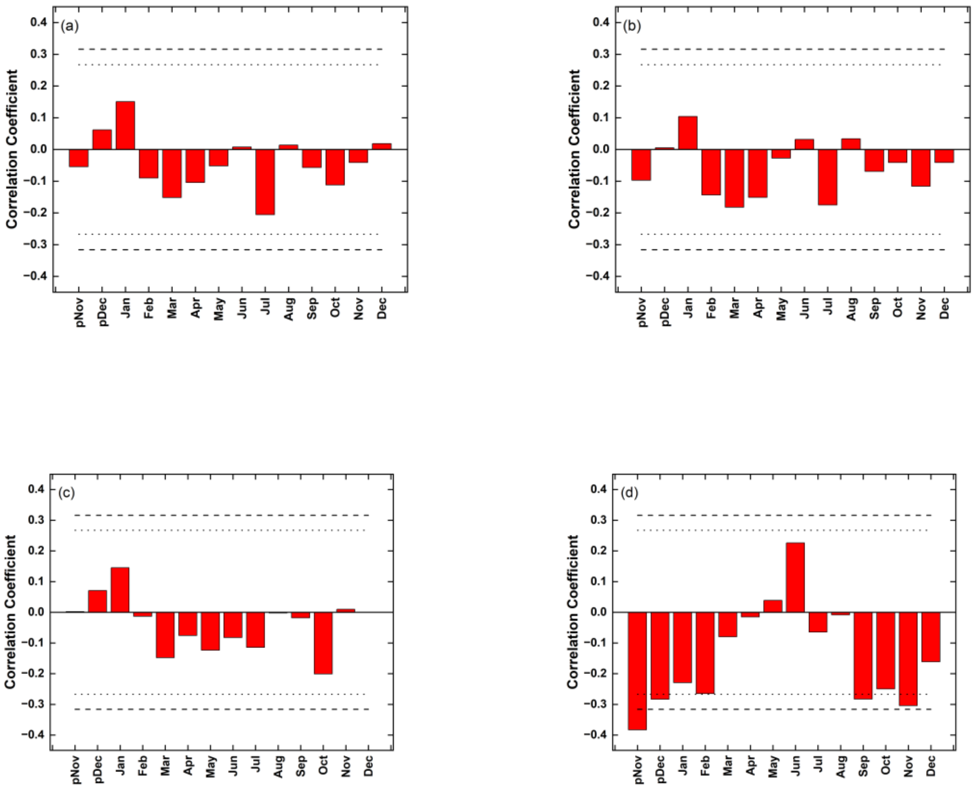


Figure 4.6. Pearson correlation between *P. patula* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly maximum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence

level, and the dashed lines represent the 95% confidence level.

4.3.1.2 Relationship with mean monthly minimum temperature

The TRW and EW of *P. patula* demonstrated a positive relationship with minimum temperature during months of the early, middle, and late growth seasons (Figure 4.7 a & b), with a noteworthy association in January ($p<0.05$) and December ($p<0.1$) for TRW, and in January ($p<0.1$) for EW. The influence of minimum temperature on the growth of *P. patula* became more evident in the latewood width chronology, showing a higher degree of positive correlation in most months, except for October, which exhibited a negative response (Figure 4.7 c). However, a consistently significant negative impact of Tmin was observed on MXD-raw (Figure 4.7 d).

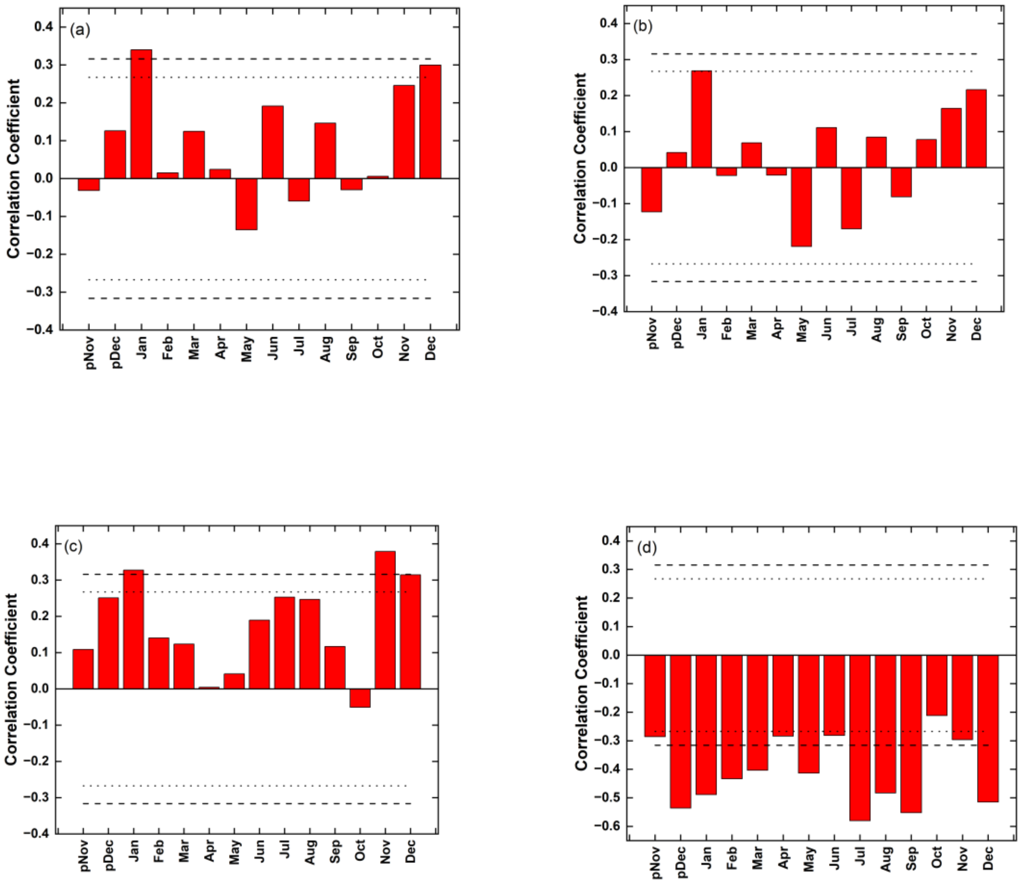
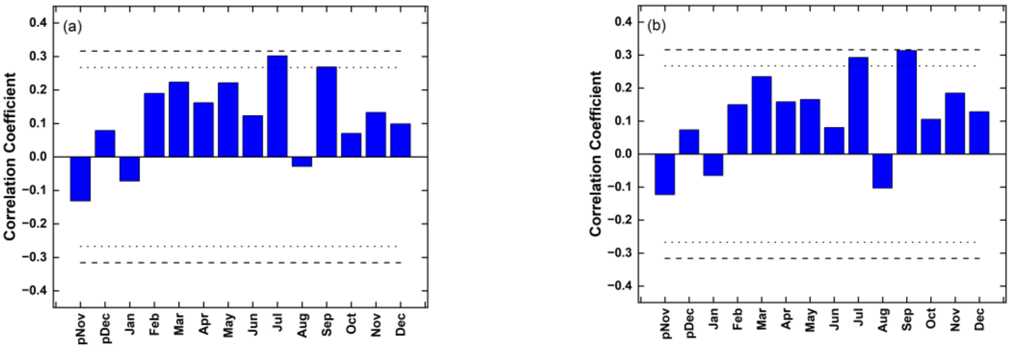


Figure 4.7. Pearson correlation between *P. patula* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly minimum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.1.3 Relationship with total monthly precipitation

The TRW and EW of *P. patula* exhibited a positive correlation with precipitation, indicating a beneficial effect of precipitation on the growth and development of the species in the region (Figure 4.7 a, b & c). The influence of rainfall was consistently positive throughout the year, with exceptions noted for the months preceding November and the current year’s January and August. Notably, significant relationships were identified during July and September (*p*<0.1) for TRW and EW, as well as in February and May (*p*<0.1) for LW. However, MXD-raw displayed a positive response only during early and late periods of the growth season (Figure 4.8 d), with a significant negative response noted in the month of August (*p*<0.05).



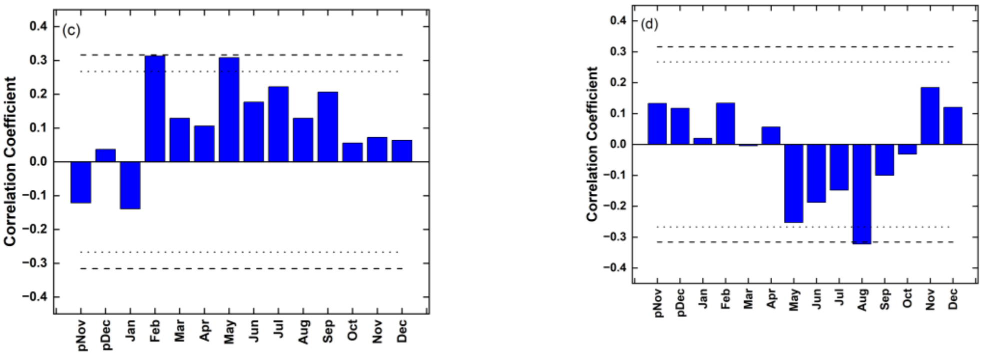


Figure 4.8. Pearson correlation between *P. patula* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and total monthly precipitation from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.1.4 Relationship with mean monthly root-zone moisture (0-100 cm)

The developed chronologies were further correlated with the root-zone moisture (0-100 cm). The analysis revealed a continuous positive correlation of root-zone moisture with TRW, EW and LW from March to December (Figure 4.9 a, b & c). This indicates an important role of moisture in growth and development of *P. patula* tree in this region. However, it showed a continuous negative correlation with maximum latewood density (MXD-raw) from previous year’s November to current year’s December (Figure 4.9 d).

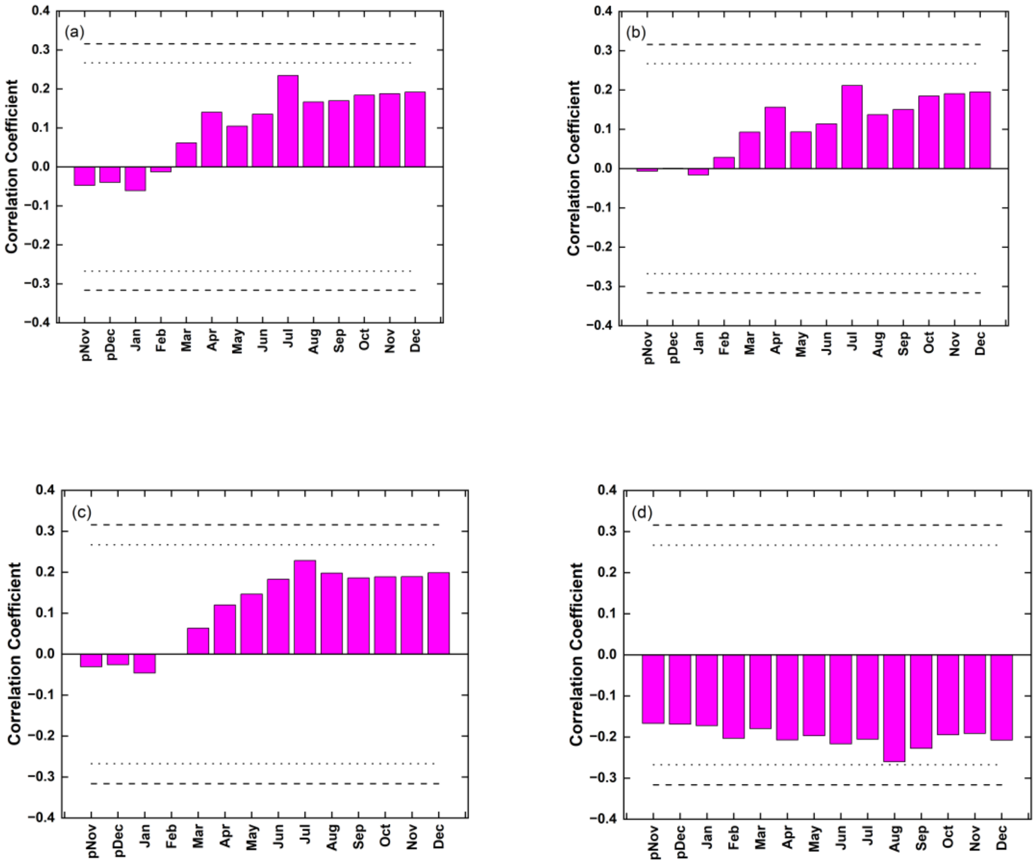


Figure 4.9. Pearson correlation between *P. patula* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly root-zone moisture (0-100 cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.2 Relationship of *P. wallichiana* radial growth with climate

The time series data for TRW, EW, LW, and MXD-raw of *P. wallichiana* were analyzed in conjunction with temperature (Tmax and Tmin) and precipitation data from CRU TS (4.07), and root-zone moisture (0-100 cm) obtained from the MERRA-2 dataset provided by the NASA.

4.3.2.1 Relationship with mean monthly maximum temperature

The TRW of *P. wallichiana* showed a positive relationship with maximum temperature of most of the months except June and November. The Significant relationship ($p<0.05$) was found in the months of previous year's December and current year's August (Figure 4.10 a). For EW, the positive association was found from previous year's November to current year's December except for the months of March and November. The significant relationship was witnessed in July ($p<0.1$) and August ($p<0.05$) (Figure 4.10 b). However, in the case of LW, the positive correlation was obtained in different months including previous year's December ($p<0.1$), February-May, and August-September (Figure 4.10 c). Similarly, the MXD-raw showed positive influence of Tmax in the months of Apr-May, Jul-Sep, and December (Figure 4.10 d).

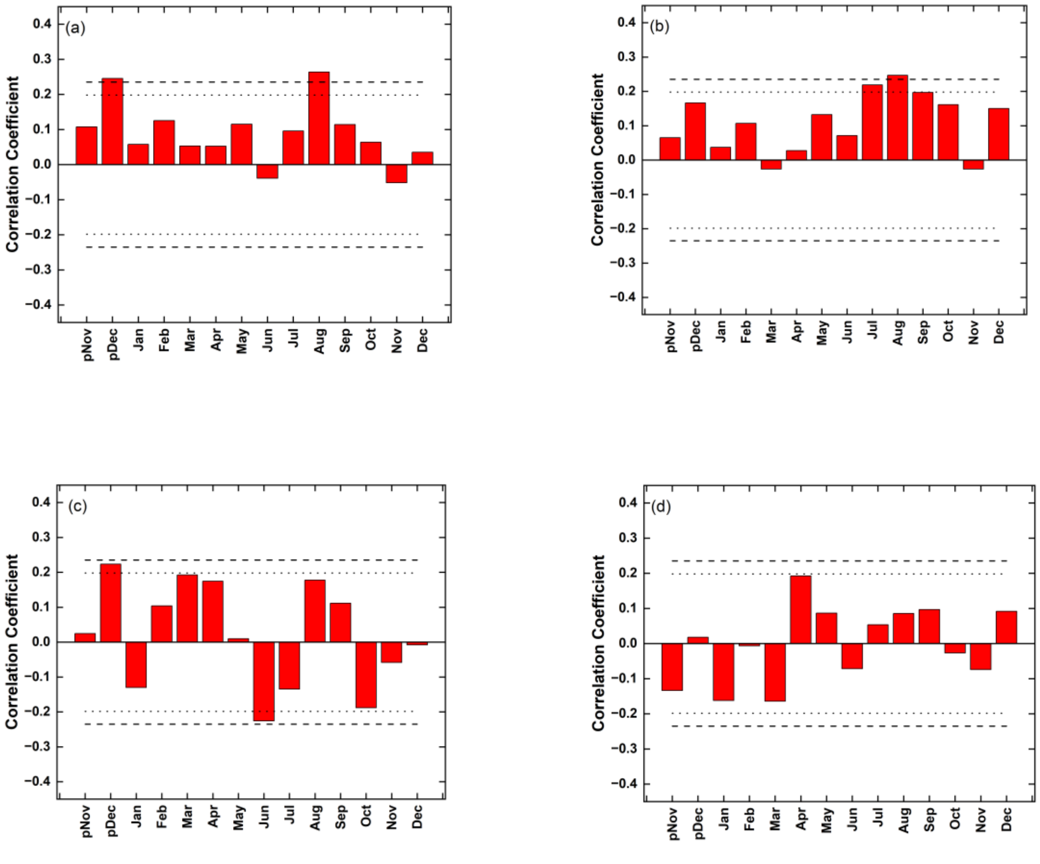
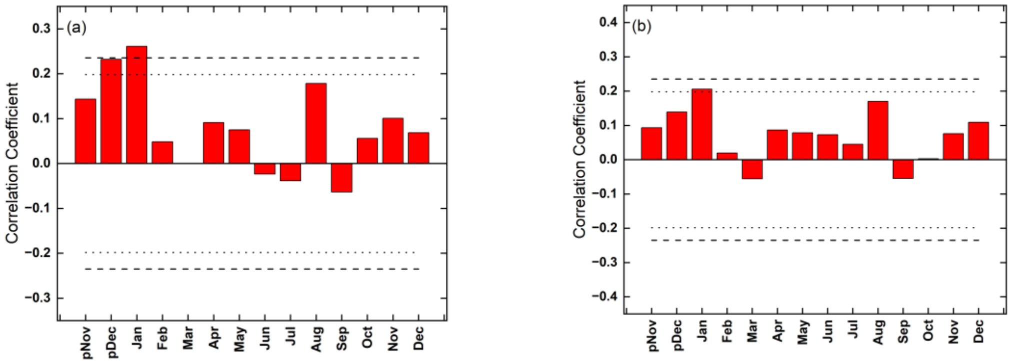


Figure 4.10. Pearson correlation between *P. wallichiana* (a) TRW, (b) EW, (c) LW,

and (d) MXD-raw raw and mean monthly maximum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.2.2 Relationship with mean monthly minimum temperature

The TRW of *P. wallichiana* showed positive relationship with minimum temperature of previous year's November-current year's February, April-May, August, and October-December months. The Significant relationship was found in the months of previous year's December ((*p<0.1*) and current year's January (*p<0.05*) (Figure 4.11 a). The EW exhibited the positive association with Tmin of previous year November-current year February, March-August, October-December. However, the significant relationship was witnessed only in the month January (*p*<0.1) (Figure 4.11 b). In case of LW, the positive correlation of Tmin was witnessed from previous year November to current year May, August, and October-December (Figure 4.11 c), with significant association (*p*<0.1) in the months of previous year's December and current year April. However, a continuous negative correlation of MXD-raw was observed with Tmin from previous year's November to current year's December, with significant (*p*<0.05) negative relationship in January-March (Figure 4.11 d).



