DETERMINING CARBON SEQUESTRATION POTENTIAL OF IMPORTANT TREE SPECIES FROM DIFFERENT ECOLOGICAL REGIONS OF MANIPUR USING DENDROCHRONOLOGY

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CERTIFICATE

This is to certify that the thesis entitled **"Determining carbon sequestration potential of important tree species from different ecological regions of Manipur using Dendrochronology"** is a research work carried out by **Ng. Polbina Monsang, Ph.D. Scholar, Department of Forestry, Mizoram University Reg no. MZU/Ph.D./1179 of 28.08.2018** under my guidance and supervision. She has been duly registered and the thesis presented is worthy of being considered for the award of the Ph.D. degree. The candidate has fulfilled all the requirements laid down in the Ph.D. regulations of the Mizoram University. The thesis is the original work of the scholar, and has not been submitted for any degree to any other university.

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DECLARATION

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DECEMBER, 2023

I, Ng. Polbina Monsang, hereby declare that the subject matter of this thesis entitled "**Determining Carbon Sequestration Potential of Important Tree Species from Different Ecological Regions of Manipur using Dendrochronology**" is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to do 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/Institution.

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

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Place:

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Abbreviations

AC-1	First order Auto-Correlation
AGB	Aboveground Biomass
AIC	Akaike Information Criterion
BAI	Basal Area Increment
BD	Bulk Density
C	Carbon
C.E	Current Era
CF	Correction Factor
CLF	Chandel site Lithocarpus (*Lithocarpus* spp.) Forest
CMPF	Chandel site of Mixed Pine Forest
CO_2	Carbon dioxide
DBH/D	Diameter at Breast Height
e.g.	Example gratia
EPS	Expressed Population Signal
et al.	Et alia, ‘and others’
Etc	Etcetera
FAO	Food and Agriculture Organization
H	Height of a Tree
i.e.	That is
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
ln	Natural Logarithm
MAD	Mean Absolute Deviation
MS	Mean Sensitivity
MSE	Mean Square Error
MSL	Mean Segment Length

N	Nitrogen
NT/NC	Number of Trees/ Number of Tree Cores
P	Phosphorus
RE	Relative error
RMSE	Root Mean Square Error
RSE	Residual Standard Error
SD	Standard Deviation
SIC	Series Inter-Correlation
SMC	Soil Moisture Content
SNR	Signal to Noise Ratio
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SPP	Senapati site Pine Plantation
SQF	Senapati site Quercus (*Quercus* spp.) Forest
SSE	Sum of Square Error
SSS	Sub Sample Strength
TDF	Tengnoupal site Depterocarp (*Dipterocarpus* spp.) Forest
TS	Time Span of the Chronology in years
UNFCCC	United Nations Framework Convention on Climate Change
WD	Wood Density
WHC	Water Holding Capacity

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CHAPTER 1

Introduction

1.1. Dendrochronology

Dendrochronology is the science dealing with the analysis of annual growth patterns of tree rings and to infer valuable information on tree age, patterns of annual growth rates, past abiotic and biotic events. These events are recorded as outbreaks of forest fire and insect pests and environmental/climatic aberrations such as drought, flood, landslides, ice storms etc. (Speer, 2010; Upadhyay and Tripathi, 2019a). In ecological studies, dendrochronology has been widely used for assessing the historical state of environmental and vegetation patterns because of the tendency of tree rings to record past events. Further, it has been employed in various fields of studies viz. archeological studies emphasizing wooden dating from archeological sites, climatologic studies understanding the past climatic variations and geomorphological studies to analyse the geomorphological processes related to flood, landslide, river associated vegetation developments (Shikangalah, 2020). Dendrochronology, a multi-disciplinary science, is extensively applied in diverse studies and broadly divided into various subfields based on nature of studies viz. dendroclimatology, dendroarchaeology, dendroecology, dendrogeomorphology and dendrochemistry (Speer, 2010). Dendrochronology has achieved increasing attention in the field of research with due respect to the efforts and contributions made by Douglass and his students along with European counterparts like Bruno Huber, Walter Liese, Bernd Becker, Dieter Eckstein, and Fritz Schweingruber (Speer, 2010). A. E Douglass is known as the father of dendrochronology (Schweingruber, 1988) and was the first to employ cross-dating (Studhalter, 1956) during late 19th century and ever since it is used by dendrochronologists globally (Speer, 2010). Cross-dating is the basic principle of dendrochronology - a technique that assigns specific calendar year for each tree ring by matching similar ring-width patterns among various trees. Cross-dating method aids to identify the presence of anomalous rings which delivers a matching ring-width series for the whole length of numerous trees, which offers “an absolute time base for all tree-ring sequences” (Norton and Ogden, 1987) and enhance the accuracy of events dating.

1.1.1. Dendrochronology in estimation of tree age

Dendrochronology, also known as tree ring analysis, is a promising tool for obtaining data on tree age, growth rate, and tree age allied yield, which are essential for determining sustainable silvicultural practices (Verheyden et al., 2004; Locosselli et al., 2019). Trees typically form one growth ring per year, which reflects the growth of the same year, including early and latewoods that vary in thickness and density due to the influence of various internal and external factors (Sajad and Ahmed, 2021). Thus, tree ring analysis provides critical information on the stand age, diameter growth rates, and longevity, which is used to develop long-term sustainable forest management plans (Xu et al., 2019; Baral et al., 2022). For instance, knowledge of species lifespan is necessary to comprehend the growth patterns, mortality mechanisms, and natural succession, as reported by Castagneri et al. (2013) for spruce stands of boreal forests. As such, diameter increment and growth patterns for individual trees are primary tools for forest management operations, providing important information in selection of tree species for logging, identifying trees for preservation, estimating cutting cycles, and prescribing silvicultural practises (da Silva et al., 2002). However, not every tree species has growth rings, unlike temperate species many tropical trees often lack the presence of growth rings creating difficulty in assessment of tree age and growth rate for such trees.

Additionally, studies had been conducted on trees lacking annual growth (e.g. Verheyden et al., 2004; Xu et al., 2014) with the help of cambial marking and oxygen isotope. As such, dendrochronological studies are limited to those tree species with growth rings. The age of forest stands holds an important measure for development of tree growth model, effective time for management events and harvesting that together providing invaluable data for sustainable forest management and conservation strategies (Schumacher et al., 2020). The estimation of tree age is a potential approach for determining right time for harvesting trees and regeneration which will benefit ecologists on acquiring forest age structure and time for germination at individual tree species level. The lifespan of tree differs greatly extending 8 years in pioneer species to more than 1000 years in non-pioneer species (Laurence et al., 2004) disclosing huge variation in life history (Brienen, 2005). It has been documented in many studies that the tree growth decline in height, diameter and volume after getting older by following the sigmoidal growth trend (Weiskittel et al., 2011; Köhl et al., 2017). The same is attributed to the change in supply rate of main resources like nutrient, light and water, variation in balancing photosynthesis and respiration, lack of nutrient source, genetic variation with meristem, biomass allocation changes with age, hydraulic restraint, space competition (Sullivan et al., 2016; Köhl et al., 2017). The age of trees can be estimated by dendrochronological method that counts the annual rings taken either from increment cores or stem cross section or other attempts such as measuring diameter recurrently and radiocarbon estimations. However, the later attempts were not successful to provide reliable results for age dating except for dendrochronology revealing the most reliable and accurate method for age dating in presence of tree annual rings (Worbes, 2002).

The cross-dating method, a matching of similar ring-width patterns of wide and narrow rings in dendrochronological approach helped in determination of the accurate tree age dating. Cross-dating of various radii cores of the same or different trees and earlier constructed local chronology can permit the number of years signified in growth rings of cores to be the estimated with utter precise (Ogden, 1981). A tree ring width series may be utilized in recognising signature rings which aid to determined tree age (Ogden, 1981) and growth pattern of aged tree which play a vital role in carbon (C) accumulation (Lanner and Connor, 2001; Johnson and Abrams, 2009; Köhl et al., 2017). As such, dendrochronology method for measuring tree ages depends on the dating sureness which is attained via cross-dating of tree rings (Ogden, 1981). In addition, dendrochronological analysis allows for rapid evaluation of forest productivity at various forest stand age and ecosystems as well as in association with remote sensing may help to acquire information on various growth stages of the vegetation (Gebrekirstos et al., 2014).

1.1.2. Dendrochronology and tree growth

Tree ring studies have been used to generate long-term growth data in order to identify the pattern of tree growth changes as they can potentially produce annual growth data dating back to when a tree was first planted, i.e., retrospective growth measurements (Bowman et al., 2013; Upadhyay and Tripathi, 2019). Ecological factors such as precipitation, temperature, latitude, altitude, and even the species type have a significant impact on the establishment of annual rings in trees (Ols et al., 2018; Sajad and Ahmed, 2021). Tree growth is the proportional development of a tree over time (Bowman et al., 2013), which varies greatly between individuals' trees and is heavily influenced by forest stand and individual traits (Adame et al., 2008; Montoro Girona et al., 2017). Age structure, basal area, and tree mortality are related to the tree growth and mediate the development of a forest stand (Montoro Girona et al., 2017). The growth pattern of a tree changes over time and depends on tree species and site factors. The basal area typically grows slowly at first and then rapidly until the tree approaches senescence. Under natural circumstances, it is difficult to distinguish between the impacts of stem size and age on tree growth because simultaneous increase of both factors (Bowman et al., 2013). Absolute stand growth values expressed as basal area increment (BAI) that would help researchers to better grasp how temperature impacts radial development in trees. BAI is crucial in ecological and physiological research as it explains the changes in biomass accumulation rates along bioclimatic gradients. It is also used to forecast forest yield and determine the best silvicultural practises for forest management (Bowman et al., 2013; Sanchez-Huerta and Pompa-García, 2014). A standard assessment of absolute growth and biomass called BAI has been proposed as an accurate indicator of above-ground forest productivity (Lockwood et al., 2021). BAI is a desirable annual growth measure because it can easily be obtained from tree rings and allows for reconstruction of forest and stand biomass over time (Babst et al., 2018).

The ring width variations along with wood density, element concentration reflects significant record for paleo-climatic studies (Bradley and Jones, 1992; Luckmann, 1996) and reconstruction of historical environmental events (Dean, 1977). The environmental events indicated in a time series of radial growth is the consequence of a complex interaction among environmental inputs and the physiological response of the tree (Carrer and Urbinati, 2004). Forest stand development can be assessed through the analysis of radial growth pattern and structural characteristics of trees (Lorimer 1980; Hart et al. 2012; Kincaid, 2016). Furthermore, radial growth and historical climate reconstructions help in understanding the ecosystems retort to cumulative anthropogenic global warming as growth rate depends on annual ring widths, which changes as a function of both natural and anthropogenic circumstances (Fritts, 1976). The growth of tree is directly associated with biotic or climatic events, and thus, the radial growth records physical injury and impacting on physiological activities. This makes a strong reason that tree-rings of aged trees have been widely used for dating events specific to the factors affecting the tree growth (Norton and Ogden, 1987). Also, evaluation of tree ring widths of the same species over the years can impart invaluable information relating to changes on plant growth over space and time as a result of environmental conditions as well as growth affected by the management practices, besides relative productivity of species and sites can be assessed (Boninsegna et al., 1989). The study of tree rings may help in understanding forest dynamics (Verheyden et al., 2004) due to the fact that trees record past events which may serves as the potential proxy data for evaluating the changes in past environmental conditions and tree growth trends. As a result of this, tree rings studies have gained greater attention as a potential tool for monitoring long-term growth trends (Peters et al., 2015). In addition, data on growth rate, long-term growth dynamics, and climate sensitivity of trees along with the tree growth models will be useful in projecting future climate change and sustainable forest management strategies (Marcelo-Peña et al., 2019) to ensure better ecosystem services. Also, climate growth relationships play key role in biome net primary production assessment at eco-region scale (Rozendaal and Zuidema, 2011). Interpretation of tree growth pattern in relation to release, inhibitions and establishment of trees dates can be used for perusing historical forest stand and carbon (C) sequestration potential (Gebrekirstos et al., 2014).

Studies of annual tree rings can offer a complete time series of diameter growth for past decades in short time period which can possibly give annual information on forest growth and the stand development, and as such dendrochronology technique eliminates the shortcomings in using the permanent sample plot, a method to monitor the forest growth and its dynamics by remeasuring growth after 5 to 10 years interval (Metsaranta and Lieffers, 2009). Tree ring analysis produces tree's lifetime growth rates and are more accurate than those measured data using the permanent sample plot method (Brienen and Zuidema, 2006).) Dendrochronological studies provide annual resolve data which enables the assessment of several ecological developments and growing pattern of stands over the historical years (Biondi, 1999; Metsaranta and Lieffers, 2008). The ability of dendrochronology to provide insight into the growth of individual tree and historical data on tree growth is important. The tree ring analysis for the estimation of tree age and growth is very economical, rapid and reliable method which is useful for forest management **(**Boninsegna et al., 1989**).** Therefore, many dendrochronological studies have been conducted on monitoring the tree growth pattern over the years.

1.2. Allometric models for biomass estimation

Global forests contain an estimated 652 billion tonnes of C in aboveground biomass, litter, and soil with an average C content of 161.8 tonnes per hectare according to the FAO's Global Forest Resource Assessment (FAO, 2010). The forests represent major C sink of terrestrial ecosystems by storing about half of the C in tree biomass in tropics and half in the soil (Mapstone, 2017; Sharma et al., 2020). Compared to below-ground biomass and soil organic matter, above-ground tree biomass is a large source and sink of C sequestration (Gibbs et al., 2007). Biomass quantifies the integrated net growth of a forest over time and is used in order to analyse the regional variations in biomass distribution over a climate and topography gradient, which may reveal how climate change is affecting tree growth (Clark et al., 1998; Houghton et al., 2001). Estimating biomass is essential for computing C stocks and evaluating the productivity of forests. Thereby, providing better C assessment is necessary for achieving the goals of UNFCCC and the Kyoto Protocols for managing

C emissions to mitigate climate change through C reduction emissions (Canadell et al., 2008).

Plant biomass is an integral part of ecological process which considerably affects ecosystem net primary productivity, C and nutrient cycling (Ostadhashemi et al., 2014; Nyamjav et al., 2020). Further, it is important in mitigating global C cycle by accumulating the atmospheric C dioxide (CO_2) for longer period (Brahma et al., 2021). In view of this, different direct and indirect methods have been used for estimation of forest biomass C stock. Direct biomass estimation involves cutting of trees and measuring the dry weight of their components and developing allometric equations (Nath et al., 2019). However, it is difficult because of time consuming, cost effective and ecological implications. Among the indirect biomass estimation methods, the remote sensing and GIS applications and allometric equations are most commonly used (Kim et al., 2018; Han and Park, 2020). Allometric equations are most widely used and appropriate method of biomass estimation as it is efficient, cost effective and non-destructive (McClaran et al., 2013; Han and Park, 2020). The studies had addressed the need of development of species-specific allometric equations due to biomass bias that arise in using inappropriate allometric equations (Chave et al., 2005; Alvarez et al., 2012; Daba and Soromessa, 2019).

For different forests and ecological regions, a number of local and general allometric models based on multi-species, species-specific, or site-specific have been developed. For tropical environments, pan-tropical multi-species allometric models have been developed (Brown et al., 1989; Ketterings et al., 2001; Chave et al., 2005; Segura and Kanninen, 2005; Chave et al., 2014). Because species-specific allometric equations may forecast tree biomass more accurately than other models of various biological zones as reported by number of researchers have developed species-specific allometric models over the world (Viriyabuncha et al., 2002; Ounbun et al., 2016; Bonde et al., 2018; Kebede and Soromessa, 2018). In comparison to regional or local equations, general allometric equations are typically inappropriate because they may result in large errors in biomass calculations (Chave et al., 2005; Heiskanen, 2006). Additionally, these models varied by region and species, which are influenced by a number of factors like as topographic conditions, soil types, tree ages, species composition, and climate variations (Gentry, 1982; Alexandrov, 2007, Brown and Lugo, 1992; Laurance et al., 1999; Slik et al., 2010; Baraloto et al., 2011; Macauley et al., 2009).

It is desirable to employ species-specific allometric models to avoid significant mistakes brought on by species. In India, several species-specific allometric models have been developed. For example, *Populus deltoids* (Das et al., 2011), *Tectona grandis* (Jha, 2015; Chaturvedi and Raghubanshi, 2015), and *Dendrocalamus strictus* (Tripathi and Singh 1996; Kaushal et al., 2016). In Northeast India, species-specific allometric models for *P. kesiya*, *Camellia sinensis*, *Schizostachyum pergracile*, and *Hevea brasiliensis* have been developed by Baishya and Barik (2011), Kalita et al. (2015), Thokchom and Yadava (2017) and Brahma et al. (2017), respectively.

The present study was designed to develop allometric models of *Pinus kesiya*, *Toona ciliata* and *Magnolia champaca* from Manipur, northeast India. As per literature survey, no allometric models for biomass estimation of these species are available in the state of Manipur. Hence, this study is crucial for the estimation of biomass and C sequestration potential of the widely used economically important species of Manipur. The developed equations will be used in the management of forest and future climate change mitigation efforts of the Government.

1.3. Dendrochronology and Carbon dynamics

Tree-ring analysis provides long-term growth data spanning over centuries (Koutavas, 2013) to millennia (Esper et al., 2012), which has been widely used in determining the change in tree growth over time in temperate and boreal forests (Fritts, 2001; Villalba et al., 2012). In recent decades, tree-ring analysis has advanced significantly for its potential to assess the growth trend in the tropical trees (Rozendaal and Zuidema, 2011; Zuidema et al., 2013; van der Sleen et al., 2014; Peters et al., 2015; Köhl et al., 2017). Long-term growth data of individual trees are necessary due to the growing demand for empirical evidence of ecosystem productivity and its relationship with greenhouse gas reduction (Lewis et al., 2009). Radial growth of a tree is an indication of its health which indicates C flow into forest ecosystems. The tree growth rate might fluctuate over the time because of various internal and external factors and it declined with aged (Sullivan et al., 2016). As such, differences in the growth rates of forest trees may have a substantial impact on the global C cycle because these variations alter their net C uptake or loss (Zuidema et al., 2020).

Forests are natural C sink for atmospheric C dioxide (CO_2), which helps in the mitigation of global climate change through accumulation of CO_2 in biomass and the soil. However, due to variations in the structure and functioning of the forests, the rate of sequestration varies widely among the forests (Eguakun and Adesoye, 2015). The extent of forests and the amount of C stored in them have been dramatically reduced during the past few decades as a result of rising rates of deforestation, changing land uses, and increased agriculture expansion to feed the growing population. IPCC (2000) states that the forests can either act as a sink or source of C depending on the particular management approach and activities. Further, tree age affects the C pool of a forest ecosystem. Generally, young and middle-aged trees serve as an active C sink because of faster sequestration rates than older forest stands which can store moderately higher C depending on the type of forest and the species present (Baishya and Barik, 2011). The amount of C accumulation can be enhanced in forest through afforestation and reforestation activities by sustainable forest management programs (FAO, 2010). Forests hold close to 90% of the world's terrestrial biomass C, with tropical and subtropical forests accounting for almost half of this total (Canadell et al., 2008). A third of the world's gross and net primary productivity comes from tropical forests, which also contribute to variations in the land C sink by storing 25% of the C in terrestrial ecosystems (Zuidema et al., 2020). As such, it is important to comprehend the response of tropical forests to climatic variability since they have serious consequences for global C cycling (Schippers et al., 2015). Physiology and potential growth rates of tropical trees are affected by rising atmospheric CO_2, however these effects are probably influenced by the climate and can change over time or along climatic gradients (Körner, 2009; Cernusak et al., 2013; Zuidema et al., 2020). Increased atmospheric CO_2 enhances photosynthetic efficiency while reducing water use which help in stimulation of tree growth thus mitigate negative effects of global warming on the productivity of tropical forests (Huntingford et al., 2013; Zuidema et al., 2020).