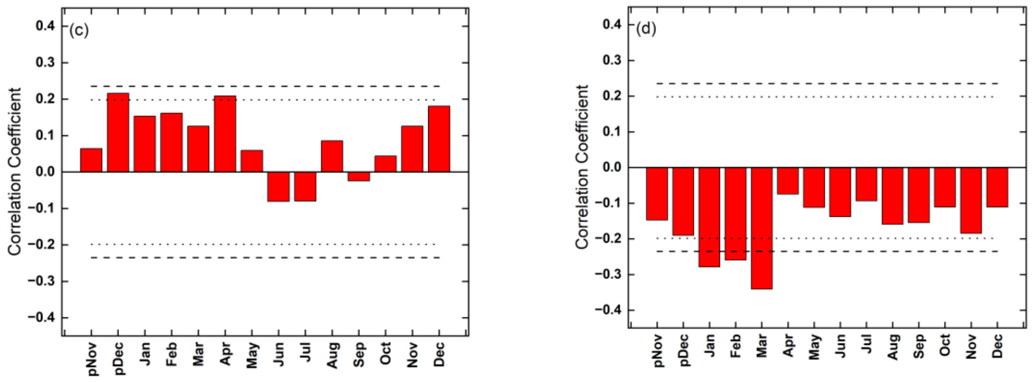
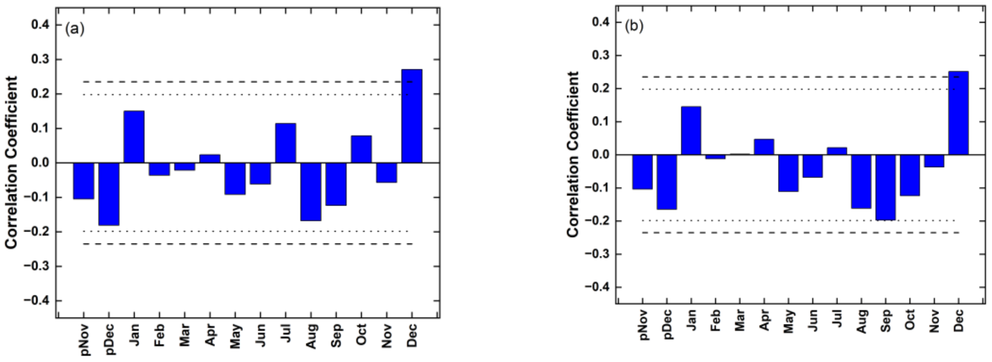


Figure 4.11. Pearson correlation between *P. wallichiana* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly minimum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.2.3 Relationship with total monthly precipitation

The analysis revealed a positive impact of precipitation on TRW, EW, and LW in the months of January, April, and July, corresponding to the early growth season, with a significant ($p<0.05$) positive effect observed in the month of December (Figure 4.12 a, b & c). Moreover, a positive correlation with MXD-raw was evident, primarily in the months of June-July and November-December (Figure 4.12 d).



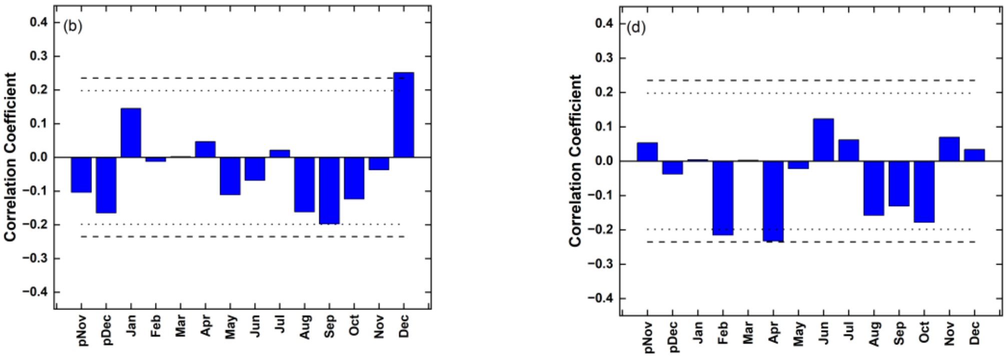


Figure 4.12. Pearson correlation between *P. wallichiana* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and total monthly precipitation from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.2.4 Relationship with mean monthly root-zone moisture (0-100 cm)

The correlations analysis of root-zone moisture with TRW revealed a positive influence during the months of March-May (Figure 4.13 a). Similarly, a positive correlation was found with EW in the months of March-July (Figure 4.13 b). However, it showed continuous positive effect of root-zone moisture on LW from previous year’s November to current year’s December, except for the month of September (Figure 4.13 c). Further, it demonstrated a positive influence of soil moisture on MXD-raw throughout the year (Figure 4.13 d), with significant relationship in the months of February and August ($p<0.1$) and March-July ($p<0.05$).

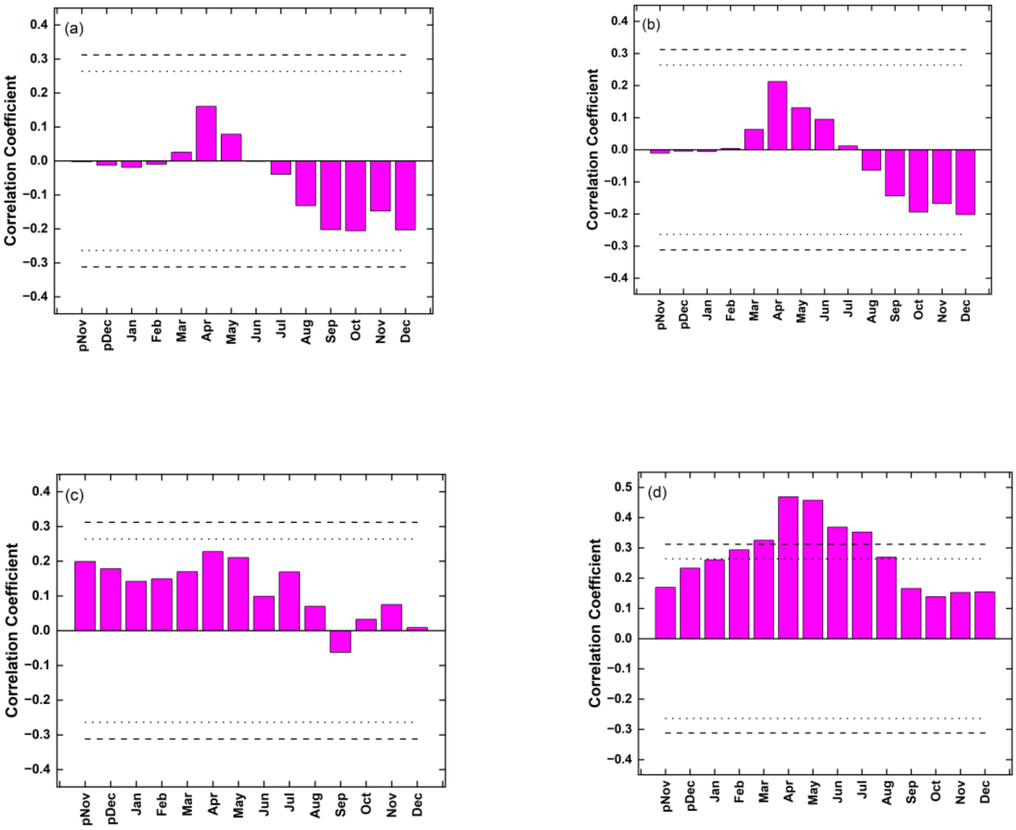


Figure 4.13. Pearson correlation between *P. wallichiana* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly root-zone moisture (0-100 cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.3 Relationship of *P. kesiya* radial growth with climate from Meghalaya

The radial growth (TRW, EW, LW) along with MXD-raw of *P. kesiya* from Meghalaya was analyzed for its relationship with climate using temperature (Tmax, Tmin), precipitation and root-zone moisture (0-100 cm) data sourced from the MERRA-2 dataset offered by the NASA.

4.3.3.1 Relationship with mean monthly maximum temperature

The climate growth analysis of *P. kesiya* radial growth (TRW and EW) with maximum temperature (Tmax) showed positive effect of temperature on growth and development of *P. kesiya* tree during early and mid-growing season in the Shillong area of Meghalaya (Figure 4.14 a, & b). The significant relationship ($p<0.05$) was observed during months of the previous year's December and current year's March. The significant negative relationship of TRW and EW with Tmax was observed in October-November. In the case of LW, the insignificant positive influence was observed during various months including previous year's November-December, February-March, May, July-September, and December (Figure 4.14 c). Further, maximum temperature showed positive impact on MXD-raw during previous year's November, March-July, September-October, and December. The significant negative response ($p<0.1$) was found in January, and positive ($p<0.05$) in May (Figure 4.14 d).

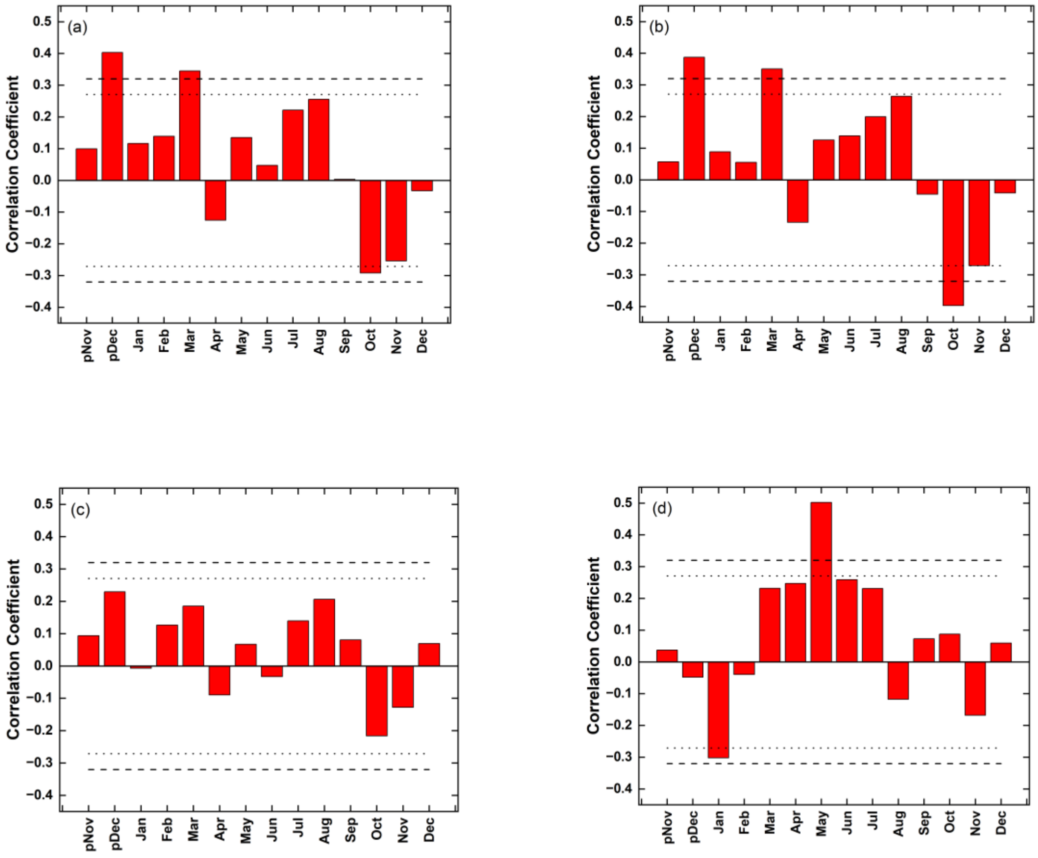
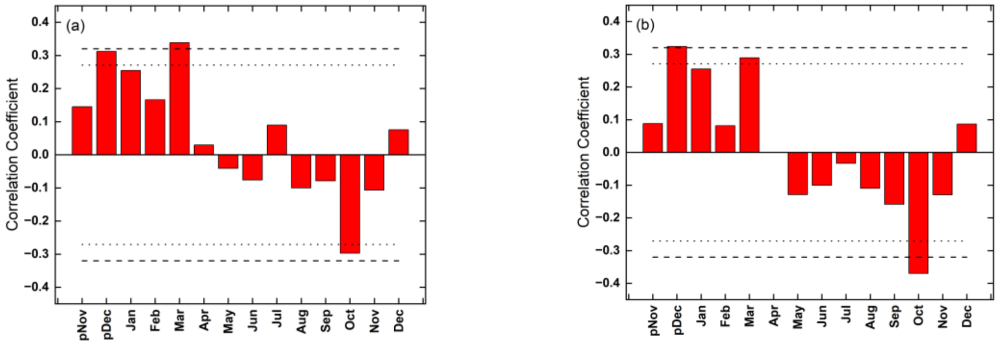


Figure 4.14. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly mximum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.3.2 Relationship with mean monthly minimum temperature

The minimum temperature also displayed the positive effect on radial growth of *P. kesiya* tree in Shillong, Meghalaya. The positive response for TRW and LW was received in the months of previous year’s November- current year’s May, July, September, and December (Figure 4.15 a & c). The significant relationship was found in previous year’s December (p<0.1) and current year’s March (p<0.05) for TRW, Current year’s March (p<0.1) for LW. However, EW exhibited positive influence of Tmin during previous year’s November-March, and in December, with significant relationship in the month of previous year’s December (p<0.05) and March (p<0.1). and current year’s March (p<0.1) for LW. In the case of MXD-raw, Tmin displayed a consistent negative influence, with significant relationship during previous year’s December-January (p<0.05), June (p<0.1), and August-September (p<0.05), November (p<0.05) and December (p<0.1) (Figure 4.15 d).



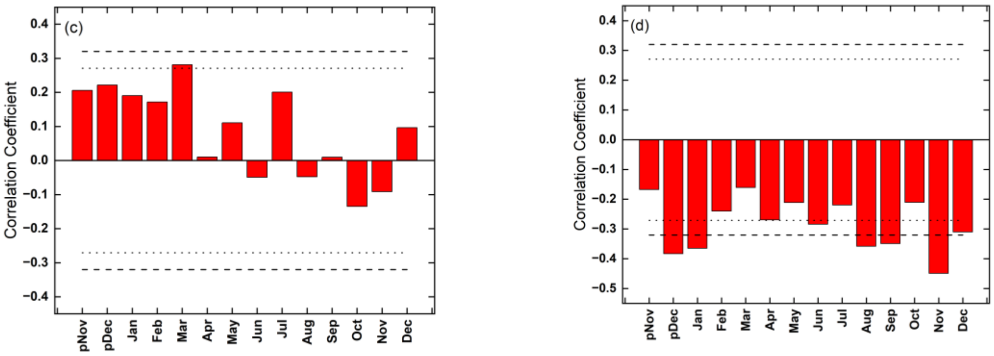


Figure 4.15. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly minimum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.3.3 Relationship with total monthly precipitation

Moreover, the radial growth of *P. kesiya* was examined to assess the impact of precipitation. The findings revealed a slight positive influence of precipitation on the growth (TRW) of the species in the early (March-April) and late growing season (November-December) (Figure 4.16 a). In case of the EW, the weak positive response was received in previous year’s December, January, March-April, July and December (Figure 4.16 b). However, LW showed more influence of precipitation, and positive relationship was witnessed in the months of March-May, July-August, and November-December (Figure 4.16 c). Further, MXD-raw exhibited a consistent negative impact of precipitation, except for the preceding year's November and current year’s January (Figure 4.16 d).