The principal method of increasing aboveground C stocks is annual C sequestration in aboveground biomass through net primary production, which may offer crucial information on ecosystem C storage (Megonigal et al., 1997; Rieger et al., 2017). Annual C sequestration rate can be determined either by the tree ring analysis or repeated measurement of tree diameter over time using allometric equations. Historically, growth trends in forests have been determined through recurrent inventories of the forest using permanent sample plots which are important for evaluation of forest C stock. However, tree rings have been recently used in tree growth trends and climate related studies because of its potential to record historical growth and biological and climate events. Further, tree ring analysis or dendrochronology could be used to assess trends in biomass production, improve growth trajectory models, and reduce the high transaction costs associated with maintaining long-term research plots (Gebrekirstos et al., 2014). Thus, tree ring analysis are more efficient than long-term growth sample plots by easily accessing data on forests radial growth, and stock and sequestration rates of C (Fritts, 1976; Chhukan, et al., 2018)**.** Recently, tree rings have been used to analyse C sequestration trends in addition to its previous application to analyse aboveground net primary-productivity trends (Acher et al., 2002; Liu et al., 2012).

At the United Nations Climate Change Conference (COP26) climate crisis summit 2021 held in Glasgow, the UK, India declared its goal to cut its emission intensity by 33-55% between 2005 and 2030, and to further reduce it to zero by 2070. Further, India committed to increase country’s forest cover and tree cover to sequester about 2.5-3.0 billion tonnes of CO_2 equivalent by 2030 (Kaushal et al., 2022). In order to fulfil the commitment, it is necessary to accurately estimate biomass and C stock of the Indian forests, and the potential of different trees species to determine C stock and sequestration rate so that effective mitigation can be brought about by intense management. In a well-managed forest, C stocks are higher than other land use types (i.e. plantations, agroforestry etc.) and serves as a significant sink of C. However, rate of C sequestration within forest varies between species and individual trees as the response of every species to environmental variation vary significantly during time (Van der Putten, 2012). Martínez et al. (2018) suggested to analysis species-specific C to determine the magnitude and spatio-temporal dynamics of C cycle. Dendrochronology, an important method for generating rapid evaluation of forest production over a range of stand ages and forest ecosystems (Schöngart, et al., 2011; Gebrekirstos et al., 2014). Therefore, it serves as marker of tree growth and help in acquiring data on tree growth rate which will directly help in estimating annual biomass and C accumulation of tree using suitable allometric model (Liu et al., 2012). In India, several dendrochronological studies are focusing on historical reconstruction of tree growth rate and climate-growth relationship, however, studies are not available to determine the potential of dendrochronology in measuring C sequestration rates. As such, this study employing dendrochronology for assessing annual C stock and sequestration rate will provide useful insights on developing strategies to increase forest resilience in the face of potential climate change.

1.4. Scope of the study

Adverse effect of climatic variations through global climate change, for example, increasing CO_2 concentration in the atmosphere, nitrogen deposition and erratic rainfall patterns has adversely affected the human health and food security to the society by affecting food production practices, increasing insect out breaks, habitat modifications, frequent natural disaster etc. Increasing C sequestration in trees is among the important processes responsible for decreasing C concentration in the environment. Therefore, such area of research has gained much attention during the recent years. This study emphasises analysing the tree growth patterns using dendrochronology and to develop allometric models for the estimation of biomass. This is one of the important tools to determine C stocks and sequestration rates in trees using a non-destructive method. The use of dendrochronology methods which provides annual growth rate will be helpful in assessing the health and productivity of individual trees and their potential to sequestration C. Further, the developed allometric model will be useful in precise estimation of tree species-specific biomass and C stock which ultimately help in the sustainable forest management. Thereby, the dendrochronology study in relation to growth rate and C sequestration will be useful to provide improved C estimates given that tree rings consider both spatial and temporal resolution to increase the accuracy in accounting forest C.

1.5. Objectives

The present work suggests the following objectives:

1. To determine age and growth patterns of the important tree species using dendrochronology.
2. To develop allometric models relating girth and biomass for the selected tree species for the estimation of above ground biomass and carbon stock.
3. To assess carbon sequestration potential of important trees from different ecological regions of Manipur using dendrochronology.

CHAPTER 2

Review of literature

Dendrochronological studies shed light on how climatic factors affect tree growth in a variety of forest habitats. The detail procedure of tree coring was given by Stokes and Smiley (1968), whereas the principle of cross-dating involving matching of the similar ring widths patterns of the trees was given by Fritts (1976). These studies are frequently and have been utilised for many years to investigate various previous environmental features since its inception during late 19th century. For example, the study on tree ring analysis during the Tunguska event (on 30th June, 1908) indicated that the growing cells were deformed during the end of 1908 due to the massive impact of meteoroid on the tree growth (Vaganov et al., 2004). Martin et al. (2018) and Kim et al. (2020) evidenced the deterioration of forest ecosystem due to concentration of heavy metals in the atmosphere which is also the pathway in trees.

Sáenz-Ceja and Pérez-Salicrup (2019) focused on reconstruction of fire history in coniferous forests. Brandis (1989) worked on sustainable silvicultural systems, which are reported to play an important role in enhancing tree growth and therefore, considered important for dendrochronological studies. It is very likely that trees managed under uniform silvicultural practice show similar sensitivity that was exposed to the environmental stress, and thus, climate and growth relationships were studies by number of researchers (Scott, 1972; Pensa et al., 2005; Ram et al., 2008; Singh et al., 2009; Sinha et al., 2011; Liang et al., 2012; Shah et al., 2014; Pandey et al., 2016; Singh et al., 2016; Jevšenak and Levanič, 2018; Upadhyay, 2019). Several authors (Schongart et al., 2011; Babst et al., 2018; Klesse et al., 2018) had studied the growth, productivity and C sequestration of trees using tree ring width measurement by reconstruction of annual diameter growth of trees.

2.1. Dendrochronological studies in relation to tree growth: A global scenario

Castagneri et al. (2013) reported a negative relationship between growth rate and total age of 91 spruce trees spanning over a period of 400 years with one as an exception showing 529 years old. It was shown that there was a negative correlation between growth rate (basal area increment) and tree age, which was more pronounced for growth rates at 126-275 years and less pronounced for early growth (26-75 years). Therefore, old age of tree was related more to low growth rate than young age. However, many of the advance age does not show decrease in growth rate which indicates that the reduce tree growth was not because of the ageing.

Ahmed et al. (2009) used dendrochronological techniques to investigate age and growth rate of 39 gymnosperms and reported that largest tree is not always the oldest tree. They recorded the highest growth (2.65 year cm^{-1}) in *Cedrus deodara* in south facing slope. Martínez et al. (2018) reported that the tree growth is dependent on age most importantly across varies climatic gradients. *Pinus halepensis* shows the most climate sensitivity and increase in growth rate in all age classes along its geographical area than the other three *Pinus* spp. hence it is reported to be the most suitable species with regards to tree growth and capability to increase C sequestration regardless of climatic changes in Iberian Peninsula.

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. Hlaing et al. (2014) studied the relationship between growth ring of teak and climate changes at different age classes and found that young age was more affected by annual precipitation than old age and vice versa as in case of temperature concerned. Ross et al. (1982) evident most of Appalachian oak stands along the topographic moisture gradient in southwestern Virginia having a prominent gap in their age distribution, which is due to the interaction of several species with the environment and the difference in their spatial and temporal niches. Since environment changes over time and landscape as a result of changing weather, forest stand structures and intervention of human and natural disturbances as well as varying topographic gradient causing alteration in moisture regime, thereby affects the species presence and growth.

Tree ring analysis has been effectively employed in determining growth rates for most tropical tree species that forms a distinct annual growth ring (Battacharya et al., 1992; Worbes et al., 2003; Sousa et al., 2012; Tetemke et al., 2016; Rahman et al., 2017; Locosselli et al., 2017). Annual basal area increments of trees can be estimated using the tree ring analysis. It characterizes a direct indicator of forest ecosystem performance (Babst et al., 2013) as growth rates estimated from tree ring width are closely related to stem productivity and net primary growth, and provides important information for understanding C location in trees (Bouriaud et al., 2005; Martínez et al., 2018). Boninsegna et al. (1989) found variation in the mean climax age of the basal mean annual increment ranging from 61 to 180 years when estimated from individual trees of *Cedrela fissilis*, and this age differences signifies different location of the trees.

Martínez et al. (2018) found a strong correlation between tree age and basal area increment of *Pinus halepensis*, *P. sylvestris*, *P. uncinata*, and *P. nigra* from the Iberian Peninsula, and significantly vary across the climate gradients; this difference in climatic conditions and tree age had strongly influenced the varying basal area increment for these conifers' species. Likewise, analyses of growth patterns of *T. ciliata* showed age-size dependent basal area increment and expressed wide growth variability among tree individuals. However, Worbes et al. (2003) evident a weak relationship between the age and tree diameter which Sarukhan et al. (1984) also indicated that tree diameter is a poor predictor of its age.

Marcelo-Peña et al. (2019) determined the growth rate in four tropical trees (*Anadenanthera colubrina*, *Cedrela kuelapensis*, *Cordia iguaguana*, and *Esenbeckia cornuta*) in Northern Peru, and found that *C. kuelapensis* had the maximum radial growth (4.3 mm year^{-1}), while *E. cornuta* showed lower radial growth (1.86 mm year^{-1}). Their findings also show that populations of *C. iguana* and *E. cornuta* in the zone are primarily made up of young trees that are under heavy anthropogenic pressure because of their timber quality. The study found a significant correlation between diameter and age in *A. colubrina* and *C. iguaguana*.

2.2. Dendrochronological studies in relation to growth: Indian scenario

Tree ring studies have been widely used in India since long back focusing mainly on assessment of growth rates, wood production and quality control, rotation periods (Gamble, 1902). At the end of 1970s, several modern dendroclimatic studies were taken up in India (Yadav, 1991). There are several dendrochronology studies for various broad-leaved and conifers species in India. However, the majority of these research are particularly from the western and eastern Himalayas (Shah et al., 2014; Upadhyay, 2019), and few studies were also reported from the North-eastern region of India (Chaudhary & Bhattacharyya, 2000; Bhattacharyya et al., 2008; Shah and Bhattacharyya, 2012; Shah et al., 2014, Yadava et al., 2015; Singh et al., 2016; Shah & Mehrotra, 2017; Borgaonkar et al., 2018; Shah et al., 2019; Upadhyay et al., 2019 and Thomte et al., 2020).

Singh and Yadav (2000) developed a 410-year-old tree ring chronology of *P. wallichiana* extending from 1590-1999 AD from western Himalaya of the Indian subcontinent and found increase growth rate in the late 20th century which is due to the upsurge in the winter temperature. Also, the lower growth was observed in the previous years to the 1950s reflecting cool temperature which indicates that Gangotri glacier could have been stagnant for a long period with some episodic progress. Nath et al. (2012) studied the growth rings of three tropical trees namely *Acrocarpus fraxinifolius*, *Dalbergia latifolia* and *Syzygium cumini* from the southern Western Ghats of and evident annual growth rings varied in their anatomical characteristics depending on the species, with the fast-growing deciduous tree (*A. fraxinifolius*) showing the most distinguishable growth rings. Due to their variability in their distinct growth rings, direct estimation of age by counting the tree rings were test against the indirect age estimation method. Their results revealed that the two methods give similar age estimation for *D. latifolia* and minimum in *S. cumini* and suggested to employed indirect age estimation method for those tree species with indistinct growth rings. However, in tropical species with reliable and distinct annual growth ring development, the results of direct age estimation by counting rings are consistent with them being annual in nature.

Battacharya et al (1992) analysed the four tropical trees, namely; *Tectona grandis*, *Toona ciliata*, *Magnolia champaca* and *M. nilagirica* in the Indian context and found the varying growth rate among the species ranging from 1 to 4.1 mm year^{-1}. The author revealed a distinct and climate sensitivity growth ring in *T. grandis* and *T. ciliata*, a potential value for dendrochronology studies. However, tree rings of *M. champaca* and *M. nilagirica* were not datable to their year of formation and also lack cross-matching within the tree radii since their wood anatomy is diffuse porous and have no distinct early and late wood zone. In Dadeli and Shimoga of India's Western Ghat region, the mean annual radial growth of teak was 2.15 mm and 3.10 mm, respectively (Deepak et al., 2010).

Shah et al. (2017) developed a 180-years-old tree ring chronology of *T. ciliata* from eastern Himalaya of India and its growth was highly correlated with the winter minimum temperature (October to February), in which a rise in temperature during these months may have increased the activity of photosynthesis. A study in western Himalayan also observed a strong positive relationship in the mean annual winter temperatures (December–February) and tree radial growth of *Cedrus deodara* and *Picea smithiana* which is because of the high intensity of snowmelt in winter and early spring that retains soil moisture for extensive period (Borgaonka et al., 2011). They concluded that increased in tree-ring growth was associated to temperature rise in Himalayan region which also enhance the snow-melting, a source of water supply. Kozlowski (1965) stated that water availability has a greater impact on tree growth than any other environmental aspect. Similarly, precipitation enhanced the cambial activity of *Gmelina arbora* which is responsible for its radial growth (Dave and Rao, 1982).

Yadav (2013) found tree growth of *C. deodara* and *P. gerardiana* grown in Himachal Pradesh of western Himalaya, positively correlated with monthly precipitation while negative correlated with monthly temperature in the boreal spring

(March to May). Comparable site indicated by cold and arid conditions and interspecies chronologies showed that the two species' growth patterns were influenced by the same forces, and revealed that cold and moist conditions were found to favourably respond to tree development. Furthermore, response function analysis, a multivariate method built on Principal Components Analysis and used in determining the relation of tree ring width and climatic variables observed a direct correlation between precipitation and tree growth of *C. deodara* and *P. gerardiana* in the studies of Singh et al. (2009) from the western Himalaya.

Pumijumnong et al. (2020) examined the cambial activity and radial growth of *Tetrameles nudiflora*, *Hopea pierrei*, and *Cleidion spiciflorum* on Chang Island, Thanland using electronic dendrometers. Their study demonstrated that growth, as shown by the quantity of cambial layers, occurred all year round and was significantly higher during the wet season than during the dry season. *T. nudiflora*'s cambium looked to be active throughout the year, peaking in activity at the end of August. Although *H. pierrei* and *C. spiciflorum*'s cambial activity did not significantly correlate with climate, it peaked at the end of June and in July, respectively.

In order to anticipate the possible scenarios of climate change for the Mediterranean region, Vieira et al. (2020) evaluated the timings and kinetics of xylem production in maritime pine trees that were subjected to field experiment. According to their findings, trees treated to rain barring decreased the duration and rates of xylem cell development, which led to a decrease in the amount of wood produced. In addition, times and rates of xylem cell formation varied amongst the given treatments, and were at highest around the spring. Their study concluded that anticipated rise in the frequency and severity of droughts might be damaging to tree productivity and reduce biomass production and C sequestration.

2.3. Allometric models for tree biomass estimation in the world

For different forests and ecological regions, a number of local and general allometric models based on multi-species, species-specific, or site-specific have been developed. For tropical environments, pan-tropical multi-species allometric models have been developed (Brown et al., 1989; Ketterings et al., 2001; Chave et al., 2005; Segura and Kanninen, 2005; Chave et al., 2014). Many researchers across the world have developed species-specific allometric equations because they can predict tree biomass more precisely than other models of different ecological regions (Viriyabuncha et al., 2002; Ounbun et al., 2016; Bonde et al., 2018; Kebede and Soromessa, 2018). General allometric equations are frequently unsuitable in comparison to regional or local equations because they might lead to significant inaccuracies in biomass estimation (Chave et al., 2005; Heiskanen, 2006). And these models differed by location and species, which are affected by a variety of parameters including climate fluctuation, tree age, species composition, altitude, soil types, and topographic condition (Gentry, 1982; Alexandrov, 2007, Brown and Lugo, 1992; Laurance et al., 1999; Slik et al., 2010; Baraloto et al., 2011; Macauley et al., 2009). Several other studies on species-species allometric models have been carried in different parts of the world. Mukuralinda et al. (2021) developed allometric models for the species of *Eucalyptus saligna*, *E. tereticornis*, *Cedrela lusitanica*, *Grevillea robusta* and *C. serrata* from the southern Province of Rwanda; Joshi et al. (2015) developed for *Paulownia tomentosa* from Nepal; Tipu et al. (2021) developed for *Chukrasia tabularis* from Bangladesh.

Jones et al. (2015) developed species-specific model of *Pinus kesiya* and other tree compartments in Philippines 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^2 values of 0.087 to 0.99 yielding more accurate biomass for *P. 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 C sequestration of *P. kesiya*. Quantification of total biomass both at individual species and stand level is necessary for perceptive forest C budget and functioning of ecosystem and sustainable resource management as in thinning and harvesting (He et al., 2018).

A total of 40 species-specific allometric models were developed through destructive manner for *Aphanamixis polystachya*, *Ficus hispida, Mangifera indica, Melia azedarach,* and *Swietenia mahagoni* from Bangladesh (Miah et al., 2020). Among the models, the best model selected based on Residual Standard Error (*RSE*) and Akaike Information Criterion (*AIC*) comprised of combined variables of tree height and diameter at breast height for all the species and the relationship between these variables were significant ($p<0.05$). The best model for each species were expressed: $ln(\text{TAGDB}) = -2.6810 + 2.9055 \ast ln(\text{DBH}) - 0.6983 \ast ln(\text{TH})$ for *Aphanamixis polystachya*; $ln(\text{TAGDB}) = - 5.9291 + 1.2205 \ast ln(\text{DBH}^2 \ast \text{TH})$ for *Ficus hispida* ; $ln(\text{TAGDB}) = -3.5905 + 0.9551 \ast ln(\text{DBH}^2 \ast \text{TH})$ for *Mangifera indica*; $ln(\text{TAGDB}) = -8.2862 + 2.2979 \ast ln(\text{DBH} \ast \text{TH})$ for *Melia azedarach*; and $ln(\text{TAGDB}) = -3.8398 + 2.8593 \ast ln(\text{DBH})$ for *Swietenia mahagoni,* where TAGDB is the total aboveground dry biomass, DBH is the diameter at breast height and TH is the total tree height. This study will provide insights for sustainable forest management and help to estimate accurate biomass and C stock in the homestead forests.

Mandal et al. (2013) build an allometric model for biomass assessment of *Eucalyptus camaldulensis* from Nepal using tree DBH and height as independent parameters. According to the study, the estimated contributions of the bole, branch, and leaves were, respectively, 76.65%, 12.69%, and 10.66% with R^2 values of 0.94, 0.95, 0.97. The model's expression for specific biomass estimation is given as: $ln\text{Y} = 0.3127 * ln(\text{X}) + 2.1332$ for bole biomass; $ln\text{Y} = 0.5915 * ln(\text{X}) - 1.3846$ for branch biomass and $ln\text{Y} = 0.7098 * ln(\text{X}) - 2.1865$ for leaves biomass. All model equations were significant under F-test and T-test. Allometric models was developed for understory tree species specifically *Quercus variabilis*, *Quercus acutissima*, *Quercus mongolica*, *Quercus serrata*, and *Carpinus laxiflora* which are significant for their role in mitigating climate change through their potential for C sequestration and nutrient cycling (Han and Park, 2020). The developed models have high value of coefficients of determination (R^2 = 0.970), and varies accordingly to specific species and tree components viz. foliage (0.824-0.984), branch (0.825-0.952) and stem (0.884-0.999), respectively.

Allometric model in power law function was developed for *Albizia grandibracteata* and *Trichilia dregeana* using the semi-destructive approach (Daba and Soromessa, 2017). The best model was selected based on statistical fit of high adjusted R^2 and low values of residual standard error (*RSE*), Akaike information criterion (*AIC*). In this study, the best model developed evident statistically significant ($p \leq 0.001$) between the total AGB and independent variables (DBH, total height, and wood density) and found higher accuracy in biomass estimation compared to other pan-tropical or generalized allometric equations.;

2.4. Allometric models for tree biomass estimation: Indian scenario

Jaiswal et al. (2013); allometric models gives more accurate biomass and C sequestration of forest ecosystem. Though species and site species models are difficult to acquire yet gives better result than general allometric models. The studied of fifteen dominant trees species in Mensa range, Gujarat reported the highest average AGB, BGB, total biomass, C stock and sequestration capacity are shared in the same level by *Vachelia nilotica*, *V. leucophloea*, *V. tortilis*, *Prosopis cineraria* and *Holoptelea integrifolia*. The general regression models developed for determining C stock were best fit and recommended for its uses in Mensa range.

The regression form of quadratic function gave the highest adjusted R^2 (0.993) and was the best allometric model based on diameter as well as tree height for estimation of *Albizia chinensis* biomass. Power law function was the best for the models based on diameter alone for the species of *Albizia lebbeck* (R^2 = 0.964), *Acacia mollissima* (R^2 = 0.992), *Melia composita* (R^2 = 0.990), *Dalbergia sissoo* (R^2 = 0.992), *T. ciliata* (R^2 = 0.888) and *Ulmus villosa* (R^2 = 0.990). While, models based on tree height as independent variable, the sigmoid function was the best for this six tree species though the adjusted R^2 were lower ranging from 0.480 to 0.645.

They had selected best fit of models was selected on the basis of higher adjusted R^2 and lower standard error following Roshanzada et al. (2018).

Singh et al. (2011) aims to established an allometric equation for smaller diameters (below 10 cm) for the species *Dalbergia sissoo*, *Acacia catechu* and *Albizia lebbeck*, an Indian native plants widely used in plantation since several published allometric models were related to those above 10 cm in diameter (Bargali et al., 1992; Lodhiyal et al., 2002). There is always a need to use a suitable model in order to avoid inaccuracy estimation of biomass and C budgeting. Errors in biomass largely depends on stand age, species, site, environment conditions and also used for unsuitable allometric models in relation of diameter ranges.

Sandeep et al. (2015) developed an allometric model using destructive manner for *Tectona grandis* above 10 cm in diameter grown in the Teak Plantations of Southern Western Ghats, India. Vidyasagaran and Paramathma (2014) developed species-specific allometric model for *Casuarina equisetifolia* using the destructive approached and revealed that logarithmically transformed models in the form of exponential function either diameter alone ($ln\text{W} = \text{b0} + \text{b1}\ ln\text{D}$) and combined of diameter and height ($ln\text{W} = \text{b0} + \text{b1}\ ln\text{D} + \text{b2}\ ln\text{H}$; $ln\text{W} = \text{b0} + \text{b1}\ ln\text{D}^2\text{H}$), showed relatively high coefficient of determination (R^2) and lesser values of Furnival index. However, when comparing of these models, the model with the diameter alone gives the best results for predicting the biomass of *C. equisetifolia*. Prasanna et al. (2017) developed an allometric model for biomass estimation of *Avicennia marina* in the Southeast coast of India.

2.4.1. Allometric models develop for biomass estimation in Northeast (NE), India

Dutta Roy et al. (2022) developed individual tree-level species-specific and generalised local allometric models in a non-destructive approach in Tripura, Northeast (NE) India. The best fit models were selected on the basis of adjusted R^2, F-statistic, Akaike information criterion (AIC), Breusch-Pagan test, Variance Inflation Factor. And found the model, $\text{AGB} = 1.03 \times \exp(-3.95 + 1.09\ ln\text{D}^2 + 0.97$

*ln*H) as the best for estimation of Forest AGB in Tripura, which also observed maximum R^2 value (0.9089) when compared with few of the existing pan-tropical and other reginal models. In addition, the author had produced a model which can be used where only tree diameter values are present and is expressed as: $AGB = 1.07 \times \exp(-2.77 + 2.55\, ln D)$.

Nath et al. (2019) developed a mixed species allometric models through destructive approach for the forest of NE India including forest of sub-tropical broad-leaved, sub-tropical pine, tropical wet evergreen and tropical semi-evergreen forest. They found the model equations such as $AGB_{est} = 0.32(D^2H\delta)^{0.75} \times 1.34$ and $AGB_{est} = 0.18D^{2.16} \times 1.32$ as the 1st and 2nd best fit biomass models in their study. They also evident that their 1st best biomass model overestimating the biomass by 197 kg $tree^{-1}$ which is quite lower than the commonly used general models of Brown (1989), Chambers et al. (2001), Chave et al. (2005) and Chave et al. (2014) that overestimated biomass by 300-591 kg $tree^{-1}$.

Allometric model for biomass estimation of the species, *P. kesiya* was developed by Baishya and Barik (2011) in the state of Meghalaya, NE India. The model form $Log(Y) = a + b \log D + c (\log D)^2 + d (\log D)^3$ was the best fit for estimation of the aboveground biomass as well as other tree components such as needle biomass, twig biomass, etc. The allometric model for estimation of *P. kesiya* aboveground biomass is in the form of $Log (AGB) = 1.3503 - 3.4145 \log D + 4.8678 (\log D)^2 - 1.532 (\log D)^3$ and this model gave higher value of coefficient of determination (R^2) and lower value in the sum of square error (*SSE*), mean square error (*MSE*) and root mean square error (*RMSE*) than those previously developed models for *Pinus* spp. (Brown, 1997; Ter-Mikaelian and Korzukhin, 1997; Delrio et al., 2008). Similarly, Chandra et al. (2021) developed four allometric models for estimating total C-sequestration potential of *P. kesiy*a from Ri-bhoi district, Meghalaya. The models were developed through destructive approached from diameter range of 65-144 cm and tree height range from 10-23 m and are either based on girth at tree breast height alone or combined with tree height, the former showed best for C estimation.

Camellia sinensis, a tea plant has significant effects on the income and food security of a significant population in NE India and has enormous potential to mitigate climate change through its significant C sink. In order to estimate its accurate biomass and caron accounting, allometric model based on destructive manner was developed for biomass estimation in Assam state, NE India (Kalita et al., 2015) and is expressed as $ln(\mathrm{Y}) = - 3.015 +1.878\ ln(\mathrm{D})$ having adjusted R^2 of 0.966. Sahoo et al. (2020) developed an allometric model for biomass estimation of Citrus sinensis from Mizoram state which could be used for stand biomass and C estimation at local and regional level. Orchard age and management systems are the main factors that determined the rate of C sequestration potential for this sweet orange orchard, and total biomass C in this orchard was estimated to be 7.69 Mg C ha^{-1}. Brahma et al. (2017) estimated the best bit models for biomass estimation of rubber trees in Assam. The study predicted the same accuracy of rubber biomass stocks when compared models, i.e., model using compound variables (D, H, and ρ) and the model with power law function based on either D or H.

Bamboo allometric model were developed by Nath et al. (2018) from the species of *Bambusa cacharensis, B. vulgaris and B. balcooa* in Barak Valley, Assam NE India through the destructive method. The development of bamboo biomass model is important since bamboo are fast growing plants and have the potential to sequester C in very short time and the rate of sequestration largely varied with age, species, management, land use types and other climatic factors (Partey et al., 2017; Monsang et al., 2019). Several studies have also claimed that bamboo have a significant potential for C sequestration (Nath et al., 2015; Yuen et al., 2016; 2017). The aboveground biomass of *Bambusa cacharensis*, *B. vulgaris* and *B. balcooa* were estimated as $16.38\ \mathrm{Mg\ ha^{-1}}$, $38.42\ \mathrm{Mg\ ha^{-1}}$ and $19.64\ \mathrm{Mg\ ha^{-1}}$ respectively (Nath et al., 2018). Thokchom and Yadava (2017) developed bamboo allometric model of *Schizostachyum pergracile* from the Manipur state, NE India. The bamboo yielded a total biomass of 143.1 to 202.62 Mg ha^{-1}, C stock of 64.65 to 91.48 Mg ha^{-1} and C sequestration rate of 26.96 Mg ha^{-1}, in which aboveground components accounts for 82% and 18% by belowground components. In additional, bamboo allometric models were also developed for *Schizostachyum dullooa*, *Pseudostachyum polymorphum* and

Melocanna baccifera grown in the Assam state (Singnar et al., 2017). The author found the regression model in the form of power law, logistic and exponential as the best models for *S. dullooa*, *P. polymorphum* and *M. baccifera,* respectively. These bamboos estimated an aboveground biomass C densities of 58 Mg ha^{-1} (*M. baccifera*), 21 Mg ha^{-1} (*P. polymorphum*), and 23 Mg ha^{-1} (*S. dullooa*), respectively. These models can significantly improve the estimation of accuracy biomass and C sequestration in Indian subcontinent forest ecosystems, where the three types of bamboo are widespread.

2.5. Estimation of tree C stock and sequestration through dendrochronology

In recent years, dendrochronology studies are widely used in the tropics and have been reported to have the potential to assess the productivity at various stand ages thus can be employed in different tropical forest ecosystems to give valuable information of the dynamics of forests as C sinks under climate changes globally. Tree-ring analysis is an effective method for determining the impacts of climate change on tree growth as well as canopy tree physiology (Zuidema et al., 2013; 2020). The use of both dendrochronological methods and allometric equations have been reported to provide a better perception of the C flux under varied climate conditions (Babst et al., 2014a, b; Frank et al., 2010). Pompa-Garcia and Venegas-Gonzalez (2016) revealed the role of wood density in reconstructing history of environmental changes and C dynamics during their investigation on wood density and C stock of *Pinus cooperi*. Schongart et al., (2011) estimated C stocks of wetland forest of central South America using tree ring analysis and allometric models and found that AGWB ranged from 7.8 to 97 Mg C ha^{-1} in four sites. Further, the authors estimated C stocks from the models developed for trees of different ages which varies from 0.50 to 3.34 Mg C ha^{-1}.

Köhl et al. (2017) studied the diameter growth-annual C accumulation in 61 trees of *Cedrela odorata*, *Hymenae acourbaril* and *Goupia glabra* which resulted to have positive trends of diameter growth and C accumulation ultimately. Averages of 39% to 50% of C stock were accumulated by *C. odorata* and *G. glabra* during the last quarter of their lifespan. Thus, old trees not only contribute to stoking of C but sustain increase rates of C accumulation at subsequent stages of their lifespan. Eguakun and Adesoye (2015) assessed the potential of C sequester by *Pinus caribaea* and *Tectona grandis* under climatic variations which shows that average C stock are 994.4 kg and 1350 kg. Therefore, choice of species is important for adapting mitigation strategies under climatic variations since different species differs in C stocking rate.

Pompa-Garcia et al. (2018) revealed the potential of species-specific ring data in providing better estimation of C accumulation given that tree ring showed individual tree and annual resolution thus minimising doubt in forest C budgets. They reported that C accumulation was not significant across different sites where representative pines species were growing. However, C accumulation varies with responds to different specific functional features of species, hydroclimate drivers, site conditions. Annual C accumulation was more sensitive to precipitation during cold season and early spring for both *Pinus arizona* and *Pinus cembroids*. Overall, C 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 fertilisation 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 fertilisation. Zuidena et al. (2020) employed the tree-ring analyses to determine how the increase in atmospheric CO_2 has changed the susceptibility of tree stem growth to yearly variations in rainfall and temperature. The study was conducted using the 5, 318 annual rings from 129 trees of *Toona ciliata* to observe the growth responses between 1950 and 2014, a time when atmospheric CO_2 augmented by 28%. Tree ring data of *T. ciliata* were studied from different sites differing in their temperatures, two cool sites having mean annual temperature of 20.5-20.7˚C and two warmer sites having 23.5-24.8˚C as their mean annual temperature. The study evident that increase atmospheric CO_2 reduced drought sensitivity and enhanced temperature sensitivity at cooler sites while drought sensitivity increased at warmer sites resulted in a growth decline. The study on *T.*

ciliata ring-width measurements showed that a recent rise in the global average temperature had a major impact on tree growth and development due to climatic variation.

Sanogo et al. (2016) studied the possibility of dendrochronology in determining growth dynamics with regard to climate change and estimation of C 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 C sequestration and that with change in climate conditions, rate of growth and C sequestration were affected. It calls for researcher's attention to evaluate C sequestration on other tree species using dendrochronological investigation. Ji et al. (2011) found that *Cinnamomum camphora* and *Platanus aceriforia* had C storage of 45 kg cm^{-2} and 104 kg cm^{-2} respectively. The main factor affecting C sequestration was the crown area in case of *C. camphora*, however both crown and age were important factors in *P. aceriforia*.

Rieger et al. (2017) proposed a novel method for simulating C sequestration in aboveground biomass using riparian *Quercus robur* and *Fraxinus excelsior* as a crucial ecosystem function of temperate forests, based on random dendrochronological sampling over time (boosted regression tree analysis; BRT) and across space (classification and regression tree analysis; CART). The C sequestration of *Q. robur* was influenced by temperature and precipitation. Further, *F. excelsior* also responded to a low water level. CART, on the other hand, showed that tree parameters that fluctuate across geography and time govern C sequestration across time.

Liu et al. (2012) built the chronologies of tree ring width and trends and uptake of C stock for birch forest, spruce plantation forest and coniferous-broad-leaved mixed forest in the region of subalpine, Southwest China. The study estimated mean ring width of 1.77 mm in birch forest, 3.07 mm in spruce plantation forest and 2.02 mm in coniferous-broad-leaved forest. The trend of C uptake rates differs in various forest; increasing trend throughout the study period was observed in birch forest while coniferous-broad-leaved mixed forest and spruce plantation forest observed constant or flat trend or constant trend in their later years. However, low C stock was observed in spruce plantation forest in the initial 25 years which in later years increases. Further, the C uptake rates and stock was found to be higher in coniferous-broad-leaved forest compared to birch forest, spruce plantation forest during the chrono-sequence. Thus, this study revealed that coniferous-broad-leaved forest had higher C sequestration potential under the climatic conditions of subalpine region, Southwest China.

Using tree ring research, Chhukan et al. (2018) determined the radial growth and C stock of *Pinus roxburghii* in Bhaktapur's Linga Guthi Community Forest. A 158-year (1854 to 2013 A.D.) ring width chronology was developed with the oldest tree recorded as 158 years old with average age of 98 years. Maximum radial growth was estimated to be 4.47 mm year^{-1}, with the mean radial growth of 2.06 ± 0.13 mm year^{-1}. The forest had mean C stock of 272.22 17.36 t ha^{-1}, of which aboveground, belowground C, soil organic C contributes 206.874.47 t ha^{-1}, 41.372.19 t ha^{-1}and 23.8141.00 t ha^{-1}, respectively. The C sequestration rate was found to be 2.22 C t ha^{-1} year^{-1}.

CHAPTER 3

Materials and methods

3.1. Description of study sites

Manipur is a state located in Northeast India with the geographical area of 22,327 km^2. The state extends between the latitude of 23˚80′ N to 25˚68′ N and longitude of 93˚03′ E to 94˚78′ E and is bounded with Nagaland to the north, Mizoram to the south, Assam to the west and share international boundary with Myanmar that bounded the east by Sagaing region and to the south by chin state of Myanmar. The forest cover about 78.01 % of its total geographical area and has ten forest types according to the classification proposed by Champion and Seth (1968) falling under five forest groups such as Sub-Tropical Broad-leaved Hill, Tropical Semi-Evergreen Forest, Tropical Moist Deciduous, Subtropical Pine and Montane Wet temperate forest. The chief important and major tree species found in the state are *Tectona grandis*, *P. kesiya*, *Quercus* species, *Phoebe* species and *Magnolia* species. The climate of Manipur falls under tropical climate with warm summer and cold winter, having 14.5 ˚C to 38 ˚C range of temperatures and 1200 mm to 2700mm of an average annual rainfall (ISFR, 2019).

The study was carried out at the forests of Japhou in Chandel district; Maram in Senapati district and Saibol in Tengnoupal district of Manipur. The Tengnoupal district is south-eastern region of Manipur, whereas, Chandel and Senapati are in the southern and northern regions of the state, respectively (Figure 3.1). Out of the total Manipur's Forest cover (17,418 km^2), Chandel and Tengnoupal together contributed 2, 863.35 km^2 and Senapati district contributing 2, 136.58 km^2 (IFSR, 2019). Furthermore, the forests are primarily communal and private forests (Niirou et al., 2015; IFSR, 2019).

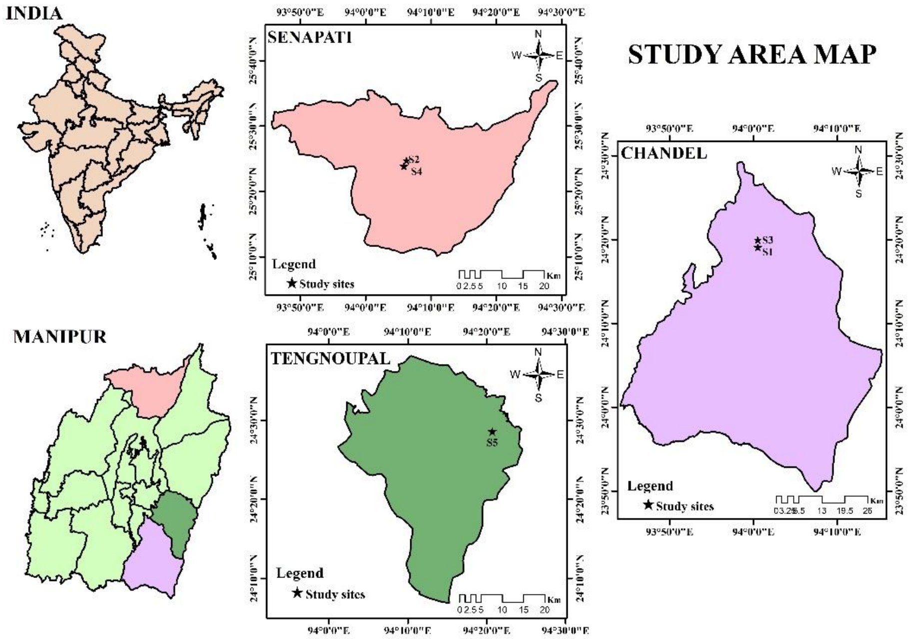


Figure 3.1. Map of the study sites.

The study site of the Chandel is located at 24˚19`05``N, 24˚19`58``N latitude and 94˚00`31``E, 94˚00`30``E Longitude. The dominant species at this site were: *P. kesiya* and *Lithocarpus* species. The other co-dominant species were: *Quercus serreta*, *T. ciliata*, *Rhus semialata*, *Gmelina arborea*, *Mangifera indica*, *M. champaca* at this site. Study area of Maram in Senapati district is located at 25˚23`51``N, 25˚24`43``N latitude and 94˚05`52``E, 94˚06`15``E longitude. Pines were particularly planted in this region about 40 years back and so the species attains almost 40 years of age. Other natural species found dominated in this forest were: *Quercus* spp., *Alnus nepalensis, T. ciliata, Schiima wallichi,* etc. The other study site of Tengnoupal district is situated at 24˚28`31``N latitude and 94˚21`04``E longitude. This forest is dominated by *Dipterocarpus turbinatus* and *D. tuberculatus*. However, at higher altitude where shifting cultivations was carried out, the *Lithocarpus* species were predominant. The study sites from Chandel and Tengnoupal districts are community owned and are under the jurisdiction of Japhou village in Chandel district and Saibol village in Tengnoupal district, respectively, while the other study site situated at Maram in Senapati district is under the private ownership. Present study sites were selected based on climatic variability mainly on the variations in mean temperature. The mean annual temperature variations in these sites were: 2-3 ˚C with a marginal annual precipitation difference of about 40 mm between Chandel and Senapati sites and about 150-200 mm between Tengnoupal and Chandel and Senapati sites. The description of study sites is given in Table 3.1.

Table 3.1. Ecological description of the study sites.