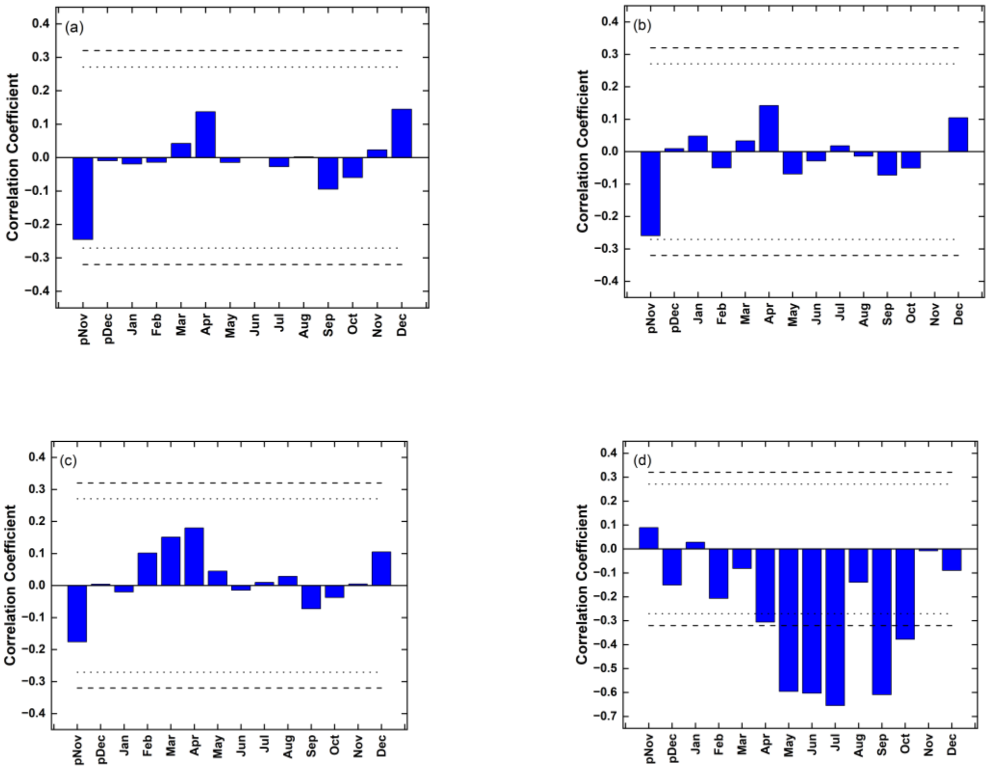


Figure 4.16. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and total monthly precipitation from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.3.4 Relationship with mean monthly root-zone moisture (0-100 cm)

The analysis revealed a positive correlation between root-zone moisture and TRW and EW in the month of April, and with LW in the months of April-May (Figure 4.17 a, b & c). Additionally, a continuous negative correlation was observed with MXD-raw throughout the analysis period (Figure 4.17 d).

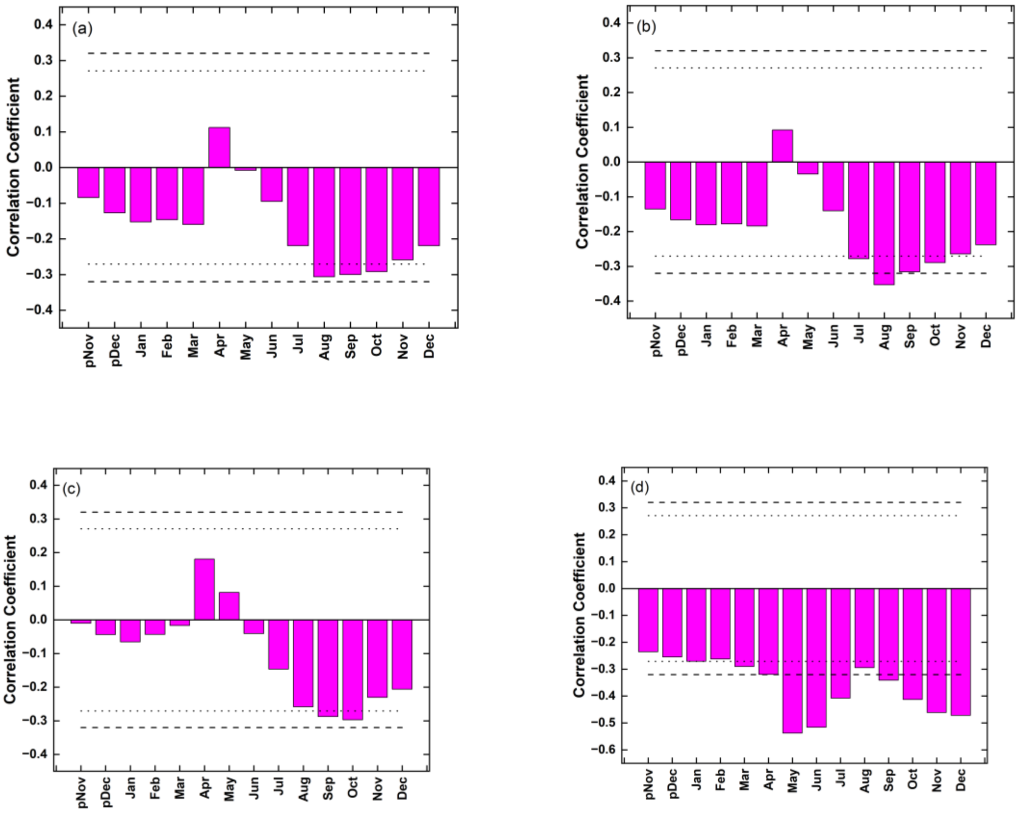


Figure 4.17. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly root-zone mositure (0-100 cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.4 Relationship of *P. kesiya* radial growth with climate from Mizoram

The time series data for TRW, EW, LW, and MXD-raw of *P. kesiya* from Champhai, Mizoram, were analyzed in relation to temperature variables (Tmax and Tmin) and precipitation data obtained from the local meteorological station, and root-zone moisture (0-100 cm) acquired from the MERRA-2 dataset provided by the NASA.

4.3.4.1 Relationship with mean monthly maximum temperature

The correlation analysis with maximum temperature (Tmax) revealed a positive impact of temperature on TRW and EW during the early phase of the growth season (pDec-Mar), but a negative effect was observed in the later part of the growth season (Figure 4.18 a & c). However, LW exhibited a positive influence of Tmax across various months (Figure 4.18 c). On the contrary, MXD-raw demonstrated a consistent negative effect of Tmax (Figure 4.18 d).

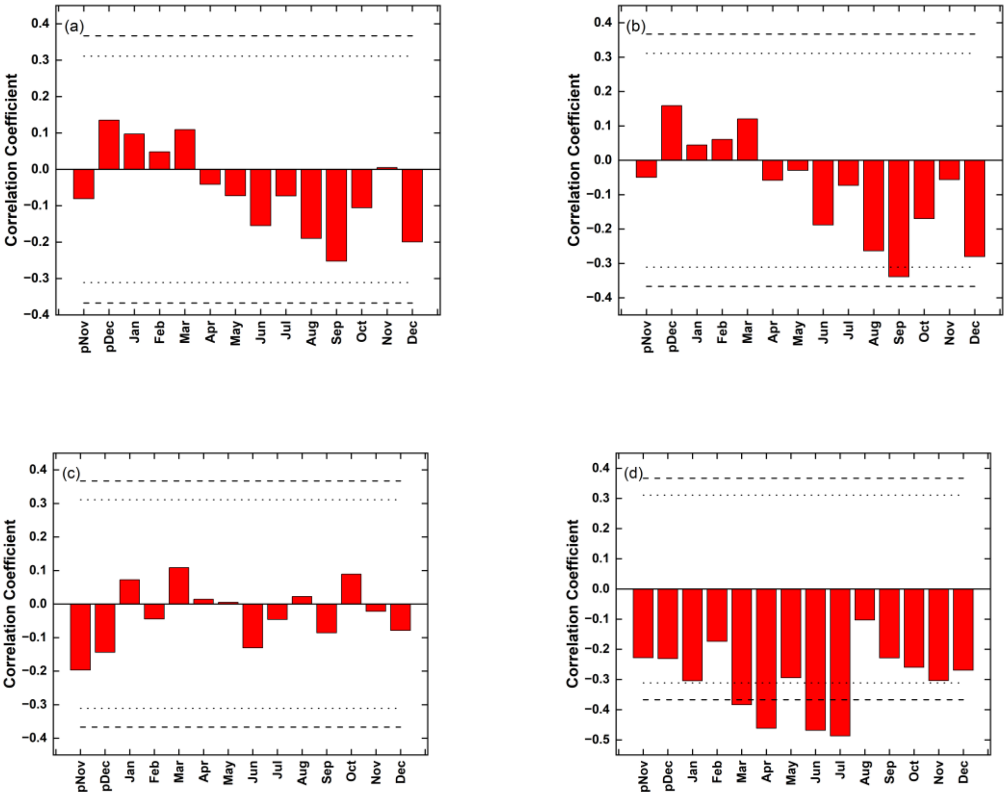


Figure 4.18. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly maximum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.4.2 Relationship with mean monthly minimum temperature

Minimum temperature did not show any noteworthy positive impact on radial growth; however, a significant negative influence was observed during the months of August-September (*p*<0.1) for TRW and EW, and in the months of July (*p*<0.1), August (*p*<0.05), and September (*p*<0.1) for LW (Figure 4.19 a, b & c). Moreover, it exhibited a positive influence on MXD-raw in the months of March-May, August, and December (Figure 4.19 d).

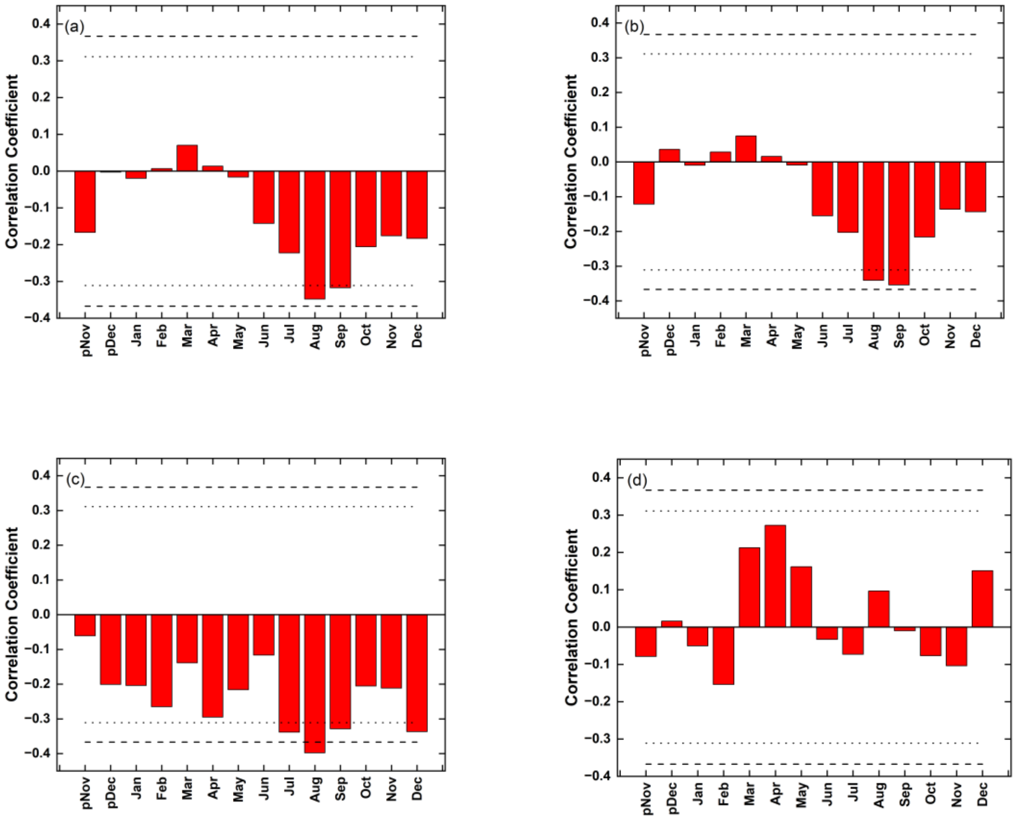
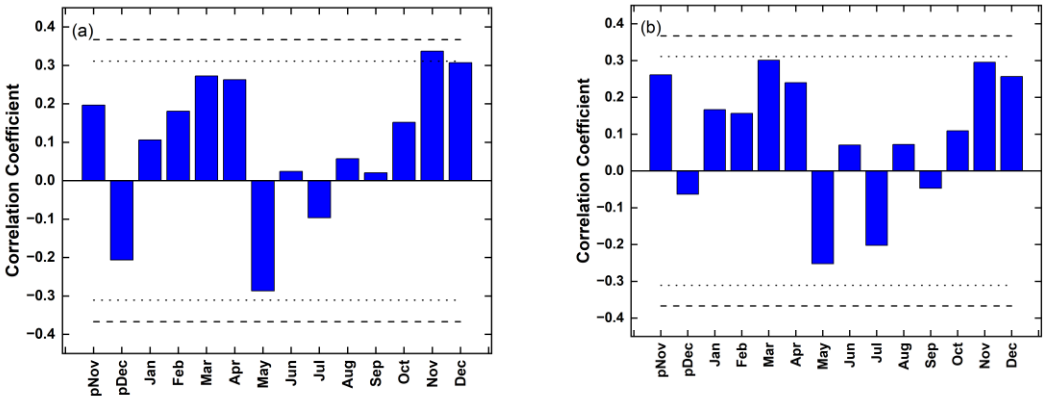


Figure 4.19. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly minimum temperature from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.4.3 Relationship with total monthly precipitation

The precipitation displayed a continuous positive effect on TRW and EW in the beginning (Jan-Apr) as well as at the end of the growth season (Oct-Dec) (Figure 4.20 a & b). A continuous positive relationship was found for TRW, except for the months of previous year's December, May, and July, and a significant positive relationship (p<0.1) was witnessed in November. For EW, a continuous positive influence was found for *P. kesiya*, except for previous year's December, May, July, and September. In the case of LW, it showed positive influence in the months of February-April, July, and September-December, with a significant relationship (p<0.1) in December (Figure 4.20 c). Additionally, MXD-raw exhibited a negative impact of precipitation during both the early and late growth seasons, with a noteworthy correlation (p<0.05) observed in March (Figure 4.20 d). Nevertheless, a positive influence of precipitation on MXD-raw was documented during the months of April-May and July-September.



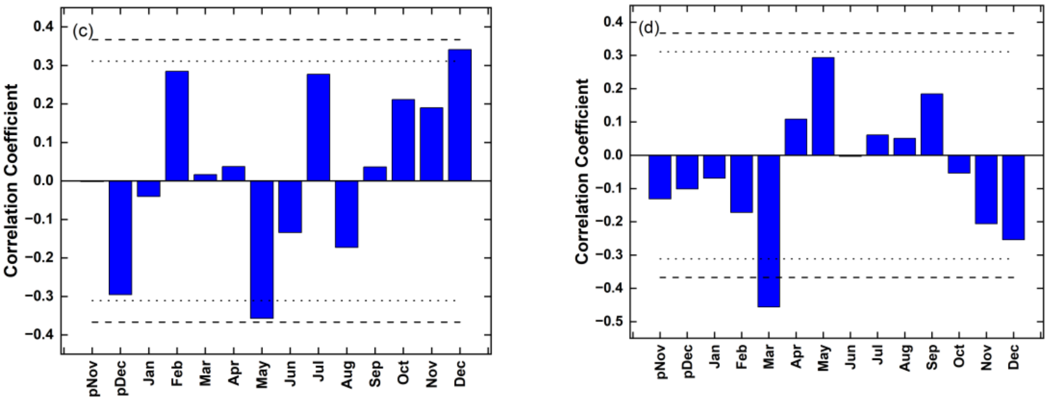


Figure 4.20. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and total monthly precipitation from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.3.4.4 Relationship with mean monthly root-zone moisture (0-100 cm)

A continuous positive influence of root-zone moisture was witnessed on radial growth of *P. kesiya*, except for the month of September in case of TRW and EW (Figure 4.21 a & b). The significant relationship between root-zone moisture and TRW and EW was witnessed in the months of March-April (p<0.05) and December (p<0.1). For LW, the significant relationship was observed in July (p<0.1) and December (p<0.05) (Figure 4.21 c). However, MXD-raw showed continuous positive influence of root-zone moisture (Figure 4.21 d), with significant association in the months of previous year’s November-February (p<0.05), and June-December (p<0.05).

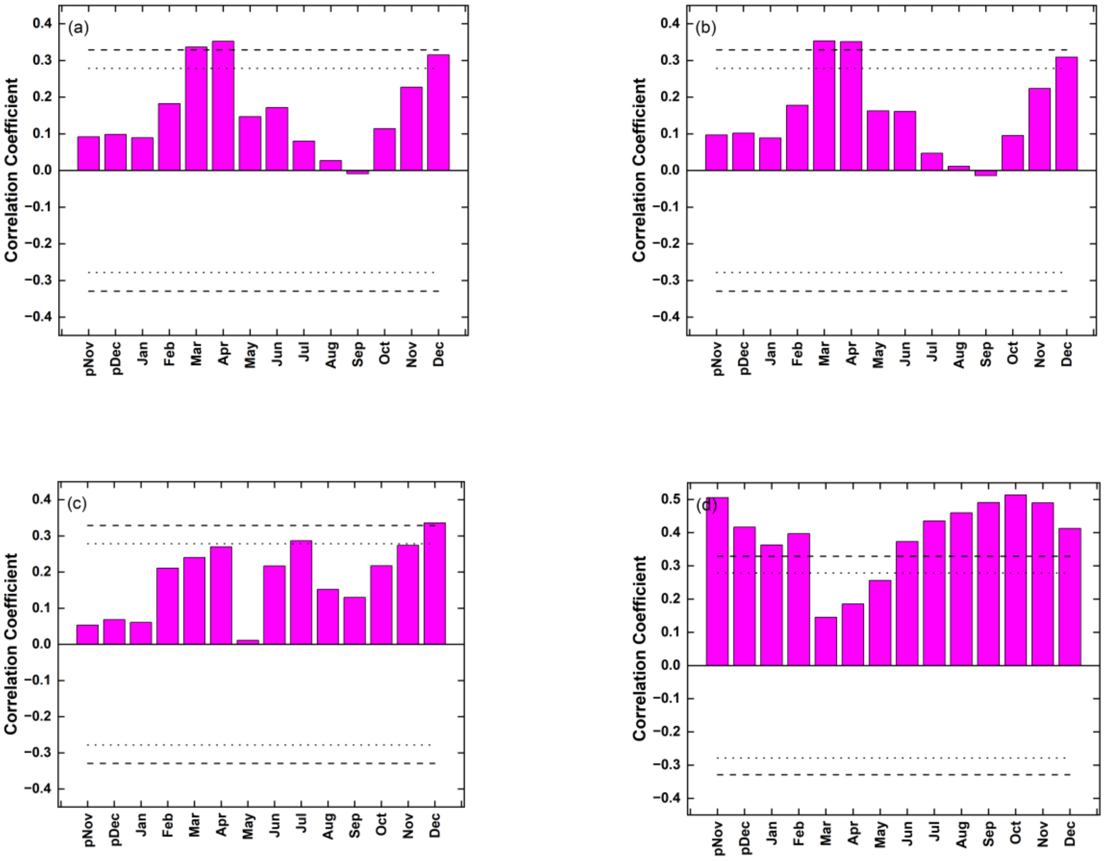


Figure 4.21. Pearson correlation between *P. kesiya* (a) TRW, (b) EW, (c) LW, and (d) MXD-raw and mean monthly roo-zone moisture (0-100 cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

4.4 Physiological explanation of tree-growth and climate relationship

4.4.1 *Pinus Patula* from Nagaland

The radial growth analysis of *P. patula* from Nagaland revealed a positive influence of both Tmax and Tmin on Tree Ring Width (TRW), Earlywood Width (EW), and Latewood Width (LW), particularly during the early phase of the growth season, aligning with the initiation of cambium activity in the species. Notably, a more pronounced relationship with radial growth was observed with Tmin, especially for LW, suggesting that minimum temperature contributes to extending the growth period for the species in the region. These findings align with findings of Reyes-Cortés et al., (2019), which highlighted the impact of temperature, particularly minimum temperature, on the radial growth of *P. patula* growing in Mexico at an altitude of 2500–2877 m.

Further, a consistent positive relationship with precipitation, with significant impact during July and September ($p<0.1$) for TRW and EW, and February and May ($p<0.1$) for LW, underscored the importance of moisture for the growth and development of the species in the region. This was further supported by the continuous positive correlation of root-zone moisture with TRW, EW, and LW from March to December. These results showed agreement with findings of Belay (2016) from Ethiopia, where the growth of *P. patula* growing at elevations from 1600 to 2580 m is influenced by both temperature (mainly Tmin) and rainfall. Additionally, the resilience component analysis of the species from Nagaland showcased the species' ability to resist the adverse effects of drought, suggesting that, under normal conditions, temperature plays a role in maintaining cambium activity at sites such as the Kohima Botanical Garden, characterized by ample precipitation, high moisture, and low temperatures. (Kharmawlong et al., 2023). This is further supported by a study conducted by Zonneveld et al., (2009) on the impact of climate change on the natural distributions of *Pinus patula* and *Pinus tecunumanii* populations in Mexico and Central America using climate envelope modeling (CEM), which revealed the robust performance of both species in a broad spectrum of climates, even in conditions predicted by CEM as unsuitable for the natural occurrence of pines.

Moreover, in this study, temperatures acted as precursors to growth, revealing a predominantly negative relationship with MXD-raw throughout most months, except for May and June. These months stand out as having the highest maximum temperatures alongside relatively low average rainfall compared to the other summer months. Additionally, MXD-raw exhibited a positive response to precipitation during the early and late periods of the growth season, where moisture tends to be limited, and even a small amount of rainfall plays a crucial role in sustaining active growth. These observations are consistent with the findings of Esper et al., (2015), suggesting that maximum latewood density is primarily influenced by instrumental temperature rather than biological memory effects, and tends to increase with decreasing precipitation and rising temperatures (Chen et al., 2012).

4.4.2 *Pinus wallichiana* from Arunachal Pradesh

The radial growth (TRW, EW, and LW) of P. wallichiana exhibited a positive correlation with maximum temperature. However, this response varied across different parameters. For TRW, the relationship was positive for most months, excluding June and November, with a significant association ($p<0.05$) observed in the months of the previous year's December and the current year's August. In the case of EW, a positive association was noted from the previous year's November to the current year's December, except for March and November. A significant relationship for EW was observed in July ($p<0.1$) and August ($p<0.05$). Conversely, LW displayed a positive correlation in various months, including the previous year's December ($p<0.1$), February-May, and August-September. Similarly, the TRW of P. wallichiana showed a positive relationship with minimum temperature from the previous year's November to the current year's February, April-May, August, and October-December months, with a significant response in the months of the previous year's December ($p<0.1$) and the current year's January ($p<0.05$). The positive association of radial growth with both Tmax and Tmin during early growing seasons, underscored the role of temperature in activating the cambium at the start of the growth season for P. wallichiana in the Tawang area. Further, the ongoing influence of temperature in subsequent months of middle and late growing seasons suggested its continuous role in keeping the cambium active for growth, especially in cold and moisture-dominated areas like Tawang.

Moreover, the correlation analysis of precipitation with TRW, EW, and LW indicated a positive impact in the months of January, April, and July, aligning with the early growth season. A noteworthy positive effect was observed in December ($p<0.05$). However, the positive effect during April and July was minimal for EW and LW. This suggests that the months of both early and late growing seasons generally experience moisture deficit conditions, and rainfall during these months positively influences species growth. This is further supported by the correlation analysis of root-zone moisture, which revealed a positive effect of moisture on TRW and EW during the early growing season (March-June) and a continuous influence on LW from the previous year's November to the current year's December, except for September. The above analysis suggests that temperature in Tawang facilitates the release of moisture and nutrients from the root zone, allowing their transport through the xylem tissues to the canopy for photosynthesis. Our findings align with previous studies conducted on *P. wallichiana* in various elevations, both higher (Shah et al., 2019; Singh and Yadav, 2000; Yadava et al., 2017) and lower (Yadav et al., 1997) sites in the Western Himalaya region. Moreover, research conducted in different regions worldwide indicates that dormant season photosynthesis rates are significant in various pine species (Hepting, 1945; Kramer, 1958). Interestingly, pines thriving in high-latitude areas exhibit substantial photosynthetic activities during warm autumn and winter seasons (Freeland, 1944; Mirov, 1967; Schulze et al., 1967; Tranquillini, 1979; Kozlowski and Pallardy, 1997), allowing for increased carbohydrate storage to support subsequent growth seasons (Kozlowski and Pallardy, 1997).

Further, the MXD-raw showed positive influence of Tmax in the months of Apr-May, Jul-Sep, and December, and positive influence of precipitation primarily in the months of June-July and November-December. The positive correlation between MXD-raw and precipitation in June-July can be attributed to highest amount of precipitation in these two months, which might have led to significant cooling in the area and resulted in slow growth with denser cell formation. This is also evident from negative (May-June) or very weak positive (July) association of precipitation with EW and LW during this period. Alternatively, temperature may play a crucial role in promoting the rapid growth of the species, resulting in the formation of less dense and wider cells. Conversely, the positive relationship during November and December highlights the importance of moisture for minimal growth at the end of growth season. The positive relationship of LW and MXD-raw with root-zone moisture further suggested that high amount of moisture creates cooler effect in the areas and slows down the growth, which results in denser cells responsible for maximum latewood density.

4.4.3 *Pinus kesiya* from Shillong, Meghalaya

Pinus kesiya is an early successional, light demanding species, which displays 3 flushes of leaves in a year. In *P. kesiya*, fascicle length, area and weight are governed by temperature, and exhibits remarkable decrease under low temperatures (Das and Ramakrishnan, 1986). A research investigation involving five pine species from Duke Forest in Durham revealed an increase in mechanical tissue fraction corresponding to an elongation in needle length. This was succeeded by a decline in needle dry density, a fourfold increase in leaf hydraulic conductance observed across the spectrum of needle length for all species, and an associated but less pronounced upward trend in both stomatal conductance and photosynthetic capacity (Wang et al., 2019). It indicates that shorter needles developed under low temperatures results in poor physiological functions and low rate of photosynthesis. The positive influence of temperature during previous year's November to current year's March may be attributed to proper needle development and activation of cambium. This is also evident from climograph of study site (Figure 3.5), where both maximum and minimum temperature remains below the optimum range (i.e., 23.5/17.5) suggested for growth and development of *P. kesiya* (Verma and Tandon, 1988). Further, Chaudhary and Bhattacharyya (2002) noted a positive correlation in the TRW chronologies of *P. kesiya*, established in neighboring areas of Shillong, with mean monthly temperature and precipitation during different months of both the early and late growing seasons, revealing a diverse climatic response of *P. kesiya* growing at various locations within this region. The positive correlation of precipitation with radial growth (TRW, EW, and LW), particularly with LW, underscores the significance of moisture during both the early and late growing seasons. These periods experience a reduction in precipitation and soil moisture in the region, as illustrated in the climograph figure (Figure 3.5). This observation is further supported by correlation analysis with soil moisture, revealing a positive response only during March, April, and May, as moisture reaches its lowest levels in March and begins to gradually increase from April onward with the rise in precipitation. Our findings also align with a study conducted by Fu et al., (2017) in the Ailao Mountains, Yunnan Province, southwestern China, which shares similar climatic conditions with our study site. They reported a positive correlation of *P. kesiya* with mean monthly temperature from the previous year's July to the current year's September. Further, they observed a stronger temperature signal in the earlywood and a precipitation signal in the latewood portion. Our study exhibited a comparable trend, wherein earlywood demonstrated a stronger correlation with temperature, while latewood exhibited a more pronounced relationship with precipitation and moisture.

Further, MXD-raw showed positive influence of maximum temperature mainly during March to July. The observed phenomenon may be linked to the initial deceleration in cambium activity during the early phase of this period, characterized by low moisture and rising temperatures, followed by a subsequent phase of slow growth influenced by the cooling effect of abundant moisture from high rainfall, where the temperature sustains cambium activity but results in gradual growth marked by the formation of narrow and dense cells. These observations were further supported by the consistent negative correlation of MXD-raw with precipitation and soil moisture at the study site.

4.4.4 *Pinus kesiya* from Champhai, Mizoram

In Champhai, Mizoram, TRW and EW of *P. kesiya* exhibited positive correlations with maximum temperature (Tmax) during the early months of the growing season (from the previous year's December to March). This association could be linked to the activation of cambium and the emergence and development of new needles, as this period in Champhai experiences the Tmax just above the optimum range (23.5°C; Verma and Tandon, 1988) suggested for growth and development of *P. kesiya*, where the Tmin generally remains below the suggested optimum range (17.5°C; Verma and Tandon, 1988). However, Tmax together with Tmin rapidly increases from March, surpassing the optimum range, and results in a negative association of temperature with TRW and EW for the mid and late growth season. Zonneveld et al., (2009) have also predicted that places experiencing a maximum temperature of 32 °C in the warmest month and precipitation of 60.4 mm in the driest quarter may witness a high negative impact of climate change on *P. kesiya* tree species.

Moreover, the correlation analysis with precipitation data demonstrated a favourable impact of rainfall on Khasi pine growth during both the early and late growing seasons, with a noteworthy relationship observed in November ($p<0.1$) for TRW and December ($p<0.1$) for LW. This indicates that precipitation plays a crucial role in maintaining soil moisture levels during these periods, alleviating the adverse effects of high temperatures associated with increased water conductance and moisture deficit. *P. kesiya*, identified as an anisohydric tree species (Kiianmaa 2005) with low intrinsic water use efficiency (iWUE; Fu et al., 2017), relies on a substantial amount of moisture for its growth and development. The decline in precipitation in the area may potentially impact its physiological processes (Grossiord et al., 2017). These observations are further supported by the consistent positive correlation of radial growth (TRW, EW, and LW) with root-zone soil moisture. This underscores the species' requirement for higher water amounts, particularly in regions where the maximum temperature exceeds the suggested optimum range for most months of the year. Similar climate-growth trends have been identified in studies conducted by Pumijumnong and Wanyaphet (2006) in Thailand, Upadhyay (2019) in Mizoram, and Thomte et al., (2020, 2022) in Manipur, where *P. kesiya* thrives in similar environmental settings.

Additionally, an analysis of maximum latewood density (MXD-raw) with climate data unveiled a substantial reliance on root-zone soil moisture. This dependency may be associated with a high transpiration rate and low water use efficiency in the species. Under such conditions, root-zone soil moisture likely fulfils the water requirements necessary to sustain growth. The negative correlation of Tmax with maximum latewood density could be attributed to the synergistic effect of temperature on cell division under adequate rainfall and soil moisture. However, the positive association of MXD with Tmin during March-May, August, and December might be linked to cell maturation and cell wall thickening, as Tmin during this period reaches the optimum range (17.5°C). This association is further confirmed by previous studies that have identified a connection between night temperatures and the thickening and lignification of xylem cells (Hosoo et al., 2002; Liang et al., 2016), a phenomenon directly influencing changes in MXD.

4.5 Statistical growth model

Statistical growth models were created to provide a deeper understanding of the influence of climate on the growth of three pine species across four distinct environmental settings and to assess their impact on carbon sequestration potential.

4.5.1 *P. patula* from Kohima Botanical Garden, Nagaland

The developed model accounted for 96% of the variability in TRW of *P. patula* at Kohima Botanical Garden (Table 4.6). The Predicted R^2 (86.89%), calculated by systematically removing each observation from the dataset, estimating the regression equation, and assessing the model's ability to predict the removed observation, exhibited favourable values, indicating the robustness of the model. These results were further supported by the significantly negative values of AIC (-93.40) and BIC (-106.80), along with a notable 10-fold R^2 value (86.54%). The positive and negative coefficients of different climatic variables (Tmax, Tmin, Precip, and RZSM) entered into the regression equation highlighted the primary influence of temperature, especially minimum temperature, on the growth of *P. patula* at Kohima Botanical Garden, Nagaland. This further validates the results obtained with correlation analysis.