Study sites		**Vegetation**	**Species collected**	**Coordinates**	**Elevation (m a.s.l.)**
S1	Japhou, Chandel district	This site is a mixed pine forest with *P. kesiya* dominating and presence of few tree species such as *Castanopsis hystrix*, *Castanea* spp, *Quercus serrata etc.*	*Pinus kesiya*	24˚19`05``N, 94˚00`31``E	1019
S2	Maram, Senapati district	This site is purely of *Pinus kesiya* plantation which is more than 40 years in approx.	*Pinus kesiya*	25˚23`51``N, 94˚05`52``E	1325
S3	Japhou, Chandel district	*Lithocarpus* spp were dominant at this site and *Quercus serreta*, *Toona ciliata*, *Rhus semialata*, *Gmelina arborea*, *Mangifera indica*, *Machilus villosa* are few species found.	*Toona ciliata, Magnolia champaca*	24˚19`58``N, 94˚00`30``E	960
S4	Maram, Senapati district	This site is dominated by *Quercus* spp. and other species found were *Alnus nepalensis, Toona ciliata, Schiima wallichi etc.*	*Toona ciliata*	25˚24`43``N, 94˚06`15``E	1318
S5	Saibol, Tengnoupal district	This site is dominated by *Dipterocarpus turbinatus* and *D. tuberculatus*. Other species found were *Melanorrhoea usitata*, *Tectona grandis*, *Lithocarpus* spp., *Rhus semialata*, *Magnolia champaca*, etc.	*Toona ciliata, Magnolia champaca*	24˚28`31``N, 94˚21`04``E	536

3.2. Climatic description of the study sites

The climatic data (1981 to 2019) of the study sites used for the study were NASA's MERRA-2 reanalysis model data downloaded from NASA power project that provides global meteorological data sets on daily or monthly basis for various research purposes. Different climatic data of the study sites are shown in the Figure 3.2. The study sites observed a significant difference in annual temperatures. In Chandel site, mean annual temperature is 21.19˚C ± 0.07 with mean annual maximum temperature of 34.94˚C ± 0.21 and mean annual minimum temperature of 5.08˚C ± 0.18. In Senapati site, mean annual temperature is 18.20˚C ± 0.08 with mean annual maximum temperature of 32.39˚C ± 0.19 and mean annual minimum temperature of 1.99˚C ± 0.20. And in Tengnoupal site, mean annual temperature is 23.53˚C ± 0.10 with mean annual maximum temperature of 38.86˚C ± 0.20 and mean annual minimum temperature of 6.13˚C ± 0.20. Total annual precipitation of the study sites does not vary significantly except for Chandel and Tengnoupal sites. The total annual precipitation for Chandel, Senapati and Tengnoupal sites were: 1093.90 mm, 1057.93 mm and 902.30 mm, respectively. The mean annual relative humidity of the Tengnoupal district (63.61 % ± 0.89) vary significantly from the Chandel (70.17 % ± 0.75) and Senapati (71.94 % ± 0.63) sites.

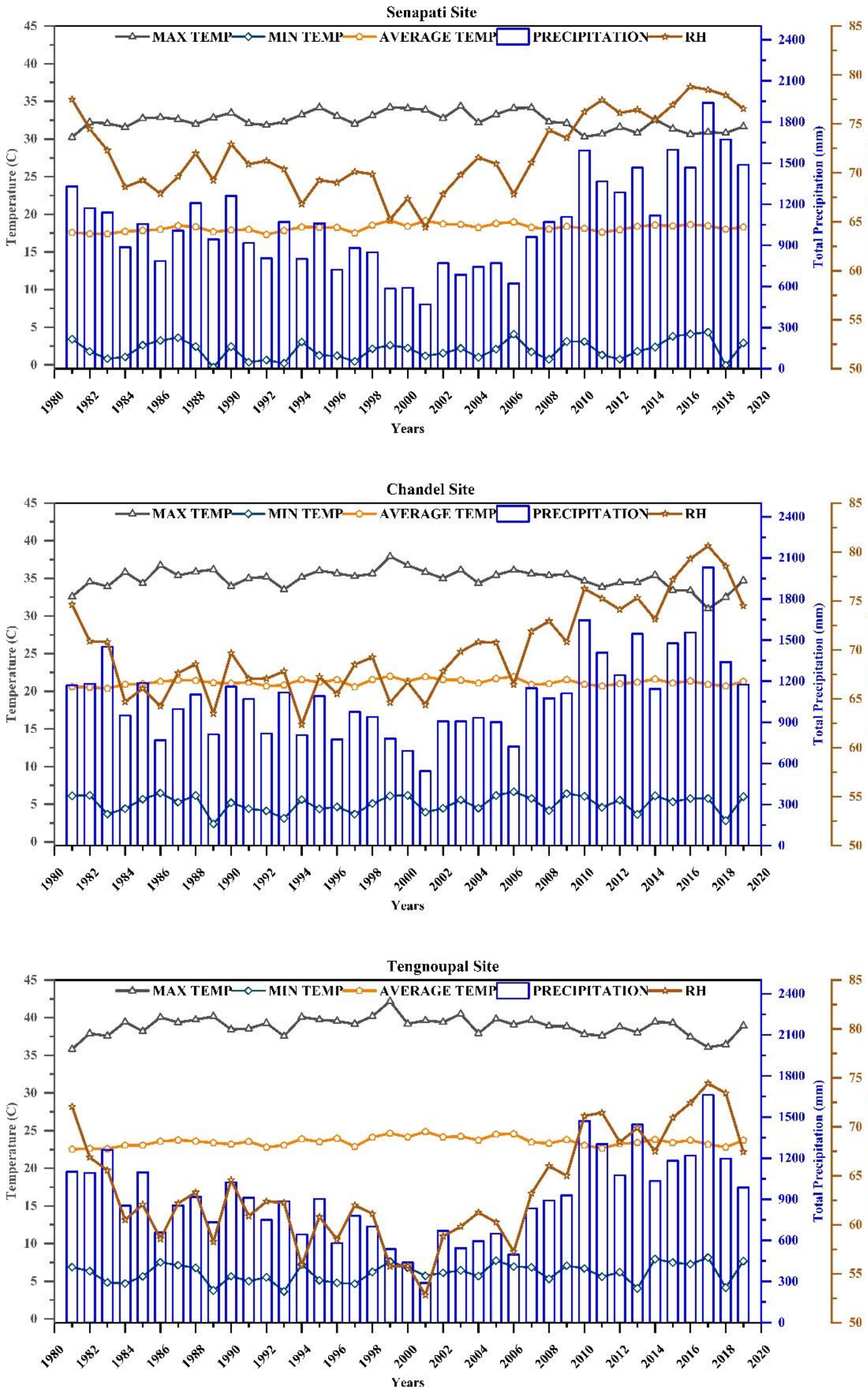


Figure 3.2. Mean annual Climatic variables of Senapati, Chandel and Tengnoupal sites for about 40 years (i.e.1981 to 2019).

3.3. Soil sampling and analysis of the study sites

The soils of the study sites were randomly collected from 3 different locations from three depths (0–10 cm, 10–20 cm, and 20–30 cm) and stored in a well-labelled zip-polybag and brought to the laboratory for physico-chemical analysis. The soil texture was analysed using hydrometer methods following United States Department of Agriculture (USDA) classification (Bouyoucos, 1962). Gravimetric soil moisture content (SMC) was measured as the method prescribed by Verstraeten et al., (2008). The soil pH was measured using a digital pH metre using soil: water ratio of 1: 2.5 (Bandyopadhyay et al., 2012). The maximum water holding capacity (WHC) was determined using Keen Raczkowski box as per Piper (1966). Soil bulk density (BD) was measured using the method proposed by Anderson and Ingram (1993). Soil organic C (SOC) was assessed through Walkley and Black method (1934). Soil organic matter (SOM) was calculated estimated in accordance with the Van Bemmelen factor of 1.724. Available nitrogen (N) was determined following (Subbiah and Asija, 1956), available phosphorus (P) was estimated using the Bray and Kurtz technique (1945), and exchangeable potassium (K) was determined by the flame photometry method (Jackson, 1973).

3.4. Description of tree species

Magnolia champaca L. Baill. ex Pierre, *Toona ciliata* M. Roem and *Pinus kesiya* Royle ex Gordon has distinct growth rings (Bhattacharyya et al., 1992; Chaudhary and Bhattacharyya, 2002). This is one of the critical criterions for tree ring-based studies. All species selected has wide distribution and significance for timber yielding in the state.

Magnolia champaca

Magnolia champaca (L.) Baill. ex Pierre commonly called champak is an important commercial tree belonging to the family Magnoliaceae. *M. champaca* earlier known as *Michelia champaca* (Nehru at al., 2014; Husin et al., 2020) is indigenous to the Southeast Asian countries such as China, Indonesia, India, Malaysia, Myanmar, Nepal, Sri Lanka, Thailand and Vietnam (Al-Sagheer, 2021).

The tree grows naturally at the altitudes of 600-1300 metres in the regions of Himalayan, North-eastern India, South India and South-East Asia (Husin et al., 2020). Meanwhile, *M. champaca* has been introduced as a potential primary tree species in restoration and reforestation programmes throughout the South and South Eastern Asia (Hoque et al., 2004; Raman et al., 2009; Bhatt et al., 2010; Fernando et al., 2013). It is extensively acknowledged for its flower fragrance which are widely beneficial in cosmetic industry (Iyer et al.,2016) and are chiefly cultivated for its high timber value that are used for house construction, furniture, toys and carvings (Mitra et al., 2014). The different parts of the plant impart medicinal value such as antitumor activities, anti-inflammatory, antidiabetic, antioxidant and antimicrobial (Hoffman et al., 1977; Jarald et al., 2008; Kumar et al., 2011). The leaves, roots and stem of this plant contain various chemical moieties viz. parthenolide, michampanolide, 8-acetoxyparthenolide magnograndiolide, costunolide, dihydroparthenolide and micheliolide, β-sitosterol, liriodenine, ushinsunine, magnoflorine (Mitra et al., 2014). Also, the plant offers fodder, fuelwood and antifungal compounds (Orwa et al., 2009; Mitra et al., 2014). *M. champaca* is a large evergreen tree attaining up to 30 m in height (Mitra et al., 2014; Husin et al., 2020) under favourable condition and are used as in urban landscaping and as ornamental tree in temperate regions of coastal California (Mitra et al., 2014). The anatomical wood of *M. champaca* as of diffuse porous with no distinction of early and latewood formation. The consecutive growth ring was delineated by Concentrical parenchyma bands; earlier, a few rows of fibres separated two bands of parenchyma where the initial band is often continuous throughout the stem disc while the last band of the season was left unfinished. (Bhattacharya et al., 1992).

Toona ciliata

Toona ciliata, a large timber species growing 25 to 35 m in height, is a member of the Meliaceae family and habitually found in South China (Feng et al., 2015; Li et al., 2018), as well as sporadically in the highlands of Central and Southern India and in the tropical Himalayas from the Indus eastward, Laos, Myanmar, Pakistan, and in the east coast of Australia (Kumar et al., 2012; Li et al., 2017; Li et al., 2018). In India, it grows widely on sub-Himalayas and is found in

Assam, Khasi Hills of Meghalaya, Manipur, Bihar, Madhya Pradesh, the Western and Eastern Ghats (Shah and Mehrotra, 2017). They grow best in rich, well-draining soil and struggle in poor sandy soil and dense clayey soil (Tomazello et al., 2001). They are ecologically and economically very valuable since every part of it were utilized for benefitting the economic welfare of the community. For instance, barks are used as medicine, tanning leather, leaves as source of important aromatic components, flower as red or yellow dye for silk and its wood as a source of aromatic oils as well as furniture, cabinets, cigar cases and tea boxes (Kumar et al., 2012). Furthermore, the trees are used in various reforestation programme for their capability to reach high growth increment in short time and as ornamental tree in parks (Tomazello et al., 2001; Kumar et al., 2012). The growth rings of *T. ciliata* are very distinct and characteristically defined by large pores and early parenchyma. The rings are either fully or partially ring porous and occasionally produce false tree rings by lines of concentric parenchymatous cells within early wood cells that resembles the initial parenchyma type though the associated vessels does not exhibit significant size changes as in the yearly growth ring in early and preceding late wood (Bhattacharya et al., 1992).

Pinus kesiya

P. kesiya also called khasi pine or benquet pine is a fast-growing evergreen tree belonging to the family Pinaceae. It frequently grows in pure stands with grass understorey, and other associated species were *P. merkusii*, *Quercus* spp., *Castanopsis* spp., *Dipterocarps* and *Ericaceous* genera. Generally, *P. kesiya* is found in lower montane and montane forest in sub-tropical or temperate regions (Pornleesangsuwan, 2012). Under favourable growing conditions, it grows above 30 meters in height and 3 meter in circumference (Upadhyay, 2019). It is well distributed at the elevation range of 762 to 1950 m asl, however thrives fine at 1200 to 1400 m asl in Khai hills (Sahni, 1990) and requires annual rainfall of 200 cm with proper drain soils (Krishnamurthi, 1969; Thomte et al., 2020). Khasi pine is indigenous to Laos, Myanmar, Philippines, Thailand, Vietnam, China, Cambodia, and India (Armitage et al., 1980). In India, it can be found in the Mizo hills of Mizoram, the Khasi hills of Meghalaya, and the Naga highlands of Nagaland and

Manipur (Sahni, 1990; Upadhyay, 2019; Thomte et al., 2020). Khasi pines have straight cylindrical bole and are extremely prized for its lumber and find quality resin, pale brown to red in colour and produce turpentine oil (Chaudhary and Battacharya, 2002). It bears branchlets and a waxy bloom, as well as a thick, reticulate, and deeply fissured reddish grey bark (Gogoi et al., 2014; Missanjo and Matsumura, 2016). Further, it acts as the foremost reforestation species due to its ability to thrive to the site even on relatively poor soil conditions and fire resistant (Racelis et al., 2017). There is a distinct zonation of earlywood and latewood in the annual rings of *P. kesiya* with the colour changing from whitish to dark brown which serves as a potential tree for dendrochronological studies (Upadhyay, 2019).

3.5. Method of sampling tree cores

3.5.1. Collection of tree core samples

Using the Haglof increment corer, cores from healthy trees of *M. champaca*, *T. ciliata* and *P. kesiya* were randomly collected at breast height (1.37 m) from three diameter classes (10-30 cm, 11-50 cm and > 51 cm), with typically two cores per tree. There were 62 cores collected from 31 trees of *P. kesiya* from each Chandel and Senapati sites, respectively. And 50 cores from 25 trees, 54 cores from 27 trees and 40 cores form 20 trees of *T. ciliata* were collected from Chandel, Senapati and Tengnoupal sites, respectively. Further, 44 cores from 22 trees and 40 cores from 20 trees of *M. champaca* were collected for Chandel and Tengnoupal sites, respectively. The cores were immediately placed in the plastic straw pipe after being properly given labelled with indication of sites, species, serial code number and date/year of collection. Every tree's DBH, height, and GPS coordinates were recorded as well. Labelling was done in the format following Upadhyay (2019).

JAP/MACH001A/July, 2019 and JAP/MACH001B/July, 2019

Where, JAP denotes Japhou, MACH as species name viz. *Magnolia champaca*, 001 as number of tree, A and B indicates the radii for individual core samples and July, 2019 as the month and year of sample collection.

3.5.2. Processing of core samples

The sample cores were processed and analysed using a standard dendrochronological method (Speer, 2010). To prevent shrinkage, the tree cores were allowed to air dry for 2-3 days before being mounted on wooden grooved using the water-based glue. While mounting on wooden groove, the cores' cross-sectional area was maintained on the upper side and secured tightly using masking tape to keep it from bending while waiting for the glue to dry. To make the growth ring border readily apparent under a microscope, all core samples were sanded with different sandpaper grades ranging from 100, 120, 200, 320, 400, 600 and 1200. They were then further dated to the calendar year by marking a single dot for each decade.

3.5.3. Tree ring analysis

The polished rings were placed on scanner and their images were recorded. These ring images were analysed using Windendro Software. The width of the rings were measured with accuracy of the nearest 0.001 mm. Using the quality control computer application COFECHA, the errors in the cross-dating were examined for those measured ring width (Holmes, 1983; Grissino-Mayer, 2001). Each raw ring width series was standardised using the computer programme ARSTAN (Cook, 1985), which also preserved the climate and environmental variables while removing the age-growth trend and stand dynamics that appeared as noise in the dendrochronological analysis (Fritts, 1976). During standardisation, raw measurement of each series was first power transformed and then 1st Friedman super smoother and alpha curve were used for detrending with the sensitivity set to the moderate flexibility alpha value of 5 (Friedman, 1984). To get the detrended ring width indices, the ring width values for each year are divided by the matching fitted curve values. The detrended indices of all the series were averaged using a bi-weight robust mean to generate a standard form of tree ring chronology that lessens the impact of outliers (Cook and Kairiukstis, 1990). Through auto-regressive modelling, the existed first order auto-correlation was removed to take into account the growing influence of the previous year on the current year. A decline in sample size has been observed in initial part of the tree-ring chronology. As such subsample signal strength (SSS) criteria (Wigley et al., 1984) with a threshold value of 0.85 was used to ascertain the most reliable period of the chronology. For the common period, Pearson Correlation Analysis was also used to show the degree of relationship between the tree ring series.

3.6. Estimation of tree age and growth pattern

The age of trees was directly estimated from cores by counting number of rings from the inner pith, which was counted as 1 year age from the pith to the bark. Basal area increment (BAI) is typically favoured over ring width for assessing growth patterns because it is a two-dimensional measure that provides a better proxy for the three-dimensional mass increment (Visser 1995 and Castagneri et al., 2013). BAI helps to determine variations in tree and stand growth which aids in accurately quantifying the tree productivity (Tiwari et al., 2020; Baral et al., 2022). Here, the measured ring width data were transformed into tree BAI using the following equation (Biondi, 1999; Baral et al., 2022).

$$BAI_t = \pi R_t^3 - \pi R_{t-1}^2$$

where R is the value of tree radius and t is the year that the tree rings were formed.

The bai out function in the R dplR package was used to convert measurements of ring-width to BAI (Bunn, 2008). Then, we generated mean and unstandardized BAI series for each year using the individual tree BAI.

3.7. Modelling of allometric equations

3.7.1. Data sampling for tree volume

The study relied on non-destructive methods for tree sampling. Furthermore, the study focuses on healthy trees for estimating tree volume and biomass, malformations and disease trees are not taken into account. Healthy trees of *P. kesiya* (46), *T. ciliata* (54) and *M. champaca* (34) were selected at random from different diameter class (10-30 cm, 31- 50 cm and 51< cm). These trees were measured for tree total height using haga altimeter, basal diameter, diameter at breast height

(DBH), diameter at different points of tree heights (diameters at top, middle and base of the tree) using a measuring tape, which were then used to compute volume of the trees. These parameters (diameter at different tree height and tree total height) were used to calculate tree volume using the Newton's formula (Shamika et al., 2011).

$$V = \frac{\pi H}{24}(D_b^2 + D_m^2 + D_t^2)$$

where, V= tree volume in metre cube, H = tree height in metre, D_b, D_m and D_t denotes the diameters at base, middle and top points of the tree stem.

3.7.2. Estimation of wood density and aboveground biomass

The wood cores from sampled trees were extracted using Sweden increment borer and used for analysing the wood density by water displacement method following Chave (2006), in which the cores were oven dried at 100° C until constant weight was reached after measuring their volume. Further, tree biomass was calculated using wood density and tree volume (Thokchom and Yadava, 2013; Giri et al., 2019).

$$\text{Biomass (tonnes)} = \text{Volume (m}^3\text{)} * \text{Specific Gravity (g cm}^{-3}\text{)}$$

3.7.3. Allometric model development

Allometric equations were developed through correlation and regression analysis. Variables of both axes (x and y) were used in the regression analysis after log natural (*ln*) transformation to avoid heteroscedasticity. The regression equations were developed using either DBH alone or in combination with height, and wood density. The most common form of regression equation was expressed as: *ln*(y)=a+b**ln*(x), where, y represents the aboveground biomass of the selected tree species (*P. kesiya*, *T. ciliata* and *M. champaca*) and x represents the tree parameters (i.e. DBH, tree height and wood density) alone or in combinations. Initially, allometric equations were selected based on level of significance of correlation coefficients and later the best fit selection models were based on highest co-efficient of determination (adjusted R^2 closer to 1) and other parameters [i.e. high *F* value, lower value of root mean square error (*RMSE*), sum of square error (*SSE*), mean absolute deviation (*MAD*) and akaike's information criteria (*AIC*)]. The prediction error of the best fitted models was examined using the percentage of relative error (RE%). In addition, the correction factor (CF) was calculated for each best fit models which is necessary for correcting the bias that arises when natural logarithm biomass is back transformed to original units (Mwakalukwa et al., 2014). Therefore, the predicted biomass values will be multiplied by its CF since the variables of the allometric equations were transformed with natural logarithm. The RE (%) and CF was calculated using the formula as given below:

$$\text{RE (\%)} = [(\text{predicted biomass} - \text{observed biomass}) / \text{observed biomass}] * 100$$

$$\text{CF} = \exp(\text{RSE}^2/2)$$

These data analysis was performed using SPSS statistics v16.0 and Sigma plot 12.0 softwares.

3.8. Dendrochronology approach for estimating tree biomass

Allometric equations have been found easiest way to estimate C stocks and C sequestration potential of forest trees using diameter, wood density and height as predictor variables (Chave et al., 2005) by reducing errors with employment of suitable allometric equation (Ketterings et al., 2001; Chave et al., 2004). The allometric equations developed from other parts of the world (Brown et al., 1989, Chave et al., 2014, Ounbun et al., 2016; Bonde et al., 2018) are not appropriate for the estimation C stock and sequestration potential of trees in this region because of changes in soil, topographic and environmental conditions. However, Nath et al. (2019) developed an allometric equation for estimation of biomass for mixed tree species for the North-eastern region, India. As such, to estimate accurate site-specific biomass, we employed the diameter alone allometric model develop for NE, India by Nath et al. (2019).

$$\text{AGB} = 0.18 * D^{2.16} * 1.32$$

Where, AGB=aboveground biomass (Kg); D= diameter at breast height (cm).

In order to estimate D, the annual radial growth value was multiplied by 2, taking into account that stems are perfectly round (Pompa-Garcia et al., 2018). The taper value was calculated by measuring the girth of tree species at different heights

(DBH, middle and top). Diameter of 54 individual trees was recorded for *T. ciliata*, 34 individuals for *M. champaca*, and 46 individuals for *P. kesiya*. The biomass obtained was then multiplied with their taper calculated using the following formula.

$$\frac{\{(D_t/D_b) + (D_m/D_b)\}}{2}$$

Where, D_t , D_m , D_b represents the diameters at different point viz. top, bottom and middle of the tree.

The standardized tree ring widths developed using Arstan programme were used for estimation of biomass and C stock for respective tree species for different study sites.

3.8.1. Determination of C stock and C sequestration

The C concentration was estimated using CHN analyser (LECO Truspec, NEIST, Jorhat Assam) and ashing method as the procedure outlined (Prasad et al., 2010; Choudhary et al., 2014). The value of C concentration was multiplied with the respective biomass value obtained from the radial growth rings in order to get the C stock. The annual C sequestration rate was calculated as the difference of total C content between two consecutive years divided by their corresponding age.

3.8.2. Statistical analysis

Descriptive statistical tools were employed to calculate mean and standard deviation of the datatsets. One-way ANOVA and t- test were performed to compare for significant differences ($p < 0.05$) of biomass, C stock and C sequestration rate for various tree species between the sites.

CHAPTER 4

Results and discussion

4.1. Soil characteristics of the study sites

The value of sand, silt and clay in different study sites ranged from 51.33% - 82.75%, 5.17% - 34.18% and 12.08% - 18.16%, respectively (Figure 4.1). The soils of the study sites were sandy loam to loamy sand in texture. The highest amounts of sand (82.8%), silt (34.2%), and clay (18.2%) were found at Tengnoupal site (S5), Senapati site (S4), and Chandel site (S3), respectively. The Tengnoupal site (S5), Senapati site (S4) and Chandel sites (S3) were dominated by Depterocarp (*Dipterocarpus* spp.) Forest (TDF), Quercus (*Quercus* spp.) Forest (SQF) and Lithoacrapus (*Lithocarpus* spp.) Forest (CLF), respectively. The values of sand (70.90 %), silt (17.90%) and clay (12.01%) content reported by Devi and Yadava (2015) in *Dipterocarpus tuberculatus* forest of Manipur were broadly comparable. Niirou et al (2015) reported different land use types soils as sandy soil in Manipur. Soil BD in different study sites ranged from 0.85 to 1.04 g cm^3 and was found to increase with soil depth (Figure 4.1). The highest value (1.04 g cm^3) was observed in the CLF and SQF while the lowest (0.85 g cm^3) was found in TDF. Less BD in upper soil layer may be attributed to higher presence of organic matter due to increase input of litters. Manpoong and Tripathi (2019) reported low soil BD in the natural forests of Mizoram and cited high accumulation of litters as possible cause for that.

Soil moisture content was highest (37.25%) in TDF and lowest (29.66%) in Chandel site (S1) of Mixed Pine Forest (CMPF). Lesser ground vegetation and open canopy in CMPF may result in lower soil MC. Similar result was reported by Bargali et al. (2018) where an open-bed chir-pine forest had a lower MC. The WHC ranged from 55.5 to 84.9%, with Senapati site (S2) Pine plantation (SPP) and CLF recording the highest and lowest WHC, respectively. High WHC in the SPP may be due to the presence of high soil organic matter and higher content of clay and silt. The study sites had acidic soil with a pH ranged from 4.3 to 5.3. SPP had the highest value of SOM (59.5 Mg ha^{-1}), while CMPF had the lowest value (11.22 Mg ha^{-1}). SOC was significantly higher in the upper soil layer (0-10 cm) compared to the lower soil layers. The high concentration of SOC in the surface soil is due to the presence of higher inputs of litter biomass which accelerates the amount of SOM and SOC in the soil through the process of decomposition (Wapongnungsang et al., 2017; Hauchhum and Tripathi, 2017; Shah et al., 2021). The SOC in different study sites was in order: SPP > SQF > CLF > TDF > CMPF (Table 4.1). SPP had the highest value (30.2 Mg ha^{-1}), whereas CMPF had the lowest value (6.6 Mg ha^{-1}) of SOC. The high concentration of SOC in the SPP is associated with high altitude and low temperature which slow down the decomposition of pine leaf.

In the present study sites, available N ranged from 282.81 to 438.65 kg ha^{-1} to 30 cm soil depth. The range of available N in the present study is broadly comparable to the reports of N availability (219.80 to 878.1 kg ha^{-1}) of different land use types of Manipur (Singh and Athokpham, 2018). Kumar et al. (2017) had reported available N value of 584.6 in natural forest of Mokokchung, Nagaland. High N content (438.65 kg ha^{-1}) was recorded in the middle soil layer (10-20 cm) in CLF. This reflects the movement of available N from the upper soil layer to the lower soil layer due to the process of leaching. The low N value (250.45 kg ha^{-1}) in CMPF of the bottom layer (20-30 cm) corresponds to the low SOC value in CMPF (Table 4.1). High P concentrations were observed at SPP (37.64 to 54.75 kg ha^{-1}) which may have the effect of litter decay and high concentrations of organic matter. The low P was in SQF (12.74 to 15.14 kg ha^{-1}), which is in the reported range (11-30 kg ha^{-1}) for disturbed mixed oak forest in Manipur (Niirou et al., 2015). The highest K values were observed at CLF (187.13 to 236.20 kg ha^{-1}) which may be due to the input of high amount of leaf litter from very deep trees (Table 4.1).

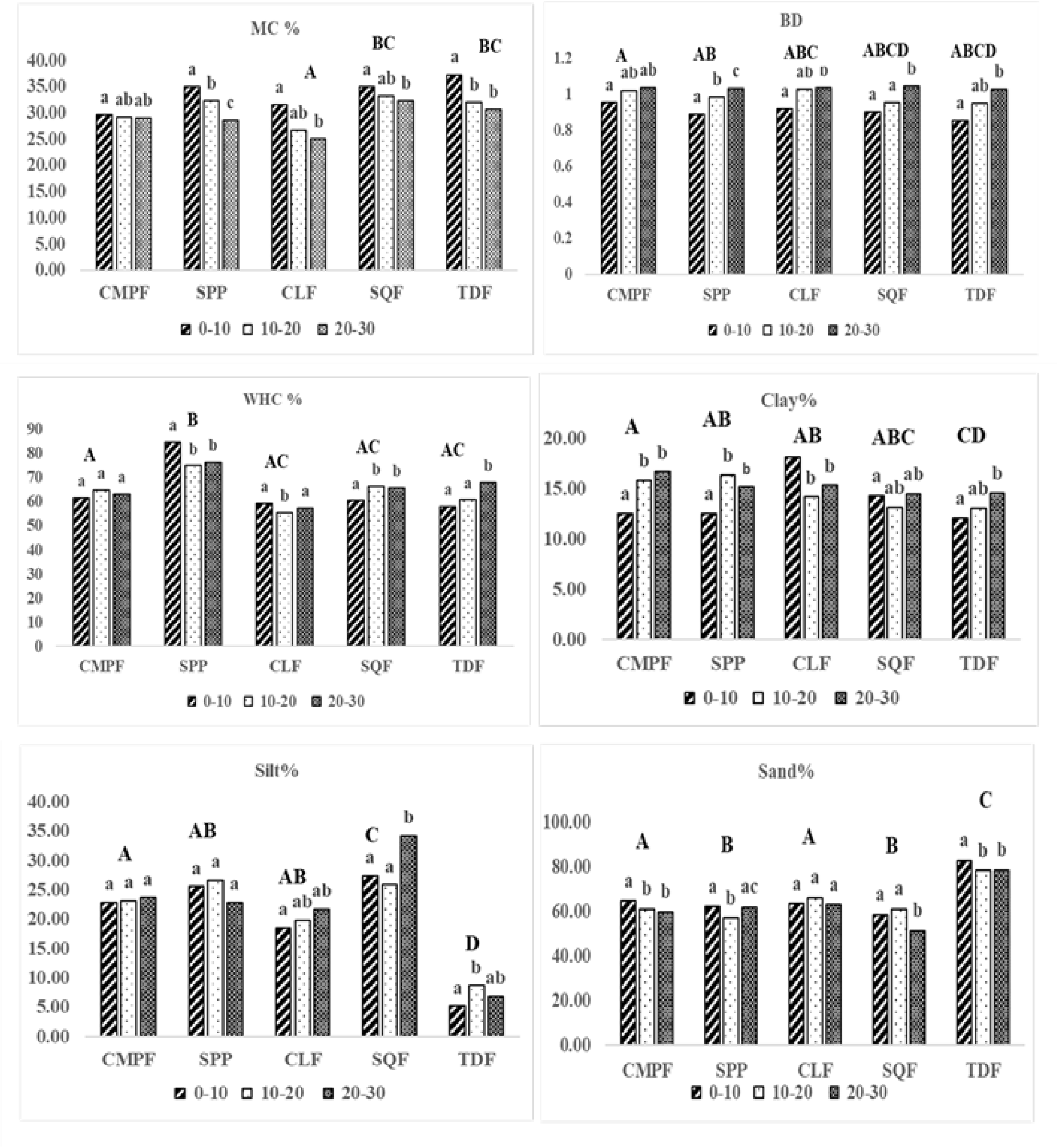


Figure 4.1. Depth wise soil parameters from different study sites. Different capital letter on the graph indicates significant differences (P <0.05) among sites and small superscript show significant differences (P <0.05) within soil depth (n-3, Mean ± 1SE). MC-moisture content, WHC-water holding capacity and BD-bulk density, CMPF=Chandel site of Mixed Pine Forest, SPP=Senapati site with Pine plantation, CLF= Chandel site with *Lithocarpus* spp. dominated forest, SQF= Senapati site with *Quercus* dominated forest, TDF=Tengnoupal site with *Dipterocarpus spp.* dominated forest.

Table 4.1. Depth wise chemical properties of the soil from various forest types.

Soil Parameters	Depth (cm)	Study sites					LSD$_{0.05}$
		CMPF	SPP	CLF	SQF	TDF	
SOM (Mg ha^{-1})	0-10	29.9^{a}	59.5^{a}	36.5^{a}	38.2^{a}	32.3^{a}	9.27
	10-20	11.8^{b}	42.4^{b}	18.2^{b}	33.8^{ab}	19.3^{b}	5.04
	20-30	11.2^{bc}	27.4^{c}	16.8^{bc}	26.7^{b}	16.7^{bc}	9.52
SOC (Mg ha^{-1})	0-10	16.5^{a}	30.6^{a}	19.3^{a}	19.9^{a}	16.2^{a}	4.98
	10-20	7^{b}	24.3^{b}	10.9^{b}	18.7^{a}	10.6^{ab}	3.25
	20-30	6.6^{bc}	16.4^{c}	10.1^{bc}	16.1^{b}	10.1^{bc}	5.50
N (kg ha^{-1})	0-10	282.8^{a}	343.6^{a}	376.3^{a}	360.5^{a}	376.1^{a}	152
	10-20	345.4^{b}	346.0^{ab}	438.7^{b}	406.4^{b}	344.5^{b}	172
	20-30	250.5^{c}	376.7^{c}	314.1^{c}	407.8^{b}	282.4^{c}	255
P (kg ha^{-1})	0-10	49.2^{a}	54.8^{a}	52.1^{a}	15.1^{a}	26.8^{a}	2.2
	10-20	42.4^{b}	47.6^{b}	49.9^{b}	13.0^{ab}	41.0^{b}	1.8
	20-30	29.1^{c}	37.6^{c}	34.9^{c}	12.7^{ab}	16.3^{b}	1.9
K (kg ha^{-1})	0-10	125.8^{a}	109.9^{a}	236.2^{a}	122.3^{a}	120.6^{a}	1.3
	10-20	116.4^{b}	122.7^{b}	195.4^{b}	109.2^{b}	103.9^{b}	1.3
	20-30	113.0^{c}	109.5^{a}	187.1^{c}	115.0^{c}	102.3^{b}	1.8
pH	0-10	4.4^{a}	4.8^{a}	4.3^{a}	5.1^{a}	4.6^{a}	0.54
	10-20	4.4^{ab}	4.8^{ab}	4.5^{ab}	5.1^{a}	4.8^{b}	0.19
	20-30	4.9^{b}	5.3^{b}	4.8^{b}	5.2^{b}	4.9^{b}	0.13

Different small superscript letters indicate significant differences ($P < 0.05$) among the soil depths. (n-3, mean±1SE), CMPF=Chandel site of Mixed Pine Forest, SPP=Senapati site with Pine plantation, CLF= Chandel site with *Lithocarpus* spp. dominated forest, SQF= Senapati site with *Quercus* dominated forest, TDF=Tengnoupal site with *Dipterocarpus* spp. dominated forest.

4.2. Statistics of tree ring chronology

4.2.1. COFECHA analysis

COFECHA analysis measures the accuracy of cross-dating for three-species measured tree ring series (i.e. *P. kesiya*, *T. ciliata* and *M. champaca*) from different sites (Table 4.2, 4.3, and 4.4). The COFECHA result showed high correlation with the master series of each species and/or site, with high series inter–correlation (SIC) that is above conventional threshold limit of 0.321 (Table 4.2, 4.3, and 4.4) (Wigley et al., 1984). For *P. kesiya*, out of 62 cores collected, 59 cores from 31 trees were successfully cross-dated for Chandel site and 57 cores from 31 trees for Senapati site. Similarly, out of 44 cores collected for *M. champaca*, 36 cores from 22 trees and 40 cores from 20 trees were cross dated successfully for Chandel and Tengnoupal sites, respectively. However, all 50 cores from 25 trees, 54 cores from 27 trees and 40 cores form 20 trees of *T. ciliata* were successfully cross-dated from Chandel, Senapati and Tengnoupal sites. The master series and the tree ring series that had a weak correlation were not included in the analysis. This SIC revealed that the individual series of all the species which make up the site chronology share a greater degree of commonality. The value of SIC for *P. kesiya* was 0.350 and 0.367 for Chandel and Senapati sites, respectively. SIC for *T. ciliata* was 0.397, 0.336 and 0.342 for Chandel site, Senapati site and Tengnoupal site, respectively. The SIC value for *M. champaca* was 0.334 and 0.366 for Chandel and Tengnoupal sites, respectively.

Table 4.2. Detail statistics of *P. kesiya* tree ring chronology.

Species	***P. kesiya***	
Sites	**Chandel**	**Senapati**
TS(YRS)	37 (1982-2018)	30 (1989-2018)
SIC	0.350	0.367
MSL	23	24.5
NT/NC	31/59	31/57
MS	0.196	0.152
SD	0.175	0.127
AC-1	0.238	0.090
Common Period Analysis		
TS(YRS)	2003-2018 (16)	2008-2018 (11)
NT/NC	31/57	31/55
Common variance (PC-1)	23.8%	24.3%
SNR	7.979	6.195
Year with SSS >0.85	0.882 (1994)	0.927 (1991)
EPS	0.889	0.861

TS (YRS) = time span of the chronology (years); SIC = series inter-correlation; MSL = mean segment length in years; NT/NC = number of trees/ number of tree cores; MS = mean sensitivity; SD = standard deviation; AC-1 = first order auto-correlation; SSS = sub sample strength as function of the number of trees in sample, SNR = signal to noise ratio, EPS = Expressed population signal.

Table 4.3. Detail statistics of *T. ciliata* tree ring chronology.

Species		***T. ciliata***	
Sites	**Chandel**	**Senapati**	**Tengnoupal**
TS(YRS)	35 (1984-2018)	38 (1981-2018)	36 (1984-2019)
SIC	0.397	0.336	0.342
MSL	22.1	24.4	19.8
NT/NC	25/50	27/54	20/40
MS	0.265	0.253	0.223
SD	0.197	0.175	0.180
AC-1	-0.102	-0.116	0.045
		Common Period Analysis	
TS(YRS)	2004-2018 (15)	2013-2018 (6)	2010-2019 (10)
NT/NC	25/50	27/54	20/40
Common variance (PC-1)	19.4%	31.8%	19.8%
SNR	7.126	9.354	5.099
Year with SSS >0.85	0.888 (1997)	0.856 (1990)	0.856 (2003)
EPS	0.877	0.903	0.836

TS (YRS) = time span of the chronology (years); SIC = series inter-correlation; MSL = mean segment length in years; NT/NC = number of trees/ number of tree cores; MS = mean sensitivity; SD = standard deviation; AC-1 = first order auto-correlation; SSS = sub sample strength as function of the number of trees in sample, SNR = signal to noise ratio, EPS = Expressed population signal.

Table 4.4. Detail statistics of the *M. champaca* tree ring chronology.

Species	***M. champaca***	
Sites	**Chandel**	**Tengnoupal**
TS(YRS)	38 (1981-2018)	46 (1974-2019)
SIC	0.334	0.366
MSL	26.2	22.6
NT/NC	22/36	20/40
MS	0.226	0.326
SD	0.190	0.291
AC-1	0.044	0.050
Common Period Analysis		
TS(YRS)	2003-2018 (16)	2006-2019 (14)
NT/NC	21/33	19/36
Common variance (PC-1)	18.2%	18.3%
SNR	3.961	3.187
Year with SSS >0.85	0.885 (1991)	0.858 (1997)
EPS	0.798	0.761

TS (YRS) = time span of the chronology (years); SIC = series inter-correlation; MSL = mean segment length in years; NT/NC = number of trees/ number of tree cores; MS = mean sensitivity; SD = standard deviation; AC-1 = first order auto-correlation; SSS = sub sample strength as function of the number of trees in sample, SNR = signal to noise ratio, EPS = Expressed population signal.