Table 4.6: Multiple liner regression of tree-ring width (TRW) with climate variables

Site	**Regression Equation**	**Observed R^2**	**Adjusted R^2**	**Predicted R^2**	**AIC**	**BIC**	**Validation 10-fold R^2**
Kohima Botanical Garden, Nagaland	***P. patula*_TRW_Kohima** = 5.664 - 0.0699 Jan_Tmax - 0.0869 Feb_Tmax + 0.0890 pDec_Tmin + 0.1162 Jan_Tmin + 0.0697 Feb_Tmin - 0.2269 May_Tmin + 0.1136 Jun_Tmin - 0.0708 Sep_Tmin + 0.0589 Oct_Tmin - 0.001834 Apr_Precip - 0.000438 Jul_Precip - 0.000891 Aug_Precip - 5.930 pNov_RZSM + 13.41 pDec_RZSM - 8.81 Jan_RZSM - 3.151 Feb_RZSM + 3.258 Jul_RZSM - 0.596 Oct_RZSM	96.71%	93.75%	86.89%	-93.40	-106.80	86.54%
Tawang, Arunachal Pradesh	***P. wallichiana*_TRW_Tawang** = 0.908 + 0.02172 pDec_Tmax + 0.1180 pNov_Tmin + 0.0439 Jan_Tmin - 0.00802 pNov_Precip + 0.01235 Jan_Precip + 0.001471	84.32%	78.91%	66.80%	-83.87	-75.16	63.00%

	Oct_Precip - 6.14 pNov_RZSM + 6.41 pDec_RZSM + 2.982 Apr_RZSM - 2.291 Aug_RZSM						
Shillong, Meghalaya	***P. kesiya*** **TRW_Shillong** = -8.77 + 0.0815 pDec_Tmax + 0.1912 Mar_Tmax - 0.0971 Mar_Tmin -0.0851 Apr_Tmin + 0.4079 Jul_Tmin - 0.1676 Aug_Tmin - 0.004866 pNov_Precip + 0.002435 pDec_Precip - 0.000989 Apr_Precip + 4.621 Apr_RZSM - 1.841 Aug_RZSM	81.99%	74.38%	56.63%	-42.77	-36.64	52.01%
Champhai, Mizoram	***P. kesiya*****_TRW_Champhai** = 2.671 - 0.01010 Jan_Tmax - 0.0723 Sep_Tmax + 0.0265 Oct_Tmax + 0.04061 Feb_Tmin - 0.02401 Mar_Tmin - 0.03648 Nov_Tmin + 0.002325 Feb_Precip + 0.000608 Jun_Precip + 0.002645 Dec_Precip	83.76%	75.16%	56.62%	-32.70	-36.05	60.59%
TRW = Tree Ring Width, Tmax = Maximum Temperature, Tmin = Minimum Temperature, Precip = Total Precipitation, RZSM = Root-Zone Soil Moisture (0-100cm). The lowercase "p" before the months indicates the previous year.							

4.5.2 *P. wallichiana* from Tawnag, Arunachal Pradesh

In case of *P. wallichiana*, developed model explained 84% variability in the tree-ring width growth at Tawang (Table 4.6). The effectiveness of model was affirmed by the notably good values of predicted R^2 (66.80%) and 10-fold R^2 (63%), as well as substantial negative values of AIC (-83.87) and BIC (-7516). The entered correlation coefficients of climatic variables into the regression equation suggests a substantial impact of temperatures on the tree ring width (TRW) growth of *P. wallichiana*, especially at the beginning of the growth season, along with precipitation at both the commencement and conclusion of the growth season. Additionally, analysing the months of climatic variables entered into the regression equation indicates that the predominant growth occurs during the early stages of the growth season. These findings further align with the research of various scholars from different regions worldwide, highlighting substantial dormant season photosynthesis rates in various pine species (Hepting, 1945; Kramer, 1958). Pines in high-latitude regions have been documented to display notable photosynthetic activities during the warm autumn and winter seasons (Freeland, 1944; Mirov, 1967; Schulze et al., 1967; Tranquillini, 1979; Kozlowski and Pallardy, 1997). This phenomenon enables enhanced carbohydrate storage to sustain subsequent growth seasons (Kozlowski and Pallardy, 1997).

4.5.3 *P. kesiya* from Shillong, Meghalaya

The model developed for *P. kesiya* elucidated 81.99% of the variability in TRW growth at the Shillong site (Table 4.6). The effectiveness of model was reinforced by favourable values in predicted R^2 (56.63%), AIC (-42.77), BIC (-36.64), and 10-fold R^2 (52.01%). The model revealed the significance of maximum temperature and precipitation in the initial months of the growing season, while minimum temperature and soil moisture played a positive role during the mid-growth season. In this context, temperature can be associated with needle enlargement and cambium activity, while precipitation and moisture fulfil the water requirements essential for stomatal conductance during photosynthesis. This further supports the results obtained in correlation analysis.

4.5.4 *P. kesiya* from Champhai, Mizoram

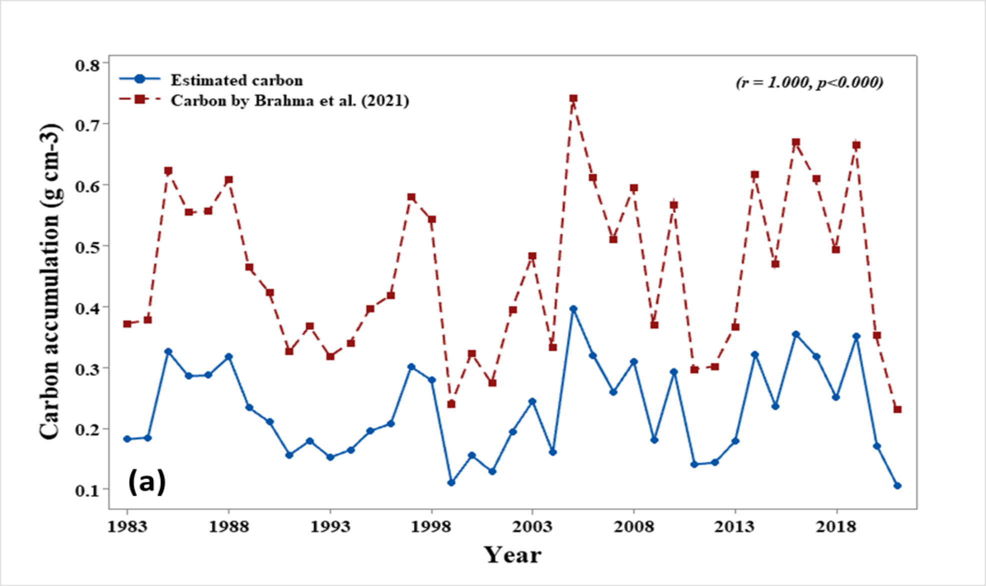
The statistical model for *P. kesiya* from Champhai explained 83.76% variability in TRW growth (Table 4.6). The model fit was supported by the moderate values of predicted R^2 (56.62%), AIC (-32.70), BIC (-36.05), and 10-fold R^2 (60.59%). The model equation highlighted the significant influence of precipitation from early to late in the growing season, consistent with correlation analysis. This could be attributed to the observed temperatures exceeding the optimum threshold at the study site from the early to late months of the growing season.

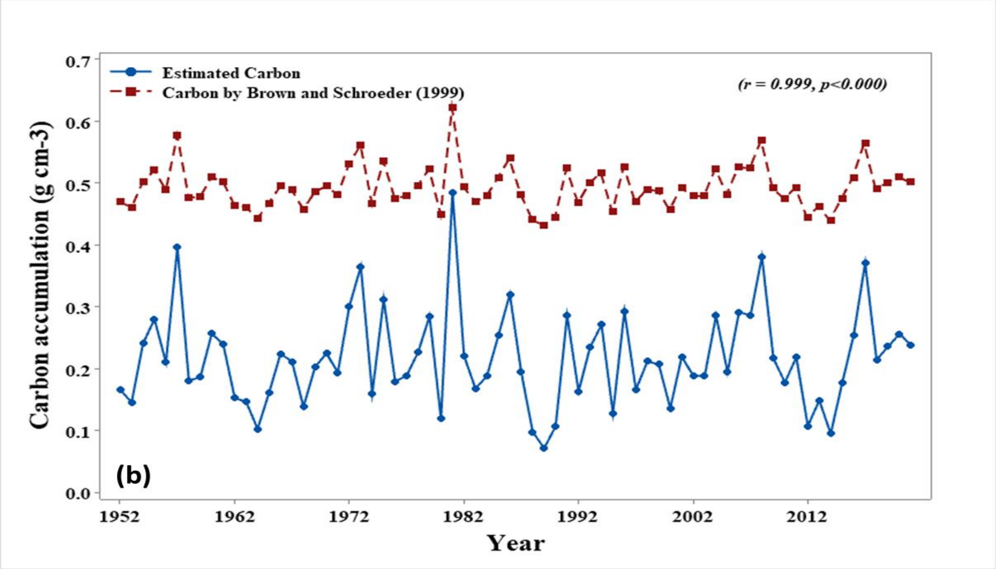
4.6 Annual carbon accumulation

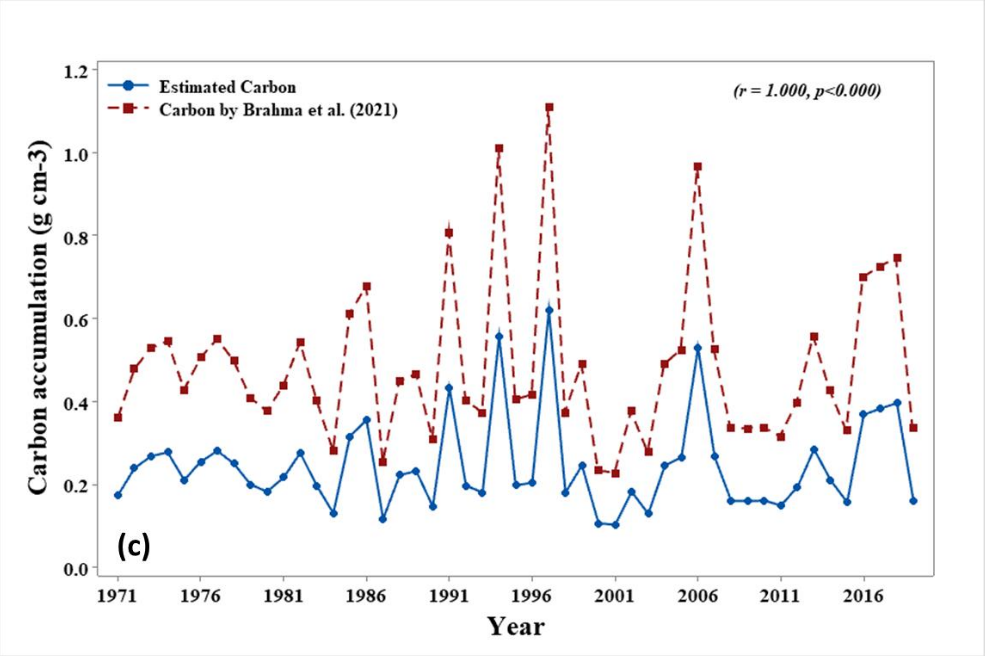
The annual carbon accumulation was computed for all three pine species across their designated sites, and the obtained results were juxtaposed with estimates derived from other available allometric equations of species within the region.

In the case of *P. patula* and *P. kesiya*, a comparison was conducted using the optimal allometric equation proposed for these species by Brahma et al., (2021). The carbon accumulation series estimated in this study exhibited a strong correlation with the results obtained from Brahma et al., (2021). Nevertheless, the outcomes derived from Brahma et al., (2021) showcased higher accumulation values compared to those obtained in this study using annually resolved records (Figure 4.22 a, c, and d).

Similarly, for *P. wallichiana*, the estimated carbon series exhibited a significant correlation with the outcomes of the allometric equation provided by Brown and Schroeder (1999). However, the equation led to an overestimation of carbon values (Figure 4.22 b).


Estimated carbon
Carbon by Brahma et al. (2021)
(r = 1.000, p<0.000)
Carbon accumulation (g cm-3)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
(a)
1983
1988
1993
1998
2003
2008
2013
2018
Year


Estimated Carbon
Carbon by Brown and Schroeder (1999)
(r = 0.999, p<0.000)
Carbon accumulation (g cm-3)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
(b)
1952
1962
1972
1982
1992
2002
2012
Year



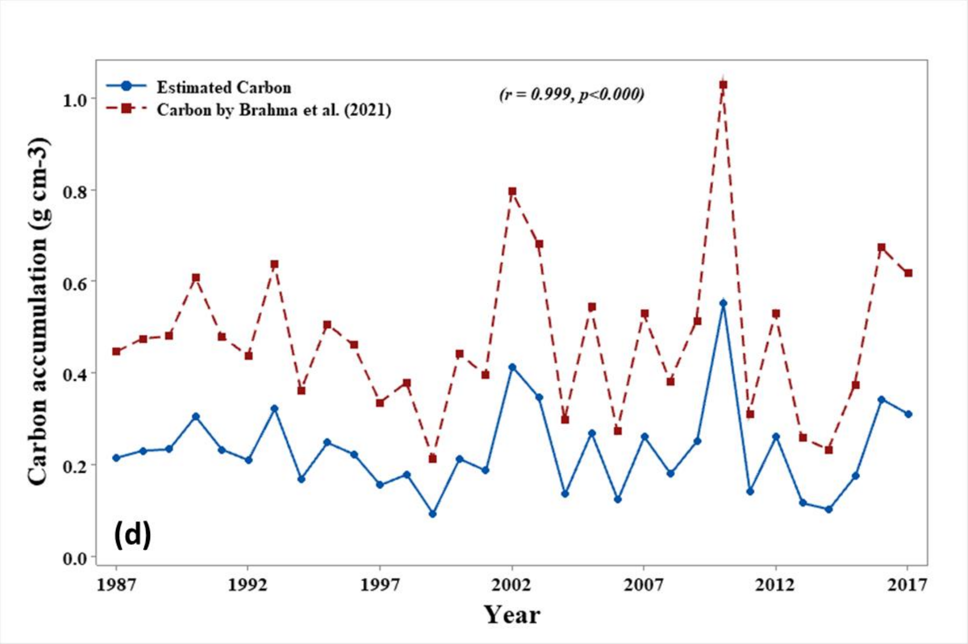


Figure 4.22. Annula carbon accumulation (g cm^{-3}) in (a) *P. patula* (Kohima Botanical Garden), (b) *P. wallichiana* (Tawang site), (c) *P. kesiya* (Shillong site), and (d) *P. kesiya* (Champhai site).

4.7 Relationship of carbon accumulation with climate

To understand the connection between climate and the carbon sequestration capacity of selected tree species, the carbon accumulation series were correlated with climatic variables (Figure 4.23, 4.24, 4.25, and 4.26). The results of the correlation analysis mirrored the findings obtained from the correlation analysis of Tree Ring Width (TRW) for each species with climatic variables. This suggests a direct association between carbon accumulation and variations in TRW. Consequently, any alterations in climatic conditions influencing TRW growth will impact the amount of accumulated carbon in the tree stem wood.

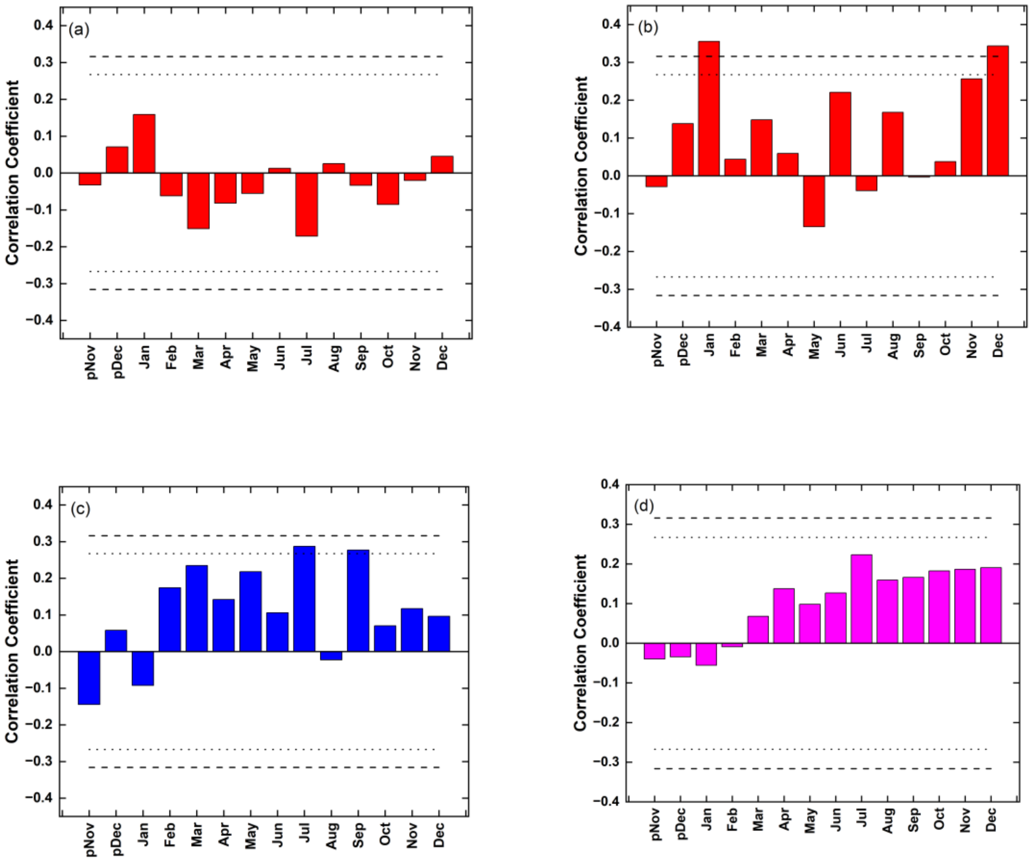


Figure 4.23. Pearson correlation of accumulated carbon in *P. patula* at Kohima Botanical Garden site with monthly (a) Tmax, (b) Tmin, (c) Precipitation, and (d)

Root-zone soil moisture (0-100cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

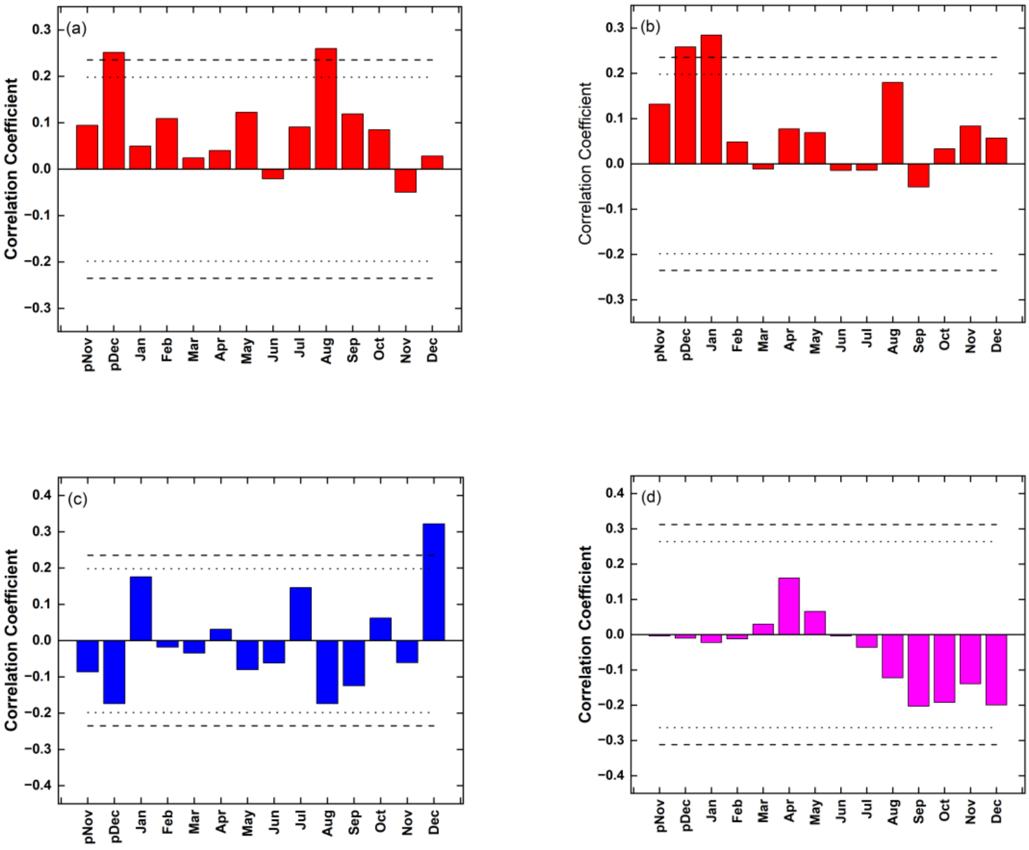


Figure 4.24. Pearson correlation of accumulated carbon in *P. wallichiana* at Tawang site with monthly (a) Tmax, (b) Tmin, (c) Precipitation, and (d) Root-zone soil moisture (0-100cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

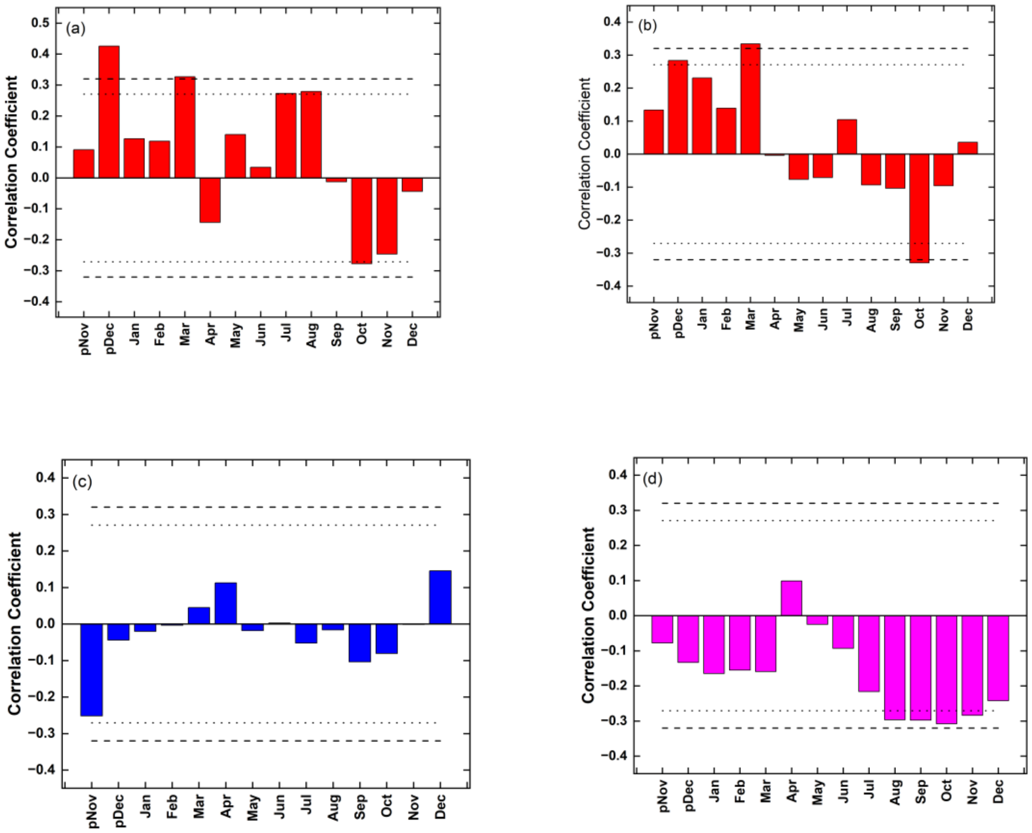
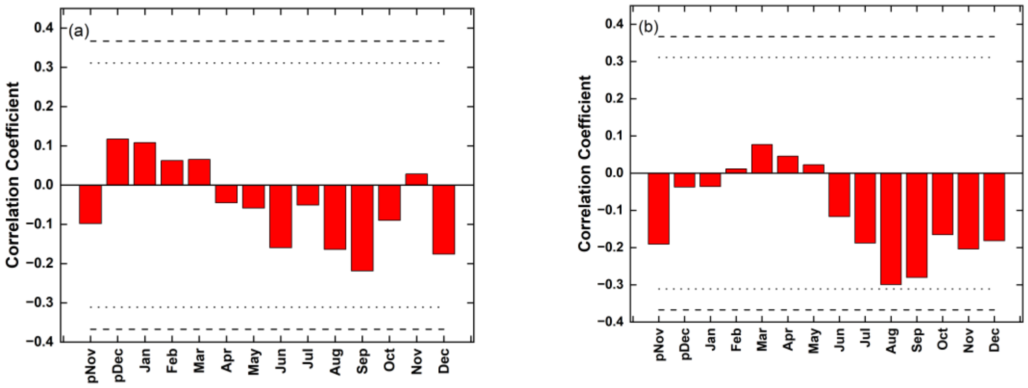


Figure 4.25. Pearson correlation of accumulated carbon in *P. kesiya* at Shillong site with monthly (a) Tmax, (b) Tmin, (c) Precipitation, and (d) Root-zone soil moisture (0-100cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.



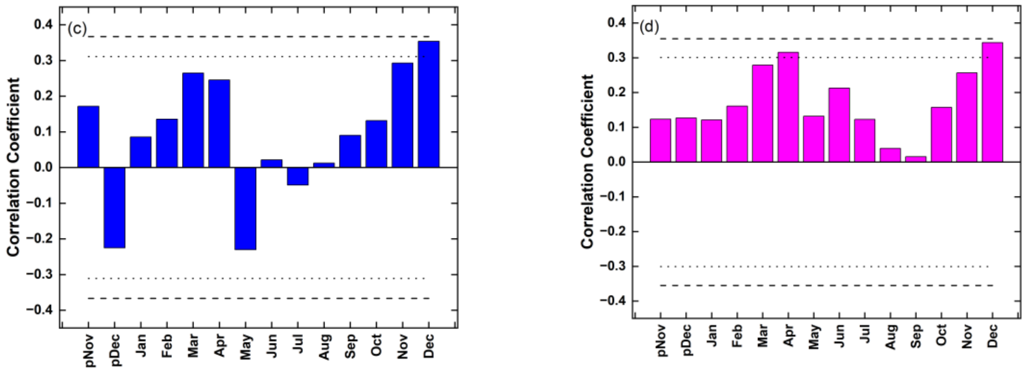


Figure 4.26. Pearson correlation of accumulated carbon in *P. kesiya* at Champhai site with monthly (a) Tmax, (b) Tmin, (c) Precipitation, and (d) Root-zone soil moisture (0-100cm) from the previous year's November to the growth year's December. The lowercase "p" before the months indicates the previous year. The horizontal dot lines represent the 90% confidence level, and the dashed lines represent the 95% confidence level.

Chapter 5

Summary and conclusion

The anthropogenically derived climate change, particularly altering patterns of temperature and precipitation is largely affecting structure and functioning of the forest ecosystem. Such changes in temperature and precipitation regime have direct influence on the patterns of growth and development of forest species, which profoundly affect the vitality of forest ecosystems and their ability to provide goods and services to the society. Therefore, long term data on the analysis of growth trends, species adaptation patterns, physiological responses to stressed conditions and frequency and patterns of different disturbance events with respect to climate changes will be required for the formulation of mitigation strategies for sustainable forest management under climate change. In this respect, analysis of tree rings act as an archive for these events and provide such long-term data on different time scales which can be used for the management of forest in changing climate scenario. Hence dendrochronological studies using tree ring analysis have high potential for the management of forest in different regions of the world

The current research extensively examined the wood and tree ring characteristics of three selected tree species *P. patula*, *P. kesiya,* and *P. wallichiana* – utilizing high-resolution scanned images from an Epson professional scanner. Each species exhibited well-defined growth rings, with distinct zonation between earlywood and latewood observed in *P. patula* and *P. kesiya*. In contrast, *P. wallichiana* displayed a less pronounced zonation in older rings, particularly in the sapwood portion. Additionally, *P. wallichiana* showed varying earlywood colors, transitioning from brownish yellow to a very dark brown shade in the latewood portion. While *P. patula* and *P. kesiya* exhibited a gradual change in wood color from yellowish white in earlywood to dark brown in latewood, there was no clear distinction between sapwood and heartwood. The wood of all three species displayed a straight grain with a medium texture.

Moving into the core of the study, the development of tree ring width chronologies was a pivotal aspect. Four tree ring width chronologies, including *P. patula* from Nagaland, *P. wallichiana* from Arunachal Pradesh, and *P. kesiya* from Meghalaya and Mizoram, were established. The corresponding partial ring width chronologies for earlywood (EW) and latewood (LW) were also developed for each site.

The accuracy of cross-dating was rigorously assessed using the COFECHA program, where tree ring series with high correlation were included, while poorly dated series with low correlation were excluded from the analysis. The mean inter-correlation among series for each species and site revealed a degree of commonality among the samples, contributing to the overall site chronology. However, challenges were identified, such as lower sample depth in *P. wallichiana* due to resin content in older annual rings, impacting the ability to delineate ring boundaries. Furthermore, the study highlighted the influence of moist climatic conditions in Arunachal Pradesh, Nagaland, and Mizoram on the observed low to moderate values of series mean inter-correlation.

Following successful cross-dating, four tree ring width chronologies, along with corresponding partial chronologies for earlywood and latewood, were developed for each site – Nagaland, Arunachal Pradesh, Meghalaya, and Mizoram. These chronologies covered varying temporal expanses, ranging from 39 years for P. patula in Nagaland to 121 years for P. wallichiana in Arunachal Pradesh. Descriptive statistics for each species and site provided insights into the variability and characteristics of the developed tree ring chronologies.

Nagaland (*P. patula*):

Chronologies spanning from 1983 to 2021 demonstrated robust mean series inter-correlation values for tree ring width (TRW), earlywood width (EW), and latewood width (LW). Moderate values of mean sensitivity, standard deviation, and autocorrelation indicated the significant role of current climatic factors in the species' growth.

Arunachal Pradesh (*P. wallichiana*):

Chronologies extending from 1901 to 2021 exhibited a robust mean series inter-correlation for tree ring width (TRW), but a decrease in values for earlywood width (EW) and latewood width (LW). Challenges such as low sample size and high moisture levels at the site were identified as potential factors influencing the chronologies.

Meghalaya (*P. kesiya*):

Chronologies covering 124 years for tree ring width (TRW) and latewood width (LW), and 118 years for earlywood width (EW), revealed robust mean series inter-correlation values for TRW and EW. A decline in mean series inter-correlation was observed for LW. Moderate to high values of mean sensitivity, standard deviation, and autocorrelation highlighted the substantial influence of current climatic factors on species growth.

Mizoram (*P. kesiya*):

Chronologies spanning 40 years for tree ring width (TRW) and earlywood width (EW), and 38 years for latewood width (LW), displayed robust mean series inter-correlation values. Moderate values of mean sensitivity, standard deviation, and autocorrelation underscored the significant impact of current climatic factors on species growth.

Further, ring width density (RD) and maximum latewood density (MXD) investigation of three species, namely *P. patula*, *P. wallichiana*, and *P. kesiya*, was conducted across four different sites. The WinDendro Density software was employed for estimation. *P. patula* exhibited RD values ranged from 0.345 to 0.474 gm cm^{-3}, with a mean value ($\overline{RD}$) of 0.383 gm cm^{-3}, aligning with previous studies. MXD for *P. patula* ranged from 0.484 to 0.582 gm cm^{-3}, with a mean value ($\overline{MXD}$) of 0.517 gm cm^{-3}. RD values of *P. wallichiana* were between 0.250 and 0.360 gm cm^{-3} ($\overline{RD}$ = 0.305 gm cm^{-3}), consistent with reported values. Similarly, RD of *P. kesiya* ranged from 0.299 to 0.388 gm cm^{-3} ($\overline{RD}$ = 0.370 gm cm^{-3}) at Shillong, and from 0.231 to 0.424 gm cm^{-3} (¯RD = 0.329 gm cm^{-3}) at Champhai. MXD for *P. kesiya* at Shillong ranged between 0.405 to 0.534 gm cm^{-3} ($\bar{\mathrm{M}}$XD =0.491 gm cm^{-3}) and at Champhai from 0.405 to 0.534 gm cm^{-3} ($\bar{\mathrm{M}}$XD =0.491 gm cm^{-3}).

Further, the radial growth-climate analysis of *P. patula* in Nagaland indicated a positive influence of both Tmax and Tmin on Tree Ring Width (TRW), Earlywood Width (EW), and Latewood Width (LW). This impact was particularly notable during the early growth season, corresponding to the initiation of cambium activity in the species. The results emphasized the significant contribution of Tmin, especially for LW, suggesting that minimum temperature prolongs the growth period for the species in the region. Moreover, a consistent positive relationship with precipitation, particularly in July, September, February, and May, underscored the importance of moisture for the growth of species in Nagaland. Root-zone moisture also showed continuous positive correlation with TRW, EW, and LW from March to December. The study highlighted the resilience of species to adverse drought effects, with temperature maintaining cambium activity under normal conditions at sites like the Kohima Botanical Garden. The research revealed that temperatures act as growth precursors, displaying a predominantly negative relationship with MXD-raw, except for May and June. Further, positive response of MXD-raw to precipitation both during the early and late stages of growth suggested a crucial need for water to sustain growth under moisture-limited conditions, ultimately leading to the formation of narrow and dense cells.

For *P. wallichiana*, climate-growth analysis of tree ring width (TRW), earlywood (EW), and latewood (LW), revealed a positive correlation with maximum temperature. Notably, TRW exhibited a positive association for most months, except June and November, with significant correlations in the previous December and the current August. Similarly, EW displayed a positive link from November to December of the previous year, excluding March and November, with significant relationships in July and August. Conversely, LW exhibited positive correlations in various months, including the previous December, February-May, and August-September. Moreover, TRW showed a positive relationship with minimum temperature from the previous November to the current February, April-May, August, and October-December, with significant responses in the previous December and the current January. This positive association with both maximum and minimum temperatures during early growing seasons underscored temperature's role in activating the cambium for growth, particularly in cold and moisture-dominated areas like Tawang.