4.2.2. Arstan

Tree ring chronologies of *P. kesiya*, *T. ciliata* and *M. champaca* from different study sites according to the successfully cross-dated tree-ring series using Arstan program (Figure 4.2, 4.3 and 4.4) indicated 30-46 years chronologies for different species. *P. kesiya* chronologies indicated 37- and 30-years ring-width for Chandel and Senapati study sites extending from (1982-2018 C.E.) and (1989-2018 C.E.) respectively. The ring width chronologies of *T. ciliata* from Chandel, Senapati and Tengnoupal sites were 35, 38 and 36 years extending from (1984-2018 C.E.), (1981-2018 C.E.) and (1984-2019 C.E.), respectively. Likewise, tree ring chronology for *M. champaca* from Chandel and Tengnoupal sites were 38 and 46 years extending from (1981-2018) and (1974-2019) years, respectively. These results showed that the studied trees were young, and therefore, they showed higher variation in their radial growth. These observations were consistent with the observation of Tiwari et al. (2020) 44 years old tree ring chronology of *P. roxburghii* from Nepal with high fluctuation in the ring growth over the years.

The mean sensitivity (MS) indicated relative variations in ring width between two consecutive rings (Fritts, 1976) and the potential of chronology for dendrochronologies studies by measuring the sensitivity of tree growth to the climate conditions (Strackee and Jansma, 1992). The maximum allowable value recommended for mean sensitivity is closer to 0.2 (Speer, 2010). All the seven tree ring chronologies observed a MS value closer to 0.2 except for the *P. kesiya* of Senapati and *M. champaca* of Tengnoupal sites having values of 0.152 and 0.326. Tiwari et al. (2020) observed a MS value of 0.13 in *P. roxburghii* grown in Central Nepal. However, MS of 0.30 and 0.33 had been observed in *Vitellaria paradoxa* from Mali, West Africa (Sanogo et al., 2016). It has been reflected that high values of MS are a reflection of growth-limiting phenomena (Fritts, 1976; Strackee and Jansma, 1992) and that growth is susceptible to alterations in the environment conditions. Further, our results observed a MS value of 0.265, 0.253 and 0.223 in *T. ciliata* for all sites viz. Chandel, Senapati and Tengnoupal. This is very similar to the findings of Shah and Mehrotra (2017) that observed MS value of 0.278 on *T. ciliata* from Eastern Himalaya, India.

The standard deviations recorded in these chronologies were 0.175 and 0.127 for *P. kesiya* from Chandel and Senapati sites (Table 4.2). And 0.197, 0.175 and 0.180 for *T. ciliata* for Chandel, Senapati and Tengnoupal sites, respectively (Table 4.3). Similarly, *M. champaca* observed SD of 0.190 and 0.291 for Chandel and Tengnoupal sites, respectively (Table 4.4). Results of the present study were comparable to the SD values obtained by Upadhyay (2019) and Thomte et al. (2020) on dendroclimatic studies in Mizoram and Manipur states of Northeast India. Upadhyay (2019) observed SD value of 0.174, 0.188 and 0.208 in *P. kesiya*, *T. grandis* and *Q. serrata* respectively. Thomte et al. (2020) observed SD value of 0.207 for *P. kesiya* in Manipur. However, SD values of *T. ciliata* in the present study were lower than the reported value (0.445) of *T. ciliata* from Eastern Himalaya, India (Shah and Mehrotra, 2017). The MS value reflected the variations in ring-width from year to year. The SD reflected both positive and negative departures from the mean and measured both low- and high-frequency variances. The MS and SD values of the present study reflected moderate year to year variation, which was in accordance with earlier studies conducted in *P. keisya* and *T. ciliata* (Shah and Mehrotra, 2017; Shah and Bhattacharyya, 2012; Upadhyay et al., 2019; Thomte et al., 2020). Such variations in ring width are occurring due to the moist climatic condition of the site.

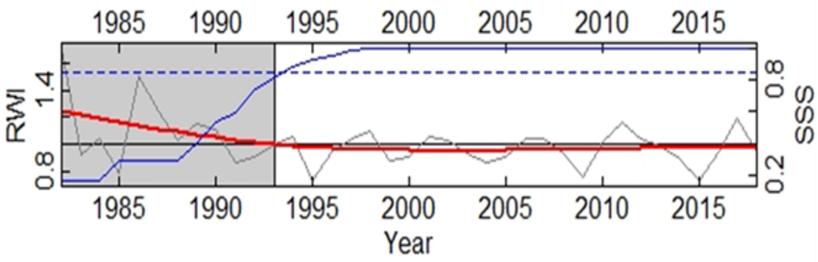
Generally, an ideal tree-ring chronology for dendroclimatological study has a low auto-correlation (AC), high to moderate mean sensitivity and standard deviation. The high values of AC indicate a substantial portion of noticed ring-width is because of the former year’s growth rather than exogenic influences (Upadhyay, 2019). Low AC values signify an effective elimination of the low-frequency persistence observed in raw tree-ring series (Carrer and Urbinati, 2004; Baral et al., 2022). The standard tree ring chronology of *P. kesiya* has a first order auto-correlation (AC-1) of 0.238, 0.090 for Chandel and Senapati sites. However, for *T. ciliata* AC-1 values of -0.102, -0.116 and 0.045 for Chandel, Senapati and Tengnoupal sites, respectively. The AC-1 values of 0.044 and 0.050 for *M. champaca* were for Chandel and Tengnoupal sites. These chronologies revealed no first order auto-correlation of any real significance and indicated that the growth of the present year is influenced by the climate of the previous year.

Various chronology statistics were computed for the common period for all the seven chronologies which observed minimum number of tree-ring series included (Table 4.2, 4.3 and 4.4). High to moderate variance percentage have been observed in all these chronologies in first Principal component, that shows the possibility of common growth variation in the area and demonstrating how frequent climatic conditions affect the growth of these trees.

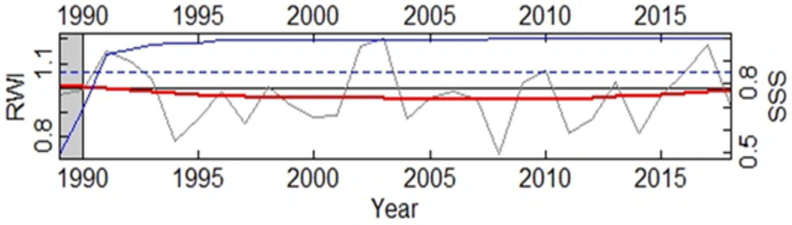
The Expressed Population Signal (EPS) value of studied trees (i.e. *P. kesiya* and *T. ciliata*) were greater than the prescribed standard value (0.85) that signify high degree of coherence between the various time series comprised of final tree ring chronologies (Sanogo et al., 2016). However, *M. champaca* observed lower value of EPS (0.798 and 0761) from both Chandel and Tengnoupal study sites than the prescribed standard value. Similarly, EPS value was observed low for both the standard (0.658) and residual chronology (0.573) of *P. roxburghii* grown in Nepal demonstrating that the population chronology is not well represented by the site chronology (Chhukan et al., 2018). The signal to noise ratio (SNR) examined from of the tree ring chronologies of *P. kesiya*, *T. ciliata* and *M. champaca* from different study sites showed that all chronologies have lower values of SNR than the standard acceptable limit (0.85), except for *T. ciliata* of Senapati study site which may be attributed to the variation in site characteristics (i.e. abiotic variations). Shah and Mehrotra (2017) found low values of SNR and EPS in the chronologies of *T. ciliata* and reported site characteristics as possible cause of temporal disturbance in the chronology. Various anthropogenic and environmental conditions may interfere with the climatic signal stored in young trees of *P. kesiya* that are undergoing vigorous growth which causes lesser value in signal to noise ratio (Thomte et al., 2020).

The most accurate time period of the tree ring chronology is determined using sub-sample signal strength (SSS), which evaluates the amount of signal collected by a subsample of cores from the master chronology. The SSS value for *P. kesiya* is

0.882 and 0.927 for Chandel and Senapati sites (Table 4.2), and 0.888, 0.856 and 0.856 for *T. ciliata* of Chandel, Senapati and Tengnoupal sites, respectively (Table 4.3). However, the SSS values for *M. champaca* for Chandel and Tengnoupal sites were 0.885 and 0.858, respectively (Table 4.4). On the basis of the SSS value surpassing the threshold value of 0.85, *P. kesiya* had an adequate common signal strength and sufficient sample depth from 1995 to 2018 for Chandel site and 1991 to 2018 for Senapati site respectively. However, a common signal strength and sufficient sample depth for *T. ciliata* of Chandel, Senapati and Tengnoupal sites ranged from 1997 to 2018, 1990 to 2018 and 2003 to 2019 years. *M. champaca* of Chandel and Tengnoupal sites had common signal strength and sufficient sample depth that varied from 1991 to 2018 and 1997 to 2019, respectively.

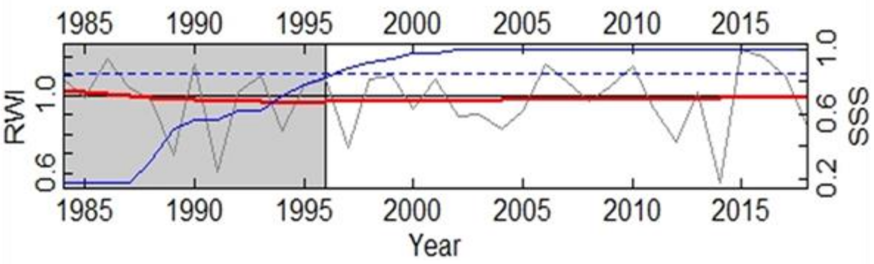


(a) *P. kesiya* (Chandel site)

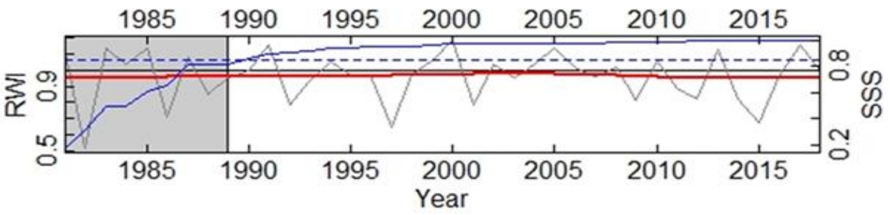


(b) *P. kesiya* (Senapati site)

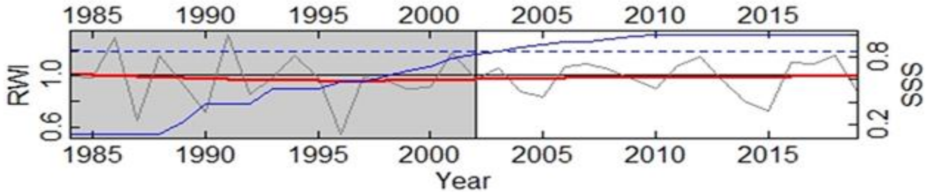
Figure 4.2. Standard tree ring chronologies of *P. kesiya* for Chandel, (a) and Senapati, (b) sites. Red colour curve representing 10 years spline-smoothing curve and blue colour curve representing sub-sample signal (SSS). RWI denotes ring-width index.



(a) ***T. ciliata*** **(Chandel site)**

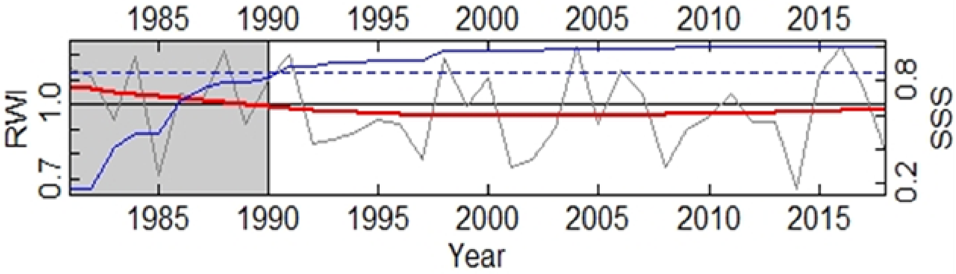


(b) ***T. ciliata*** **(Senapati site)**

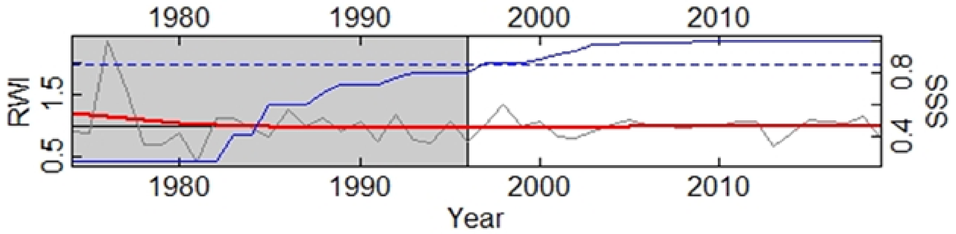


(c) ***T. ciliata*** **(Tengnoupal site)**

Figure 4.3. Standard tree ring chronologies of *T. ciliata* for Chandel (a), Senapati (b) and Tengnoupal (c) sites. Red colour curve representing 10 years spline-smoothing curve and blue colour curve representing sub-sample signal (SSS). RWI denotes ring-width index.



(a) ***M. champaca*** **(Chandel site)**



(b) ***M. champaca*** **(Tengnoupal site)**

Figure 4.4. Standard tree ring chronologies of *M. champaca* for Chandel (a) and Tengnoupal (b) sites. Red colour curve representing 10 years spline-smoothing curve and blue colour curve representing sub-sample signal (SSS). RWI denotes ring-width index.

4.3. Age analysis

The age and DBH of *P. kesiya* from Chandel site ranged from 16 to 37 years and from 23.63 to 46.85 cm, respectively. Corresponding values of age and DBH for the same species were 11 to 30 years and 15.61 to 44.59 cm from Senapati site. Similarly, for *T. ciliata*, age and DBH ranged from 13 to 35 years and 15.92 to 55.16 cm, 6 to 38 years and 15.61 to 67.20 cm, and 10 to 36 years and 11.91 cm to 62.52 cm for Chandel, Senapati and Tengnoupal sites respectively. For *M. champaca* the same values varied from 10 to 38 years and 16.62 to 53.03 cm, and 11 to 46 years and 14.55 to 65.61 cm from Chandel and Tengnoupal sites, respectively. The maximum age was observed as 46 years in *M. champaca* from Tengnoupal site followed by 38 years in both *T. ciliata* and *M. champaca* from Senapati and Chandel sites, respectively (Table 4.5). The minimum age was recoded as 6 years in *T. ciliata* from Senapati site. Tree age analysis indicates that the trees were still in juvenile phase of their growth. Forests in Northeast India are usually under the control of local community rather than Forest Department, in which Nagaland accounts for 91% of forests under the community control, followed by Meghalaya (90%), Manipur (68%), Arunachal Pradesh (62%), Assam and Mizoram each holds for 33% (Mahongnao et al., 2017). During the course of forest management activities, selected felling of mature (old) trees is permissible for local inhabitants/communities for timber, poles, firewood and practice of shifting cultivation. Therefore, community owned forests tree are generally younger in age. Rapid land use changes are putting pressure on about 30% of the total forest cover in North-East India. Prevalent practice of shifting cultivation is continuing to meet the demand for agricultural land which causes major deforestation in the regions due to rising population pressure (Lele and Joshi, 2009). A negative change in forest cover of Northeast India particularly in Arunachal Pradesh, Manipur, and Assam suggests that the degradation of the forest may be caused by forest fragmentation, forest fires, grazing, exploitation of the forest for lumber, shortening the fallow cycle under jhum, and unscientific methods of managing the forest (Mahongnao et al., 2017). Devi and Shimrah (2022) also suggested that the main drivers of Land Use and Land Cover, deforestation and forest fragmentation in the state Manipur are mostly because of human activities. Devi and Yadava (2015) found *Dipterocarpus tuberculatus* dominated forests of Manipur signifying a young secondary forest which are maintained by local inhabitants through sparse felling and burning of trees. Similarly, younger age of tree ring chronologies was observed in various trees reported from North-eastern forests of India. Thomte et al. (2020) observed 39 years tree-rings chronologies (1980-2018 C.E.) of *P. kesiya,* obtained from Sielmat, Manipur (Thomte et al., 2020). Upadhyay (2019) developed a 40 years tree ring chronologies of *P. keisya* (1978 to 2017 C. E.), 31 years chronologies of *Tectona grandis* (1987-2017 C. E.) and 47 years chronologies of *Quercus serrata* (1971 to 2017 C. E.) from different forest divisions of Mizoram.

Table 4.5. Minimum (min) and maximum (max) tree age and diameter of the studied trees.

Species	***P. kesiya***		***T. ciliata***			***M. champaca***	
Study sites	Chandel site	Senapati site	Chandel site	Senapati site	Tengnoupal site	Chandel site	Tengnoupal site
Min age (years)	16	11	13	6	10	10	11
Max age (years)	37	30	35	38	36	38	46
Mean	**25.3**	**26.1**	**22.56**	**26.85**	**20.8**	**28.45**	**24.2**
Min DBH (cm)	23.63	15.61	15.92	15.61	11.91	16.62	14.55
Max DBH (cm)	46.85	44.59	55.16	67.20	62.52	53.03	65.61
Mean	**38.61**	**33.4**	**37.31**	**37.41**	**29.88**	**33.33**	**34.15**

The relation between the age and DBH for each selected tree species were analysed (Figure 4.5, 4.6 and 4.7). The study observed that diameter is significantly related with age except in *P. kesiya* and *T. ciliata* of Chandel site and *M. champaca* of Tengnoupal site. Ahmed et al. (2009) reported significant relation between age and DBH of *P. roxburghii*, whereas, authors did not observe significant relationship between age and DBH of *P. wallichiana*, *Abies pindraw*, *Picea smithiana* and *Cedrus deodara*. Similarly, Castagneri et al. (2013) also obtained positive correlation between DBH and age of spruce trees in Norway but the relationship was weak with R^2 of 0.18. Schöngart et al. (2011) also reported significant correlation between tree age and DBH of *Vochysia divergens* with $R^2 = 0.94$. Ahmed and Sarangzai (1991) also found significant correlation between DBH and tree age in most studied tree species with wide variations and concluded that diameter is usually not a better indication of age in natural forest.

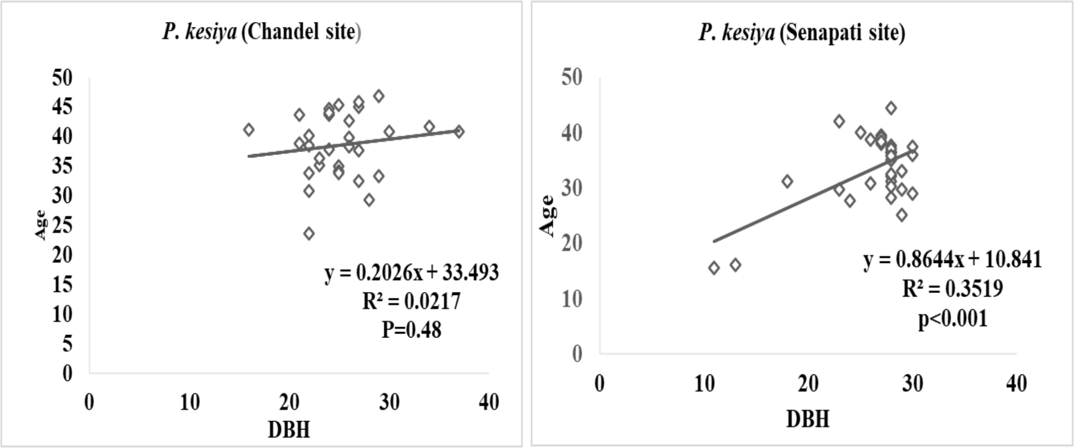


Figure 4.5. Relationship between age and diamter at breast height (DBH) of *P. kesiya* for different study site.

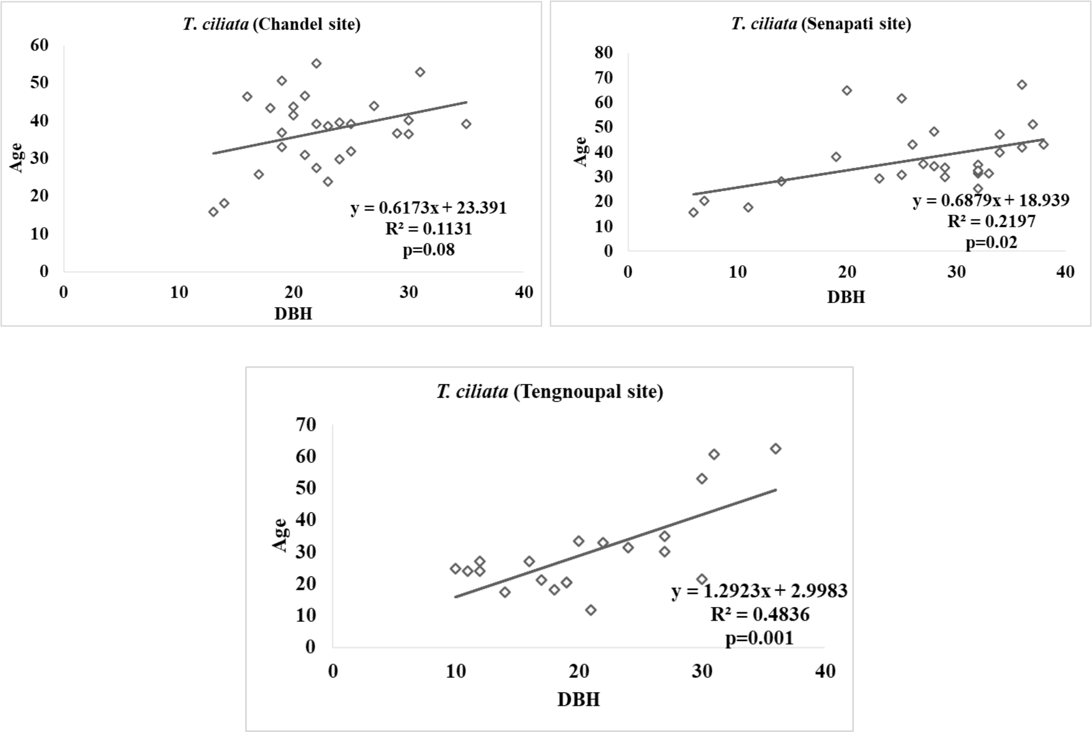


Figure 4.6. Relationship between age and diamter at breast height (DBH) of *T. ciliata* for different study site.

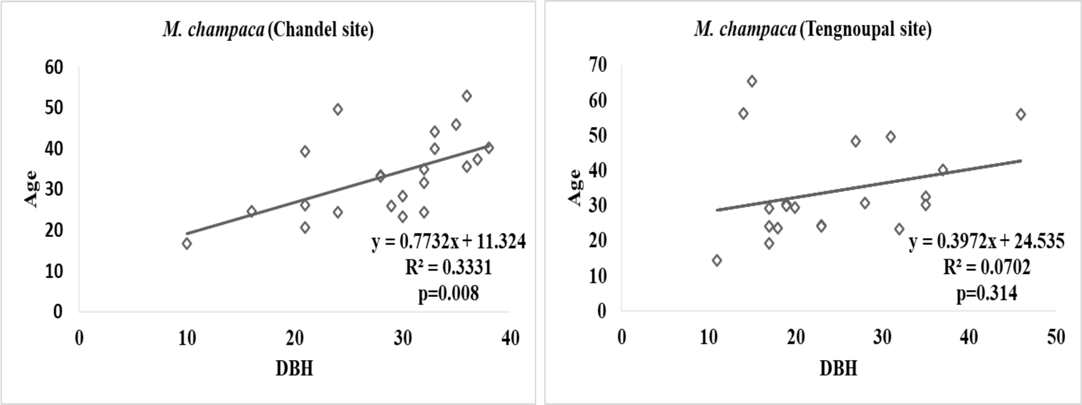


Figure 4.7. Relationship between age and diamter at breast height (DBH) of *M. champaca* for different study site.

4.4 Basal area Increment (BAI) Analysis

The radial growth rate and BAI trend of trees were quantified with biological relevance (Yan et al., 2021). It has been successfully proved that BAI can estimate growth trends without detrending, which is generally done to create a RWI chronology (Qi et al., 2015). In BAI analysis, growth of the studied species i.e. *P. kesiya* (Figure 4.8), *T. ciliata* (Figure 4.9) and *M. champaca* (Figure 4.10) showed an increasing trend in their growth over the time except *T. ciliata* at Tengnoupal site. The BAI trend of all the species showed a consistent growth increment in their common period with slight fluctuations.

The BAI of *P. kesiya* were highest in Chandel site as compared to Senapati site. *P. kesiya* of Chandel site observed an increasing BAI trend with highest (8195.1 mm^2) in the year 2017 and lowest (445.8 mm^2) in 1987. However, Senapati site showed an increasing BAI trend in the initial stage till 2005 and later stabilized from 2006 onwards and are in the range of 1467.7 to 4319.9 mm^2 with the highest BAI (4319.9 mm^2) recorded in 2003. The BAI of *T. ciliata* from Senapati site showed an increasing trend with growth fluctuations and the highest BAI (5350.0 mm^2) was observed in the year 2017. In Tengnoupal site, the BAI trend showed maximum growth in the initial years with highest (7863.6 mm^2) recorded in 1986 which was started to decrease later till 2005. Afterward, the growth started to incline gradually from 2006 onwards. In case of Chandel site, the BAI trend showed highest growth

(9228.4 mm^2 in 1986) during initial stage, which later showed a sharp decrease for short time period, and thereafter regain their growth consistently during their common period i.e., 2004-2018 (Figure 4.9). Similarly, *M. champaca* at Tengnoupal site showed initial year (1976) increase in growth (4265.7 mm^2) which gradually decreased in BAI trend till the year 2005. Later on, in the common period (2006 to 2019), the BAI trend tended to incline progressively with the highest growth (6407.2 mm^2) observed in the year 2018 (Figure 4.10). This increasing BAI growth trend in this study showed that the trees in the present sites were in juvenile states of their growth. Since the young trees usually show increasing growth rate which reach a plateau formation during maturity with a subsequent fall with age (Castagneri et al., 2013). Generally, growth trend of the BAI followed a sigmoidal curve (Tiwari et al., 2020; Baral et al., 2022). In healthy forest stands, BAI growth trend remains to increase or stabilize (LeBlanc et al., 1992; Duchesne et al., 2003), however, trees experiencing senesce or substantial growth stress showed a decreasing trend (Duchesne et al., 2003; Jump et al., 2006). Therefore, present growth trend indicates that the growth pattern of these species is in agreement with the natural biological growth trend.

The maximum growth in the initial years of *T. ciliata* and *M. champaca* followed by decreasing trend later may be attributed to the representation of only few tree ring series in the earlier series of the BAI. Further, the position of cores extracted might also trigger the decline in BAI. Extracting cores from breast height might have resulted in missing initial year's wood formation that may be responsible for decline in the BAI trend (Tiwari et al., 2020). Also, fluctuations in the growth trend in BAI analysis may be influenced by environmental factors such as precipitation, temperature, site conditions and human activities. The basal area increment of forest trees varied widely, depending on the environment, inter-tree relationships, and tree-specific factors (Vospernik, 2021). Tiwari et al. (2020) found unhealthy BAI trend in *P. roxburghii* of Nepal indicating unhealthy forest resulting from untimely resin extraction and extreme human disturbances as well as longer pre-monsoon drought frequents in the central Himalayan region and young forest stand. Previous dendrochronological studies of *T. ciliata* (Bhattacharyya et al., 1992; Shah and Mehrotra, 2017) had observed climate influenced growth.

Shah and Mehrotra (2017) observed a favourable correlation between ring width, precipitation, and scPDSI (self–calibrated Palmer Drought Severity Index) where increased precipitation helps to replenish the soil moisture and promote tree growth during the developing period. The authors further concluded that ideal temperature, amount of precipitation, and soil moisture work together to control the radial growth of *T. ciliata* in the region of subtropical forests of Kalimpong, Eastern Himalaya. Similarly, poor radial growth was observed in years of both excessive and insufficient rainfall based on tree ring chronology of *T. ciliata* grown in Southern India, Koppa, and Karnataka between 1800 and 1987 (Bhattacharyya et al., 1992; Shah and Mehrotra 2017). In Manipur, Thomte et al. (2020) and Singh et al. (2016) studied the tree rings of *P. kesiya* growing in Sielmat and Reserve Forest of Imphal, Manipur. Thomte et al. (2020) found availability of soil moisture throughout the pre-monsoon season as a crucial factor in controlling the annual growth of *P. kesiya*. High temperatures and low precipitation during pre–monsoon might trigger high temperatures and less precipitation that encouraged high evapotranspiration rates and lower soil moisture content, which could hinder the growth of trees by producing moisture-stressed condition. Similarly, Singh et al. (2016) revealed an optimal temperature during April, May and June favouring the growth of *P. kesiya* in the region of Manipur. Various dendrochronological studies of different tree species had revealed the climatic factors responsible for the tree radial growth (Singh and Yadav., 2005; Singh and Venugopal, 2011; Shah et al., 2014; Upadhyay, 2019; Carrer and Urbinati, 2004).

Increasing trend of BAI in *P. kesiya* from Senapati site in the initial stage followed by stabilization from 2006 onwards may be attributed to increasing competition for light, nutrients and management activities like control burning in the sites since *P. kesiya* are grown under large scale planation in this region. Increased competition for resources (i.e. light and nutrients) may limit tree growth during the development of stand followed a large disturbance (Dale et al., 2001, Chambers and

Silver, 2004, Rahman et al., 2017) Generally, competition for light has a strong influence on the growth of small trees, whereas, nutrients limitation affects trees of all sizes which is evident in small mountain beech trees that were inhibited by light and nutrient competition while fertilizer nitrogen inhibits the growth of large trees (Coomes and Allen, 2007). There is a variation in the tree growth rate in response to resource by altering the metabolic rates of the trees (Grubb 1992; Reich et al., 2006). Forest fires may result in large loss of organic matter, significant loss of nutrients through volatilisation, ash entrapment in smoke columns, leaching, and erosion, all of which may inhibit the growth of trees (Rahman et al., 2017).

The growth rate of both the species (*P. kesiya*, *T. ciliata*) from Senapati site is slower than the growth rates of these species at Chandel and *T. ciliata* at Tengnoupal site which may be the result of temperature fluctuations because of altitudinal variations. Higher altitude with low temperature inhibits the growth rate than those of trees grown in lower altitude. Declined in growth rate with altitude is generally linked with short growing season and summer temperatures (Wardle, 1984). Also, light intensity declined with altitude as trees become stunted and/or found in more open canopies at high altitudes. Such variations reported to cause substantial losses of productivity in mountain beech stands, resulting from fall in both photosynthesis and respiration rates (Coomes and Allen, 2007).

BAI chronology revealed a consistent increase over time in common period suggests healthy growth of trees in the area. Furthermore, observing fluctuations in BAI trend suggested that the growth may be sensitive to the climatic factors since tree ring chronology revealed the young age stand which are highly sensitive to changes in climatic conditions. *P. kesiya*, which thrives in comparable climatic conditions in Manipur, demonstrated how climatic influences can limit tree growth (Singh et al., 2016 and Thomte et al., 2020).

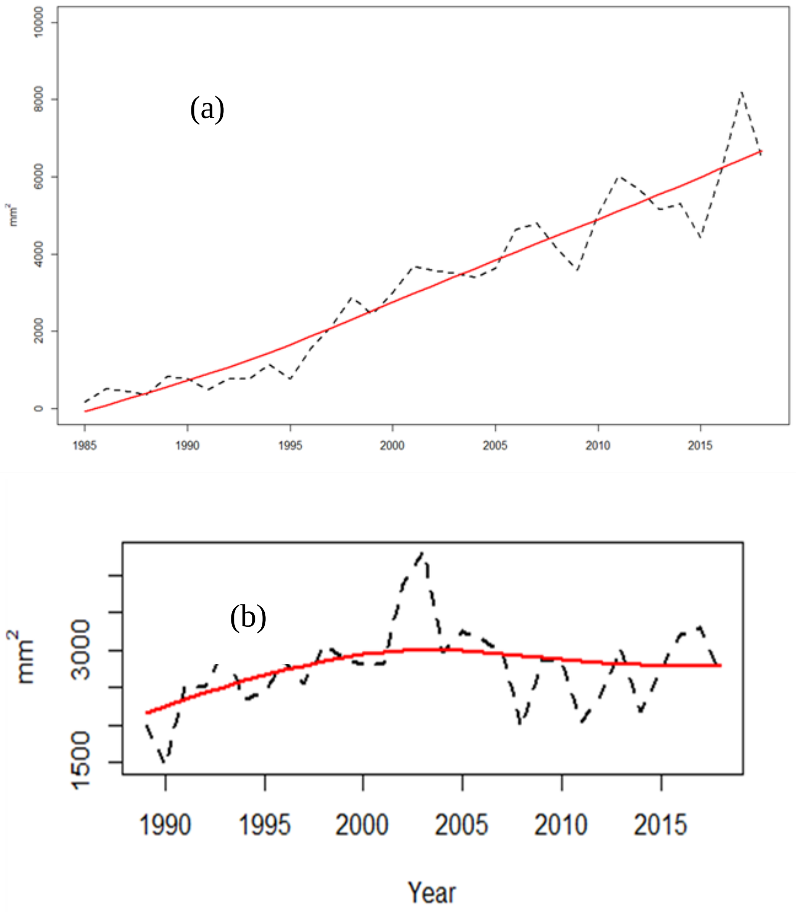


Figure 4.8. Basal Area Increment (BAI in mm^2) of *P. kesiya* for Chandel (a) and Senapati (b) sites.

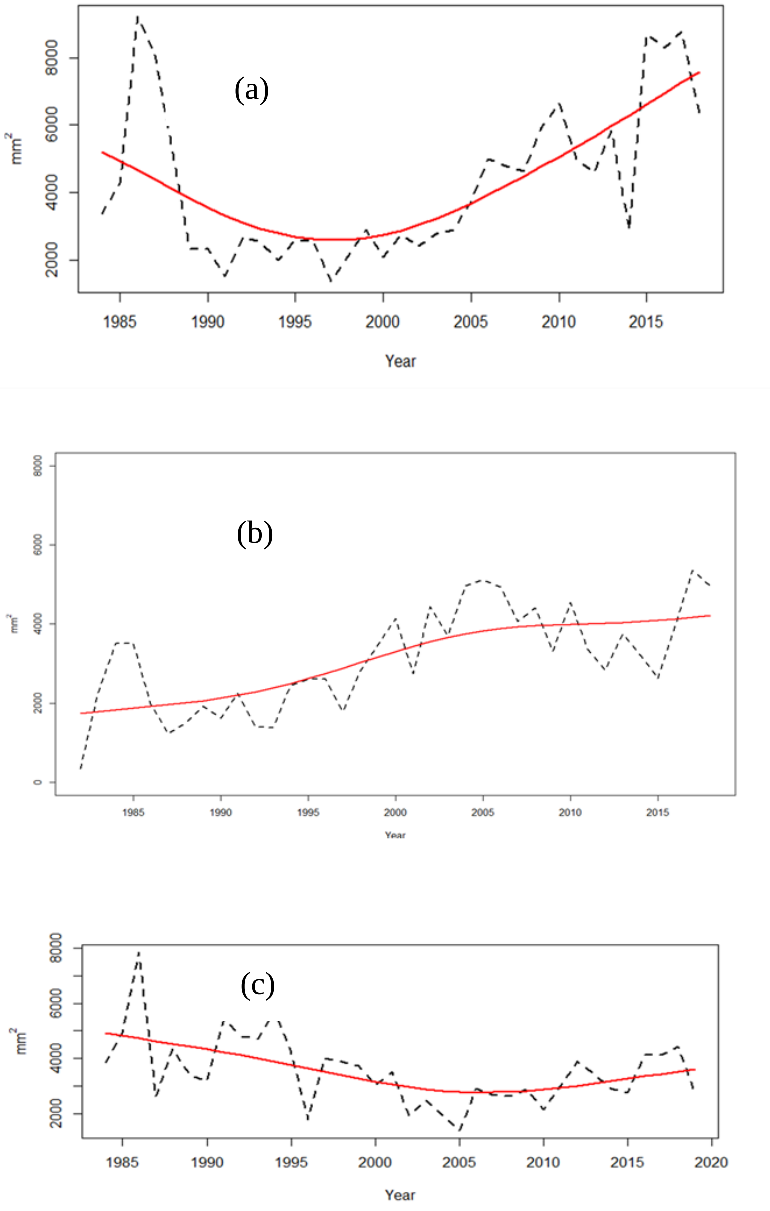


Figure 4.9. Basal Area Increment (BAI in mm^2) of *T. ciliata* for Chandel (a); Senapati (b) and Tengnoupal (c) sites.

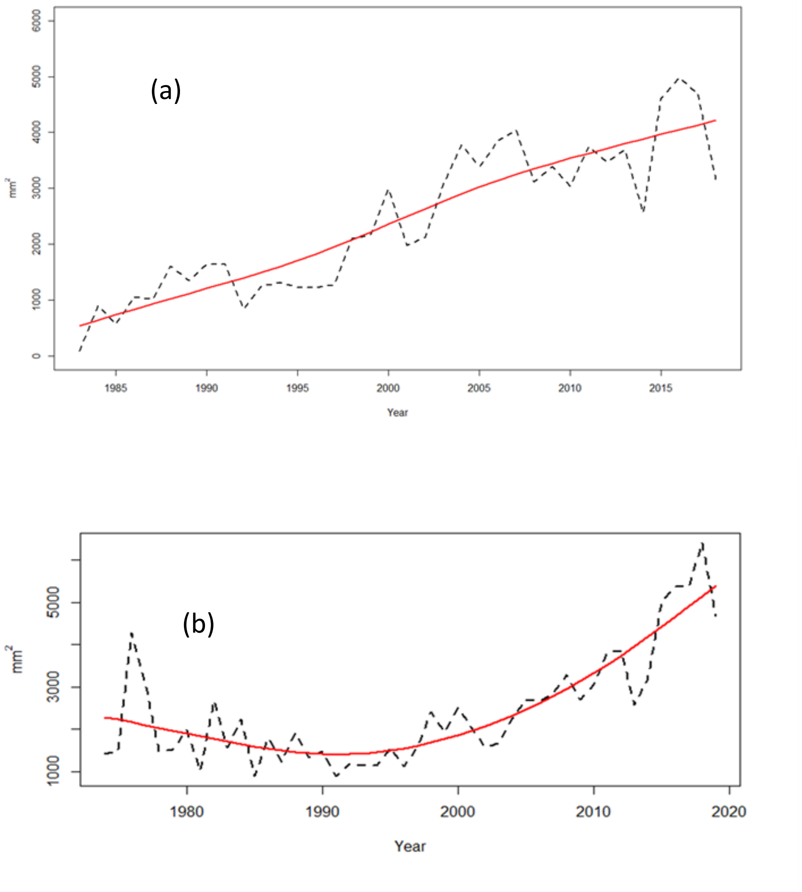


Figure 4.10. Basal Area Increment (BAI in mm^2) of *M. champaca* for Chandel (a) and Tengnoupal (b) sites.