The correlation with precipitation indicated a positive impact in January, April, and July, aligning with the early growth season, with a significant effect in December. However, the positive effect during April and July was minimal for EW and LW, suggesting that these months generally experience moisture deficit conditions. Root-zone moisture also positively influenced TRW and EW during the early growing season and LW from November to December.

Furthermore, MXD-raw exhibited a positive influence of Tmax in April-May, Jul-Sep, and December, and a positive influence of precipitation primarily in June-July and November-December. The positive correlation between MXD-raw and precipitation in June-July was attributed to significant cooling from high precipitation, resulting in slower growth with denser cell formation. Conversely, temperature played a crucial role in promoting rapid growth, forming less dense and wider cells. The positive relationship during November and December highlighted the importance of moisture for minimal growth at the end of the season. LW and MXD-raw also showed a positive relationship with root-zone moisture, suggesting that high moisture levels create a cooling effect, slowing down growth and leading to denser cells.

Pinus kesiya, an early successional and light-demanding species, exhibits three leaf flushes annually, with fascicle length, area, and weight governed by temperature. Research on five pine species from Duke Forest revealed an increase in mechanical tissue fraction accompanying needle lengthening. Subsequently, needle dry density decreased, and leaf hydraulic conductance increased fourfold across needle lengths for all species. Stomatal conductance and photosynthetic capacity also showed an upward trend, indicating that shorter needles, developed under low temperatures, result in poor physiological functions and lower photosynthetic rates.

The positive influence of temperature on *P. kesiya* at Shillong, Meghalay from the previous November to the current March indicates its association with proper needle development and cambium activation. Further, the positive correlation of precipitation with radial growth (TRW, EW, and LW), especially with LW, highlights the importance of moisture during both early and late growing seasons. The correlation analysis with soil moisture aligns with this, showing a positive response during March to May. Further, a positive influence of maximum temperature on the MXD-raw mainly from March to July may be linked to initial cambium deceleration under low moisture and rising temperatures, which is followed by a slow growth influenced by abundant moisture from precipitation, resulting in the formation of narrow and dense cells. Consistently, MXD-raw exhibits a negative correlation with precipitation and soil moisture at the study site.

In Champhai, Mizoram, the tree ring width (TRW) and earlywood (EW) of *P. kesiya* showed positive correlations with maximum temperature (Tmax) during the early growing season (December to March). This is believed to be linked with role of temperature in activation of cambium and the emergence and development of new needles in *P.* kesiya. However, a negative association with TRW and EW for the mid and late growth season could be attributed to rapid increase in Tmax and Tmin from March onwards, surpassing the optimum range (23.5/17.5℃) suggested for *P. kesiya*.

Further, the precipitation data analysis revealed a positive impact of rainfall on Khasi pine growth during both early and late growing seasons, particularly in November for TRW and December for latewood (LW). This emphasized the crucial role of precipitation in maintaining soil moisture levels, mitigating the adverse effects of high temperatures, particularly at site witnessing maximum temperature of above 30℃ during warmest months. *P. kesiya*, identified as an anisohydric tree species with low intrinsic water use efficiency, relies heavily on moisture for growth. The consistent positive correlation of radial growth with root-zone soil moisture further validated the species' need for higher water amounts, especially in regions with temperatures above suggested optimum range.

MXD-raw correlation with climate data revealed a significant dependence on root-zone soil moisture, indicating its role in sustaining growth. The negative correlation of Tmax with MXD-raw may be attributed to faster growth under adequate rainfall and soil moisture, while the positive association with Tmin during specific months suggests a connection to cell maturation and wall thickening. The night temperatures are reported to be linked with the thickening and lignification of xylem cells, directly influencing changes in MXD.

These findings received additional validation through multiple regression analysis, which assessed the tree ring width (TRW) of each species at their respective sites alongside climatic variables. Further, a parallel outcome was observed in the correlation analysis of carbon accumulation series for each species at their designated sites in relation to climatic variables. The results of this analysis closely mirrored those obtained from the correlation analysis of TRW with climate.

The findings from this study highlighted the potential of dendrochronology in comprehending the impact of climate change on the forest vegetation of the Northeast Indian region. The Northeast Indian region comes under the influence of the southwest monsoon and currently facing the risks of varying levels associated with rising temperatures and shifts in precipitation patterns. In such circumstances, a greater number of multisite tree ring studies can play a pivotal role in unraveling climate variations in this region and their repercussions on the growth of forest vegetation and carbon sequestration.

Conducting such studies can not only enhances our understanding of climate dynamics but also contributes valuable insights for developing effective management plans. These plans are crucial for the sustainable management of forest areas, especially given the evolving climate scenario. By incorporating the knowledge gained from these studies, it becomes possible to formulate more robust strategies that address the challenges posed by climate change, ensuring the long-term health and viability of forest ecosystems.

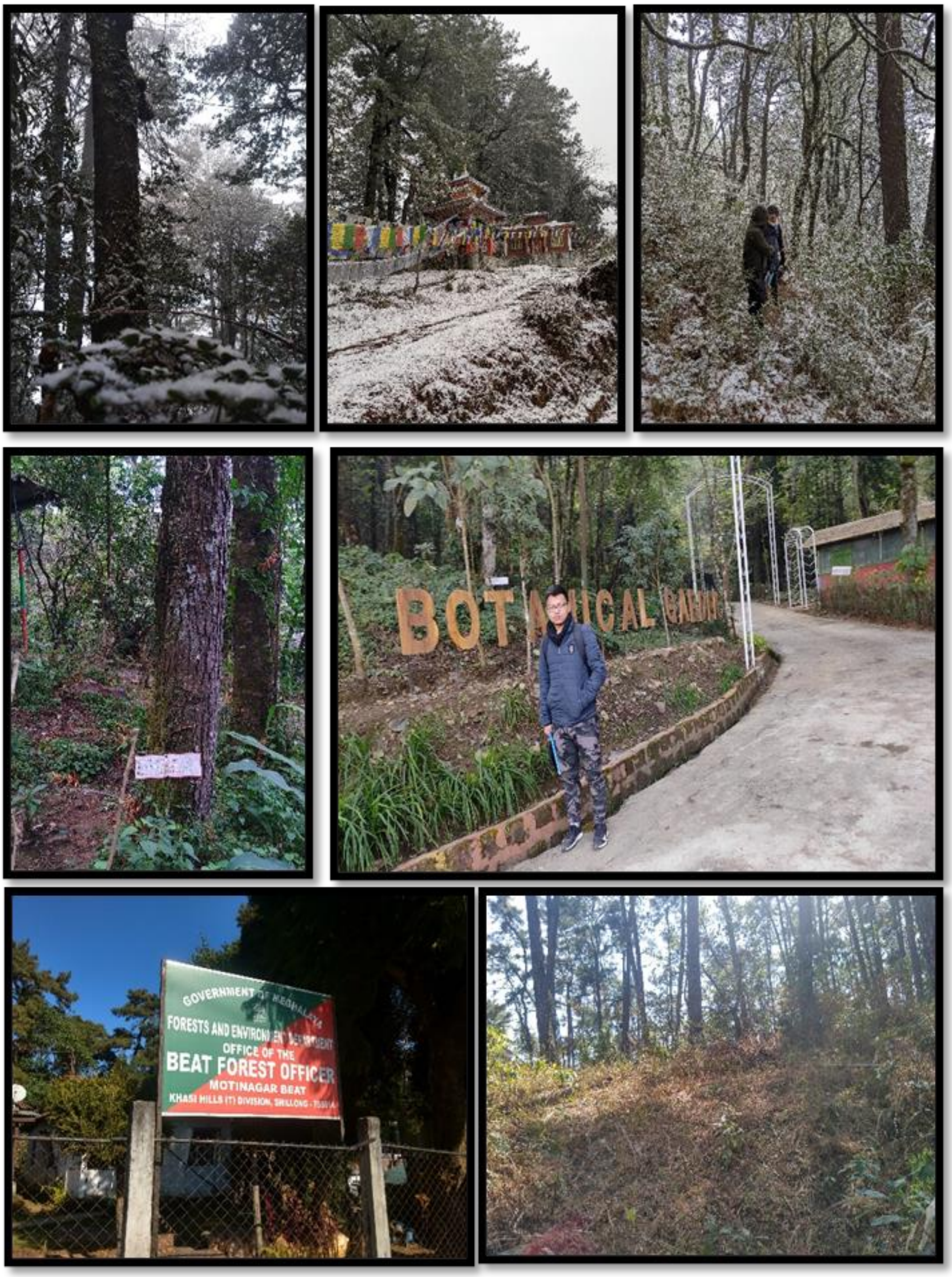


Plate No 1: Site where the sample are collected.

Plate No 2: Instruments use dunging the field work.

Plate No 3: Measure the DBH, taking reading of the GPS and the first step to core the tree.

Plate No 4: Measuring how deep of the borer that are bore into the tree, if it reached to the centre the following step should be taken.

Plate No 5: After it reach to the pit portion by measuring it, the blade of the borer is insert to the borer and then the borer should twist in anti-clock wise direction to break the wood inside the tree which connect between the borer and the trees.

Plate No 6: putting the core inside the straw and seal it with a stapler or Masking tape in which the straw is mention about the number and the side from where it take, and the straw are kept in the map tube. The portion where the tree is bore is filled with a bee wax.

Plate No 7: Sharpening and cleaning the borer.

Plate No 8: Preparation of the sample.

(A) Mounting the core on the mount stick by the glue and then role it by the masking tapr to prevent the core wich may be fall from the mounted stick, and labeling.

Plate No 8: (B) Sanding of the core sample by different girth number.

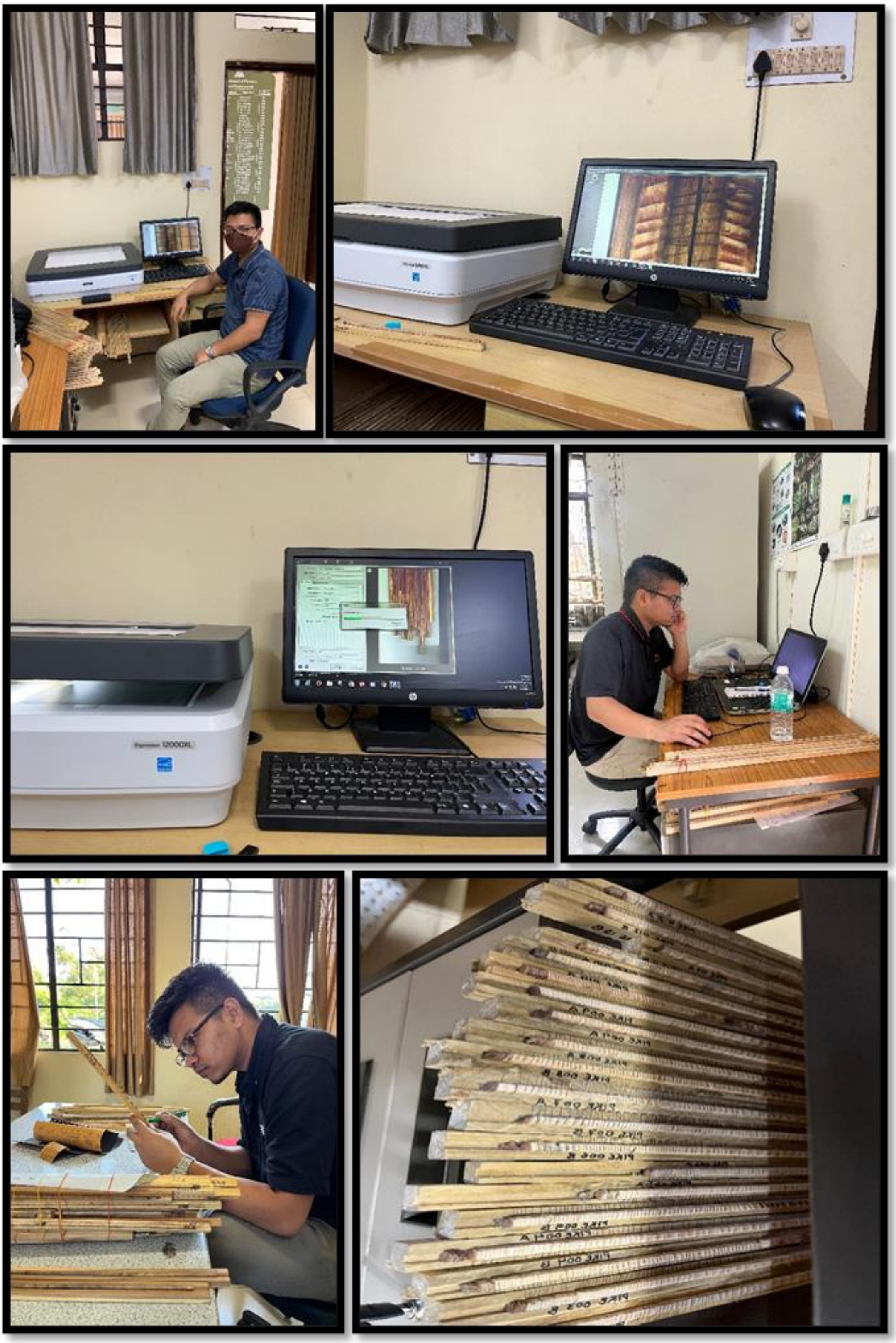


Plate No 9: scanning and analysing of tree core sample.

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Ph.D. Topic: Dendroclimatic Analysis of Forest Tree Growth in Relation to Climatic Drivers in Northeast India.

List of Publication

1. Tree Ring Analysis of Mexican Weeping Oine (Pinus Patula Schiede ex Schltdl. And Cham.) from Nagaland, Northeast India. Environment and Ecology, November 2023, DOI: 10.60151/envec/UOKW9410
2. Detecting the Legacies of Climatic Extremes thought Radial Growth Releases in Pinus Kesiya ex Gordon in Shillong, Meghalaya, Northeast India. Environment and Ecology, December 2023, DOI: 10.60151/envec/XSSD6939

Paper(s) presented on Workshop/Conference/ Seminar

1. Suitable of Cryptomaria Japponica (Thunb. Ex L. f.) D. Don for Dendrochronology Application from Upper Shillong Protected Forest of Meghalaya.
2. Dendroclimatology of Cryptomaria japonica (L.f.) D. Don from Upper Shillong Protected Forest of Meghalaya.

Seminars/Course/Workshop Attended

1. Tree improvement at a glance and wildlife conservation – why and how?
2. Recent advances in science: mankind and change
3. Integrating energy, climate change and development
4. Climate change adaptation for natural resource management for the state of Mizoram

Research Interest:

- Dendrochronology: Dendroclimatology and Dendroecology
- Agroforestry:

- Forest Products: Value addition, marketing and entrepreneurship development

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DEPARTMENT : FORESTRY

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ABSTRACT

DENDROCLIMATIC ANALYSIS OF FOREST TREE GROWTH IN RELATION TO CLIMATIC DRIVERS IN NORTHEAST INDIA

AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT

DENDROCLIMATIC ANALYSIS OF FOREST TREE GROWTH IN RELATION TO CLIMATIC DRIVERS IN NORTHEAST INDIA

BY
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Submitted
In partial fulfillment of the requirement of the Degree of Doctor of Philosophy
in Forestry of Mizoram University, Aizawl

Title: Dendroclimatic Analysis of Forest Tree Growth in Relation to Climatic Drivers in Northeast India

Background

Anthropogenic climate change, particularly the alteration of temperature and precipitation patterns, is significantly impacting the structure and functioning of forest ecosystems. The shifts in temperature and precipitation directly influence the growth and development patterns of forest species, profoundly affecting the vitality of forest ecosystems and their capacity to provide goods and services to society. Therefore, obtaining long-term data on growth trends, species adaptation patterns, physiological responses to stressed conditions, and the frequency and patterns of various disturbance events in relation to climate changes is crucial for formulating mitigation strategies for sustainable forest management amid climate change.

To address this need, analyzing tree rings serves as an archive for these events, providing extensive, long-term data on different time scales. Such data is invaluable for managing forests in the face of a changing climate scenario. Hence, dendrochronological studies utilizing tree ring analysis hold high potential for effective forest management in various regions of the world.

Dendrochronology

Dendrochronology, the science of dating tree rings, emerges as a valuable tool to study historical, prehistoric, and contemporary environmental factors. By analyzing annual growth rings, dendrochronology provides insights into the effects of changing climates on forest trees, carbon sequestration potential, and climate reconstruction models. The method's rising impact in paleo-environmental studies, spanning from yearly to decadal resolutions, makes it particularly relevant for assessing global climate change.

This study focuses on developing a tree ring database in Northeast India, employing parameters such as ring width, latewood density, and early and latewood width to establish tree growth-climate relationships. The research aims to comprehend the impact of climate change on carbon sequestration potential in selected trees of the region. Methodologically, samples are collected from different states, and tree cores are extracted using the increment coring method. Subsequently, samples are processed, and dendrochronological analyses are conducted using various techniques and computer programs to ensure accuracy in dating and measurements.

Objectives

1. To develop tree ring database of key tree species from different states of northeast India

2. To determine tree growth- climate relationship using different parameters of tree ring data, such as ring width, latewood density, and early and latewood width etc.

3. To comprehend the effect of climate change on carbon sequestration potential of selected trees of northeast India.

Methods

Site selection

The study encompassed regions in Northeast India, specifically Nagaland, Meghalaya, Arunachal Pradesh, and Mizoram states. In Meghalaya, samples were gathered from the Riat Laban Reserved Forests under the Motinagar Beat Forest, located in the Shillong East Khasi Hills District. In Arunachal Pradesh, the samples were obtained from Tawang District. In Nagaland, the collection took place at the botanical garden in Kohima, situated in the New Ministers' Hill Ward of Kohima, Kohima District. This garden is maintained by the Nagaland Forest Department. Lastly, in Mizoram, samples were collected from Champhai District.

Sample collection

Sample collection was conducted using the Haglof increment borer by coring the standing trees at breast height. From each tree, two core samples were taken one at a

90° angle and the other at a 270° angle from the slope direction in which the tree was facing. These extracted cores were then carefully transferred to paper straws and labeled with identification codes, including the site name, species, core serial number, and collection date.

Sample processing

The core samples were air-dried and transferred onto wooden mounts using water-based glue. Masking tape was employed to secure the core samples onto the mounting strip. Details from the straw labels, including site name, species, core serial number, and collection date, were transferred to the side of the core mount. Subsequently, the core samples underwent polishing using sandpapers with various grit sizes (80, 100, 120, 240, 300, 400, and 600) to make their ring boundaries visible. For cross-dating, the skeleton plot technique was utilized, and ring width measurements were obtained using the WinDendro Density program. The accuracy of cross-dating and ring width measurements was verified using the COFECHA program.

Chronology development of tree rings

After measuring the tree rings widths, the computer program COFECHA was used to check for any dating error in the measured ring width series. (Holmes, 1983; Grissino Mayer, 2001). The samples displaying dating errors were either corrected or removed.

A programme ARSTAN was used to standardization process of an individual tree ring series to eliminate age dependent growth trends and fluctuations in forest stand, while retaining changes likely related to climate.

Ring density and maximum latewood density measurement

For the measurement of ring density (RD) and maximum latewood density (MXD), the samples were sliced into thin laths of 2 mm and underwent a 48-hour ethanol (≥99.5%) treatment in a Soxhlet apparatus to remove extractives. Subsequently, these samples were thoroughly washed in boiling deionized water, air-dried, sanded, and then scanned. The scanned samples were measured using WinDendro Density 2019 software.

Tree-ring width-climate relationship

To assess the influence of climatic variables [temperature (Tmax and Tmin), precipitation, and root-zone soil moisture (0-100cm)] on tree-ring growth, the relationship between tree-ring width and climate was examined using established statistical methods, i.e., Pearson’s correlation (Fritts 1976).

Within the correlation function, a series of coefficients were computed between the monthly climatic parameters and tree-ring chronology, organized over a timeframe spanning from the previous year's growth season to the current year. These coefficients represent univariate approximations of Pearson’s product moment correlation (Fritts 1976).

Development of statistical growth model

A statistical growth model was developed for all three species using climatic data as predictors and actual growth as predictand. Estimated values were computed by applying predictor data to model coefficients, and the resulting values were compared with those of the predictand.

Estimation of aboveground woody biomass (AWB) and carbon:

Annual tree-ring width (TRW) values, representing radial growth, were employed to reconstruct historical tree diameters and their basal area increment. These, along with mean wood density (WD), were utilized to estimate biomass and, consequently, carbon accumulation. The allometric equation by Návar (2009) was applied for this purpose, previously employed successfully by Pompa-García et al. (2018) for estimating yearly aboveground woody biomass from tree ring widths:

$$AWB=0.0752\times \mathrm{D}^{2.4448}\times 2.0331^{p} \qquad \text{(Návar, 2009).}$$

Relationship of accumulated carbon with climate:

To further validate the climate-growth analysis results of radial growth, the accumulated annual carbon values of each species were correlated with monthly climate data using Pearson's correlation. Here, a series of coefficients were computed between the monthly climatic parameters and accumulated carbon, organized over a timeframe spanning from the previous year's growth season to the current year.

The study further involves the development of statistical growth models and the estimation of aboveground woody biomass and carbon accumulation, providing a comprehensive understanding of the interplay between climate and forest dynamics. The results of this research contribute valuable insights for policymakers and environmentalists striving to mitigate the impacts of climate change in Northeast India.

Result:

The current research extensively scrutinized the wood and tree ring characteristics of three selected tree species—*P. patula, P. kesiya, and P. wallichiana* utilizing high-resolution scanned images from an Epson professional scanner. Each species exhibited well-defined growth rings, with distinct zonation between earlywood and latewood observed in *P. patula and P. kesiya*. In contrast*, P. wallichiana* displayed a less pronounced zonation in older rings, particularly in the sapwood portion. Additionally, *P. wallichiana* exhibited varying earlywood colors, transitioning from brownish yellow to a very dark brown shade in the latewood portion. While *P. patula* and *P. kesiya* displayed a gradual change in wood color from yellowish white in earlywood to dark brown in latewood, there was no clear distinction between sapwood and heartwood. The wood of all three species exhibited a straight grain with a medium texture.

Radial growth chronologies Development:

Transitioning to the core of the study, the development of tree ring width chronologies was a pivotal aspect. Four tree ring width chronologies, including *P. patula* from Nagaland, *P. wallichiana* from Arunachal Pradesh, and *P. kesiya* from Meghalaya and Mizoram, were established. Corresponding partial ring width chronologies for earlywood (EW) and latewood (LW) were also developed for each site.

Cross-dating accuracy:

The accuracy of cross-dating was rigorously assessed using the COFECHA program, including tree ring series with high correlation and excluding poorly dated series with low correlation. The mean inter-correlation among series for each species and site revealed a degree of commonality among the samples, contributing to the overall site chronology. However, challenges were identified, such as lower sample depth in *P. wallichiana* due to resin content in older annual rings, impacting the ability to delineate ring boundaries. Furthermore, the study highlighted the influence of moist climatic conditions in Arunachal Pradesh, Nagaland, and Mizoram on the observed low to moderate values of series mean inter-correlation.

Tree ring chronologies development

Following successful cross-dating, four tree ring width chronologies, along with corresponding partial chronologies for earlywood and latewood, were developed for each site – Nagaland, Arunachal Pradesh, Meghalaya, and Mizoram. These chronologies covered varying temporal expanses, ranging from 39 years for *P. patula* in Nagaland to 121 years for *P. wallichiana* in Arunachal Pradesh. Descriptive statistics for each species and site provided insights into the variability and characteristics of the developed tree ring chronologies.

Tree-ring chronologies developed from Nagaland (*P. patula*), Northeast India:

Chronologies spanning from 1983 to 2021 demonstrated robust mean series inter-correlation values for tree ring width (TRW), earlywood width (EW), and latewood width (LW). Moderate values of mean sensitivity, standard deviation, and autocorrelation indicated the significant role of current climatic factors in the species' growth.

Tree-ring chronologies developed from Arunachal Pradesh (*P. wallichiana*), Northeast India:

Chronologies extending from 1901 to 2021 exhibited a robust mean series inter-correlation for tree ring width (TRW), but a decrease in values for earlywood width (EW) and latewood width (LW). Challenges such as low sample size and high moisture levels at the site were identified as potential factors influencing the chronologies.

Tree-ring chronologies developed from Meghalaya (*P. kesiya*), Northeast India:

Chronologies covering 124 years for tree ring width (TRW) and latewood width (LW), and 118 years for earlywood width (EW), revealed robust mean series inter-correlation values for TRW and EW. A decline in mean series inter-correlation was observed for LW. Moderate to high values of mean sensitivity, standard deviation, and autocorrelation highlighted the substantial influence of current climatic factors on species growth.

Tree-ring chronologies developed from Mizoram (*P. kesiya*), Northeast India:

Chronologies spanning 40 years for tree ring width (TRW) and earlywood width (EW), and 38 years for latewood width (LW), displayed robust mean series inter-correlation values. Moderate values of mean sensitivity, standard deviation, and autocorrelation underscored the significant impact of current climatic factors on species growth.

Ring-width density (RD) and maximum latewood density (MXD):

Ring width density (RD) and maximum latewood density (MXD) investigation of three species, namely *P. patula, P. wallichiana*, and *P. kesiya*, was conducted across four different sites using the WinDendro Density software for estimation. *P. patula* exhibited RD values ranging from 0.345 to 0.474 gm cm-3, with a mean value (¯RD) of 0.383 gm cm-3, aligning with previous studies. MXD for *P. patula* ranged from 0.484 to 0.582 gm cm-3, with a mean value (M̄XD) of 0.517 gm cm-3. RD values of *P. wallichiana* were between 0.250 and 0.360 gm cm-3 (¯RD = 0.305 gm cm-3), consistent with reported values. Similarly, RD of *P. kesiya* ranged from 0.299 to 0.388 gm cm-3 (¯RD = 0.370 gm cm-3) at Shillong, and from 0.231 to 0.424 gm cm-3 (¯RD = 0.329 gm cm-3) at Champhai. MXD for *P. kesiya* at Shillong ranged between 0.405 to 0.534 gm cm-3 (M̄XD = 0.491 gm cm-3) and at Champhai from 0.405 to 0.534 gm cm-3 (M̄XD = 0.491 gm cm-3).

Tree radial growth and climate relationship for *Pinus patula*:

The radial growth-climate analysis of *P. patula* in Nagaland indicated a positive influence of both Tmax and Tmin on Tree Ring Width (TRW), Earlywood Width (EW), and Latewood Width (LW). This impact was particularly notable during the early growth season, corresponding to the initiation of cambium activity in the species. The results emphasized the significant contribution of Tmin, especially for LW, suggesting that minimum temperature prolongs the growth period for the species in the region. Moreover, a consistent positive relationship with precipitation, particularly in July, September, February, and May, underscored the importance of moisture for the growth of species in Nagaland. Root-zone moisture also showed continuous positive correlation with TRW, EW, and LW from March to December. The study highlighted the resilience of species to adverse drought effects, with temperature maintaining cambium activity under normal conditions at sites like the

Kohima Botanical Garden. The research revealed that temperatures act as growth precursors, displaying a predominantly negative relationship with MXD-raw, except for May and June.

Further, a positive response of MXD-raw to precipitation both during the early and late stages of growth suggested a crucial need for water to sustain growth under moisture-limited conditions, ultimately leading to the formation of narrow and dense cells.

Tree radial growth and climate relationship for *Pinus wallichiana*:

For *P. wallichiana*, the climate-growth analysis of tree ring width (TRW), earlywood (EW), and latewood (LW) revealed a positive correlation with maximum temperature. Notably, TRW exhibited a positive association for most months, except June and November, with significant correlations in the previous December and the current August. Similarly, EW displayed a positive link from November to December of the previous year, excluding March and November, with significant relationships in July and August. Conversely, LW exhibited positive correlations in various months, including the previous December, February-May, and August-September. Moreover, TRW showed a positive relationship with minimum temperature from the previous November to the current February, April-May, August, and October-December, with significant responses in the previous December and the current January. This positive association with both maximum and minimum temperatures during early growing seasons underscored temperature's role in activating the cambium for growth, particularly in cold and moisture-dominated areas like Tawang. The correlation with precipitation indicated a positive impact in January, April, and July, aligning with the early growth season, with a significant effect in December. However, the positive effect during April and July was minimal for EW and LW, suggesting that these months generally experience moisture deficit conditions. Root-zone moisture also positively influenced TRW and EW during the early growing season and LW from November to December.

Furthermore, MXD-raw exhibited a positive influence of Tmax in April-May, Jul-Sep, and December, and a positive influence of precipitation primarily in June-July and November-December. The positive correlation between MXD-raw and precipitation in June-July was attributed to significant cooling from high precipitation, resulting in slower growth with denser cell formation. Conversely, temperature played a crucial role in promoting rapid growth, forming less dense and wider cells. The positive relationship during November and December highlighted the importance of moisture for minimal growth at the end of the season. LW and MXD-raw also showed a positive relationship with root-zone moisture, suggesting that high moisture levels create a cooling effect, slowing down growth and leading to denser cells.

Tree radial growth and climate relationship for *Pinus kesiya* from Meghalaya:

Pinus kesiya, an early successional and light-demanding species, exhibits three leaf flushes annually, with fascicle length, area, and weight governed by temperature. Research on five pine species from Duke Forest revealed an increase in mechanical tissue fraction accompanying needle lengthening. Subsequently, needle dry density decreased, and leaf hydraulic conductance increased fourfold across needle lengths for all species. Stomatal conductance and photosynthetic capacity also showed an upward trend, indicating that shorter needles, developed under low temperatures, result in poor physiological functions and lower photosynthetic rates. The positive influence of temperature on *P. kesiya* at Shillong, Meghalaya from the previous November to the current March indicates its association with proper needle development and cambium activation. Further, the positive correlation of precipitation with radial growth (TRW, EW, and LW), especially with LW, highlights the importance of moisture during both early and late growing seasons. The correlation analysis with soil moisture aligns with this, showing a positive response during March to May.

Further, a positive influence of maximum temperature on the MXD-raw mainly from March to July may be linked to initial cambium deceleration under low moisture and rising temperatures, which is followed by slow growth influenced by abundant moisture from precipitation, resulting in the formation of narrow and dense cells. Consistently, MXD-raw exhibits a negative correlation with precipitation and soil moisture at the study site.

Tree radial growth and climate relationship for *Pinus kesiya* from Mizoram:

In Champhai, Mizoram, the tree ring width (TRW) and earlywood (EW) of *P. kesiya* showed positive correlations with maximum temperature (Tmax) during the early growing season (December to March). This is believed to be linked with the role of temperature in activation of cambium and the emergence and development of new needles in *P. kesiya*. However, a negative association with TRW and EW for the mid and late growth season could be attributed to rapid increase in Tmax and Tmin from March onwards, surpassing the optimum range (23.5/17.5°C) suggested for *P. kesiya*. Further, the precipitation data analysis revealed a positive impact of rainfall on Khasi pine growth during both early and late growing seasons, particularly in November for TRW and December for latewood (LW). This emphasized the crucial role of precipitation in maintaining soil moisture levels, mitigating the adverse effects of high temperatures, particularly at the site witnessing maximum temperature of above 30°C during warmest months. *P. kesiya*, identified as an isohydric tree species with low intrinsic water use efficiency, relies heavily on moisture for growth. The consistent positive correlation of radial growth with root-zone soil moisture further validated the species' need for higher water amounts, especially in regions with temperatures above suggested optimum range.

The correlation between MXD-raw and climate data revealed a significant reliance on root-zone soil moisture, indicating its crucial role in sustaining growth. The negative correlation of Tmax with MXD-raw could be attributed to accelerated growth under sufficient rainfall and soil moisture, while the positive association with Tmin during specific months suggests a connection to cell maturation and wall thickening. Night temperatures are reportedly linked to the thickening and lignification of xylem cells, directly influencing changes in MXD.

Relationship of carbon accumulation with climate:

These findings were further validated through multiple regression analysis, which evaluated the tree ring width (TRW) of each species at their respective sites alongside climatic variables. Additionally, a parallel outcome was observed in the correlation analysis of carbon accumulation series for each species at their designated sites in relation to climatic variables. The results of this analysis closely mirrored those obtained from the correlation analysis of TRW with climate.

Conclusion:

The findings from this study underscored the potential of dendrochronology in understanding the impact of climate change on the forest vegetation of the Northeast Indian region. This region, influenced by the southwest monsoon, is currently facing risks associated with rising temperatures and shifts in precipitation patterns. In such circumstances, conducting a greater number of multisite tree ring studies can play a pivotal role in unravelling climate variations in this region and their consequences on the growth of forest vegetation and carbon sequestration.

Conducting such studies not only enhances our understanding of climate dynamics but also contributes valuable insights for developing effective management plans. These plans are crucial for the sustainable management of forest areas, especially given the evolving climate scenario. By incorporating the knowledge gained from these studies, it becomes possible to formulate more robust strategies that address the challenges posed by climate change, ensuring the long-term health and viability of forest ecosystems.