4.5. Allometric model

4.5.1. Wood density estimation

In the present study, the wood density of *P. kesiya*, *T. ciliata* and *M. champaca* were 0.545 g cm^{-3}, 0.432 g cm^{-3} and 0.634 g cm^{-3}, respectively (Table 4.6). The wood density value of *P. kesiya* in the present study falls well within the range (0.514 g cm^{-3} - 0.550 g cm^{-3}) reported for this species from Philippine (Jones and Romeo, 2015). Similarly, wood density values of *T. ciliata* in the present study were close to Rajput et al. (1985) and Reyes (1992), 0.424 g cm^{-3} and 0.43 g cm^{-3}, respectively. In case of the wood density value (0.634 g cm^{-3}) of *M. champaca* in the present study was marginally higher (0.60 g cm^{-3}) from the report of Bisleshna et al.

(2019), whereas, it was slightly lower (0.69 g cm^{-3}) than the report of Kanawjia et al. (2013). The variations in the tree wood density may occur as a result of changes in the soil and climate of the region. Kuyah et al. (2012) stated that wood density differed among and within species and do not increase with rise in DBH. Tree wood density is necessary to develop allometric equations more accurately (Basuki et al., 2009; Mukuralinda et al., 2021) through non destructive methods, which are important for calculation of biomass, carbon and nutrient budgeting in forest ecosystems.

4.5.2. Development of allometric model for biomass estimation

Allometric models for biomass estimation of *P. kesiya*, *T. ciliata* and *M. champaca* found in Manipur were developed by employing parameters such as DBH, height of the tree (H) and wood density (WD) as independent variable and aboveground biomass as dependent variable. These variables were natural log (*ln*) transformed to develop models as to minimize heteroscedasticity in the regression analysis. In regression analysis, the *log* transformation of data is used to avoid the effect of heteroscedasticity assumption in nonlinear regressions (Packard et al., 2011; He et al., 2018). The summary of the variables used in formulating the allometric models of aboveground biomass for these species were shown in Table 4.6. The diameter of *P. kesiya*, *T. ciliata* and *M. champaca* ranged from 14.01 to 45.89 cm, 11.91 to 53.03 cm and 14.55 to 65.61 cm, respectively. Whereas, tree height ranged from 10.20 to 18.20 m, 6 to 20.40 m and 8.20 to 18.30 m; and aboveground biomass from 53.13 to 1125.42 kg, 39.51 to 1052.09 kg and 72.60 to 1836.75 kg, respectively in these tree species.

It is apparent from the Table 4.6, that more aboveground biomass was recorded in the trees having greater diameter and tree heights. Since DBH is a common representative indication of biomass allocation in trees, therefore, trees allocate different amount of biomass in trees of diameter sizes (Ruiz-Peinado et al. 2012, Altanzagas et al. 2019 and Islam et al. 2021). Similarly, Mensah et al. (2016) reported tree size as the important variable that impacted biomass allocation between the wood and tree foliage.

Table 4.6. Descriptive summary of the variables used in developing allometric model of *P. kesiya, T. ciliata* and *M. champaca***.** AGB is above ground biomass in kg. Mean values are ±1SE.

Species	DBH (cm)		Tree Height (m)		AGB (kg)		Wood density (g cm^{-3})	
	Range	Mean ± 1SE	Range	Mean ± 1SE	Range	Mean ± 1SE	Range	Mean ± 1SE
P. kesiya	14.01-45.89	33.75 ± 1.26	10.20-18.20	14.82 ± 0.28	53.13-1125.42	515.53 ± 33.6	0.503-0.621	0.545 ± 0.04
T. ciliata	11.91-53.03	30.74 ± 1.14	6.40-20.40	14.08 ± 0.39	39.51-1052.09	356.83 ± 28.41	0.426-0.443	0.433 ± 0.005
M. champaca	14.55-65.61	31.27 ± 1.88	8.20-18.30	14.3 ± 0.45	72.60-1836.75	531.55 ± 72.42	0.549-0.773	0.634 ± 0.07

Several regression forms previously employed to develop allometric models/equations but they gave extremely low co-efficient of determination (R^2), low F value, and large *RMSE* (Brown, 1997; Chamber et al., 2001; Chave et al., 2014). In this study, regression analysis was made using various regression forms and the regression equation using the natural logarithm function gave optimum result with high co-efficient of determination (R^2), high F value, and low *RMSE*. Data transformation is necessary because it helps to keep datasets consistent by minimising variance by compressing higher values and widening lower values (Bhaishya and Barik, 2011) and reducing variability in allometric models. Similarly, Chaturvedi and Raghubanshi (2015) find that natural logarithm transformation provides the best estimation of teak biomass estimation. Therefore, for estimation of aboveground biomass of *P. kesiya*, *T. ciliata* and *M. champaca*, a total of 13 models were developed that had significant coefficients of the regression except for model M12, M13 and M4 (*M. champaca*), which were excluded from further statistical fittings (Table 4.7, 4.8 and 4.9). All these (13) equations were highly significant (p<0.0001) and the co-efficient of determination (adjusted R^2) for them ranged from 0.575 to 0.888 for *P. kesiya*, 0.706 to 0.882 for *T. ciliata* and 0.839 to 0.884 for *M. champaca*, respectively. The procedure for developing allometric equations (i.e. 1, 2, 7 8 and 9) were resembling the previously developed biomass models by different authors (Brown et al., 1989; Chaturvedi and Raghubanshi, 2015; Chave et al., 2005). However, the other models (3,4,5,6, and 10-13) were also tried in this study.

Table 4.7. Allometric models developed for estimating aboveground biomass of *P. kesiya*.

Allometric models		**a**	**b**	**C**	**d**	**P value**
M1	*ln*AGB= a+b (*ln*D)	-1.1334^{*}	2.074^{***}	_	_	<0.0001
M 2	*ln*AGB= a+b (*ln*D^{2})	-1.1334^{*}	1.0370^{***}	_	_	<0.0001
M 3	*ln*AGB= a+b (*ln*D^{3})	-1.1334^{*}	0.691^{***}	_	_	<0.0001
M 4	*ln*AGB= a+b (*ln*H)	-4.1783^{*}	3.8183^{***}	_	_	<0.0001
M 5	*ln*AGB= a+b *ln*(D*H)	-3.7268^{***}	1.5908^{***}	_	_	<0.0001
M 6	*ln*AGB= a+b *ln*(D*H)^{2}}	-3.7268^{***}	0.7954^{***}	_	_	<0.0001
M 7	*ln*AGB= a+b (*ln*D^{2}*H)	-2.7464^{***}	0.9154^{***}	_	_	<0.0001
M 8	*ln*AGB= a+b (*ln*D)+c (*ln*H)	-3.5218^{***}	1.6496^{***}	1.4384^{***}	_	<0.0001
M 9	*ln*AGB=a+b (*ln*D^{2}*H*WD)	-2.1908^{***}	0.9154^{***}	_	_	<0.0001
M 10	*ln*AGB=a+b (*ln*WD*D^{2}) + c (*ln*H)	-3.0212^{***}	0.8248^{***}	1.4384^{***}	_	<0.0001
M 11	*ln*AGB=a+b *ln*D*H*WD)	-2.7612^{***}	1.5908^{***}	_	_	<0.0001
M 12	*ln*AGB= a+b (*ln*D2*H) +c (*ln*WD)	0.4191^{NS}	0.9154^{NS}	5.2153^{***}	_	<0.0001
M 13	*ln*AGB= a+b (*ln*D) + c (*ln*WD) + d (*ln*H)	-10.070^{NS}	1.649^{***}	1.148^{NS}	1.438^{**}	<0.0001

*** = significant at p<0.0001; ** = significant at p<0.001* = significant at p<0.05; NS = not significant, a, b, c, d are the fitted parameters of the regression. M = model, AGB=aboveground biomass, D=diameter at breast height, H= tree height, WD=wood density.

Table 4.8. Allometric models developed for estimating aboveground biomass of *T. ciliata.*

Allometric models		a	b	C	d	P value
M1	*ln*AGB= a+b (*ln*D)	-2.3351^{***}	2.3585^{***}	_	_	<0.0001
M 2	*ln*AGB= a+b (*ln*D^2)	-2.3351^{***}	1.1793^{***}	_	_	<0.0001
M 3	*ln*AGB= a+b (*ln*D^3)	-2.3351^{***}	0.786^{***}	_	_	<0.0001
M 4	*ln*AGB= a+b (*ln*H)	-1.8033^{*}	2.8437^{***}	_	_	<0.0001
M 5	*ln*AGB= a+b *ln*(D*H)	-3.2747^{***}	1.4858^{***}	_	_	<0.0001
M 6	*ln*AGB= a+b *ln*$(D*H)^2$}	-3.2747^{***}	0.7429^{***}	_	_	<0.0001
M 7	*ln*AGB= a+b (*ln*D^2*H)	-3.1302^{***}	0.9348^{***}	_	_	<0.0001
M 8	*ln*AGB= a+b (*ln*D)+c (*ln*H)	-3.2599^{***}	1.6027^{***}	1.329^{***}	_	<0.0001
M 9	*ln*AGB=a+b (*ln*D^2*H*WD)	-2.3477^{***}	0.9348^{***}	_	_	<0.0001
M 10	*ln*AGB=a+b (*ln*WD*D^2) + c (*ln*H)	-2.5891^{***}	0.8014^{***}	1.3291^{***}	_	<0.0001
M 11	*ln*AGB=a+b *ln*D*H*WD)	-2.0311^{***}	1.4858^{***}	_	_	<0.0001
M 12	*ln*AGB= a+b (*ln*D2*H) +c (*ln*WD)	-2.1131^{NS}	0.9348^{***}	1.21521^{NS}	_	<0.0001
M 13	*ln*AGB= a+b (*ln*D) + c (*ln*WD) + d (*ln*H)	0.5424^{NS}	1.6027^{***}	4.5425^{***}	1.3291^{NS}	<0.0001

*** = significant at p<0.0001; ** = significant at p<0.001* = significant at p<0.05; NS = not significant, a, b, c, d are the fitted parameters of the regression. M = model, AGB=aboveground biomass, D=diameter at breast height, H= tree height, WD=wood density.

Table 4.9. Allometric models developed for estimating aboveground biomass of *M. champaca.*

Allometric models		a	b	c	d	P value
M1	*ln*AGB= a+b (*ln*D)	-1.1425^{*}	2.1109^{***}	_	_	<0.0001
M 2	*ln*AGB= a+b (*ln*D^{2})	-1.1425^{*}	1.0554^{***}	_	_	<0.0001
M 3	*ln*AGB= a+b (*ln*D^{3})	-1.1425^{*}	0.704^{***}	_	_	<0.0001
M 4	*ln*AGB= a+b (*ln*H)	-0.391^{NS}	2.423^{***}	_	_	<0.0001
M 5	*ln*AGB= a+b *ln*(D*H)	-3.1304^{***}	1.5157^{***}	_	_	<0.0001
M 6	*ln*AGB= a+b *ln*(D*H)^{2}}	-3.1304^{***}	0.7578^{***}	_	_	<0.0001
M 7	*ln*AGB= a+b (*ln*D^{2}*H)	-2.6033^{***}	0.9145^{***}	_	_	<0.0001
M 8	*ln*AGB= a+b (*ln*D)+c (*ln*H)	-2.5998^{**}	1.8302^{***}	0.9115^{*}	_	<0.0001
M 9	*ln*AGB=a+b (*ln*D^{2}*H*WD)	-2.1868^{*}	0.9145^{***}	_	_	<0.0001
M 10	*ln*AGB=a+b (*ln*WD*D^{2}) + c (*ln*H)	0.9151^{*}	0.9151^{***}	0.9115^{*}	_	<0.0001
M 11	*ln*AGB=a+b *ln*D*H*WD)	-2.4401^{**}	1.5157^{***}	_	_	<0.0001
M 12	*ln*AGB= a+b (*ln*D2*H) +c (*ln*WD)	-1.0808^{NS}	0.9145^{NS}	3.3429^{***}	_	<0.0001
M 13	*ln*AGB= a+b (*ln*D) + c (*ln*WD) + d (*ln*H)	0.4082^{NS}	1.8302^{***}	6.3488^{***}	0.9115^{NS}	<0.0001

*** = significant at $p<0.0001$; ** = significant at $p<0.001$* = significant at $p<0.05$; NS = not significant, a, b, c, d are the fitted parameters of the regression. M = model, AGB=aboveground biomass, D=diameter at breast height, H= tree height, WD=wood density.

4.5.3. Selection of Best fit allometric models/equations

All developed allometric equations were subjected to different statistical fitness test like adjusted R^2, *RMSE*, *SSE*, *F* value, *MAD* and *AIC* for selecting the best performing models. The lower the value of *RSME*, *SSE*, *MAD*, *AIC* with higher *F* value and adjusted R^2 closer to 1 indicate the suitability of the equations for accurate estimation of biomass (Daba and Soromessa, 2019; Altanzagas et al., 2019; Khan et al., 2020; Puc-Kauil et al., 2020). The *AIC* estimates the quality of the statistical fit of the regression models for a set of data (Chave et al., 2005 and Aho et al., 2014). Initially, the equations were ranked from best to poor fit (i.e., 1, 2, 3, 4, 5 etc.) for each statistical fits after which the mean was taken for the overall final ranking. In final ranking, the lowest mean value was ranked as the best performing model, whereas, high mean value indicated poor predicting model. Miah et al. (2020) used the magnitude of *AIC* and the residual standard error (*RSE*) to assess their generated biomass models for homestead tree species in Bangladesh. Few authors have utilised coefficient of determination (R^2, adjusted R^2), Pearson correlation (*r*), standard errors of the estimate (*SEE*), *P* values, and average deviation (percent) to fit the best models, including Giri et al. (2019), Chaturvedi and Raghubanshi (2015), and Jaiswal et al. (2013).

As per the statistical fitness test, the ranking of the best model for *P. kesiya* were: P-M5 with mean value of 1.33, followed by P-M6 & P-M11, P-M10, P-M8, P-M9, P-M7, P-M1 & P-M2 & P-M3, and P-M4 (Table 4.10). The best fit model of *P. kesiya* (P-M5) is as: lnAGB=-3.7268+1.5908 (lnD*H) with R^2=0.888, *RMSE* of 0.2326, *SSE* of 2.3786, *MAD* of 0.190, *AIC* of -130.18 and *F* value of 356.61. For *T. ciliata*, the best models were T-M5 and T-M11 with the same mean value of 1.17, followed by T-M6, T-M10, T-M8 & T-M9, T-M7, T-M1 &T-M2 & T-M3, and T-M4. (Table 4.11). Similarly, *M. champaca* best performing models were: M-M7 and M-M9 with mean value of 1, followed by M-M8 & M-M10, M-M5 & M-M6 & M-M11 and M-M1 & M-M2 & M-M3 with equal mean value (Table 4.12). Both *T. ciliata* and *M. champaca* had each two first best fit models with the same statistical fitness. The two first best fit models of *T. ciliata* (T-M5 and T-M11) were given as *ln*AGB = - 3.2747 + 1.4858 *ln*(D*H) and *ln*AGB = - 2.0311 + 1.4858 (*ln*D*H*WD) with R^2 of 0.882, *RMSE* of 0.2642, *SSE* of 3.6316, *MAD* of 0.192, *AIC* of -145.08 and *F* value of 397.5176. The two best performing models for determining aboveground biomass of *M. champaca* based on ranking of the statistical fits were: M-M7 {*ln*AGB = - 2.6033 + 0.9145(*ln*D^2*H)} and M-M9 {*ln*AGB = - 2.1868 + 0.9145 (*ln*D^2*H*WD)}. Both these equations had the same statistical fits with adjusted R^2 of 0.884, *RMSE* of 0.2558, *SSE* of 2.0939, *MAD* of 0.17514, *AIC* of -88.73 and *F* value of 251.62.

The best variables form of models for predicting aboveground biomass in *P. kesiya* and *T. ciliata* are model 5 {*ln*AGB = a+b (*ln*D*H)} and model 11 {*ln*AGB = a+b (*ln*D*H*WD)}, respectively. It produced a high R^2 value as well as low *RMSE*, *SSE*, *MAD*, and *AIC* values, which are considered an excellent criterion for model selection. Biomass estimation of *Tectona grandis, Aphanamixis polystachya, Ficus hispida, Mangifera indica, Melia azedarach*, and *Swietenia mahagoni, Olea europaea* yielded similar results (Chaturvedi and Raghubanshi., 2015; Kebede and Soromessa, 2018; Miah et al., 2020). In most cases, including tree height along the diameter in model development can increase the model's accuracy (Cai et al., 2013; Hunter et al., 2013). D and H are dendrometric variables that can be measured readily in the field (Ong et al., 2004) and may thus be utilised as predictor variables in the allometric model. Apart from the combined variables of D and H, the best model in *T. ciliata* was found to include wood density in the model with D and H. Nath et al. (2019) reported similar observation while estimating forest biomass in North-east India.

The best predictor variables for biomass in *M. champaca* were: D^2*H and D^2*H*WD. This finding is in consistent with the fact that tree diameter, height and wood density are important dendrometry variables for estimation of tree biomass since these variables are greatly influenced by climatic and physiographic factors which in turn affect the biomass allocation in the trees (Daba and Soromessa, 2019). Similarly, the accuracy of biomass estimation was best predicted by tree height and wood density in allometric models (Chave et al., 2014; Litton and Kaufman, 2008;

Feldpausch et al., 2012). Earlier studies suggested that in various tropical trees the predictions of biomass are better when the DBH is combined with the tree heights in the allometric models rather than the DBH or height alone (Chave et al., 2005; Feldpausch et al., 2012; Daba and Soromessa, 2019). Further, the compound variables (D^2H) were found as one of the best predictors for aboveground biomass estimation in various tropical trees like *Tectona grandis* (Mwangi, 2015); tropical forest (Chave et al., 2005); *Hevea brasiliensis* (Brahma et al., 2017).

In most of the allometric equations, DBH has been frequently used as a single variable for estimating AGB because of its easy and accurate recording, and predict reasonably good estimates of AGB for many tropical forest trees (Brown, 1997; Basuki et al., 2009; Jha, 2015; Aghimien et al., 2016; Bonde et al., 2018; Kumar et al., 2019). Furthermore, the precision with which the independent variables are measured is a critical component of the allometric model (Picard et al., 2012), since they provide the foundation for finding the best fit models. Jaiswal et al. (2013) were unable to establish a fitting model for estimating fresh biomass of *Ficus hispida* due to field measurement error.

In present study, allometric equations were developed using the natural log transformed values of DBH (i.e., $ln D$, $ln D^2$, $ln D^3$) as single predictor for the estimation of AGB, which ranked sixth in *P. kesiya* and yielded same value of adjusted R^2 of 0.840 (Table 4.9), fifth in *T. ciliata* with same adjusted R^2 of 0.810 (4.10) and fourth in *M. champaca* models with R^2 of 0.839 (Table 4.11). The DBH of a tree (Chaturvedi and Raghubanshi., 2015; Bonde et al., 2018) has the highest accuracy of any independent variable and is often employed as a single predictor for biomass calculations in many studies (Brown, 1997; Brown, 1989; Hashimoto et al., 2004; Chamber et al., 2001; Kalita et al., 2015; Nath et al., 2019).

Table 4.10. Ranking of the allometric models of *P. kesiya* based on statistical fittings.

Allometric models	**Adjusted R^2**	**Rank**	***RMSE***	**Rank**	***F* value**	**Rank**	***SSE***	**Rank**	***AIC***	**Rank**	***MAD***	**Rank**	**Final Ranking**
P-M 1	0.840	5	0.2778	4	236.45	3	3.3977	4	-113.82	4	0.216	4	6 (4)
P-M 2	0.840	5	0.2778	4	236.45	3	3.3977	4	-113.82	4	0.216	4	6 (4)
P-M 3	0.840	5	0.2778	4	236.45	3	3.3977	4	-113.82	4	0.216	4	6 (4)
P-M4	0.575	6	0.4522	5	61.90	5	8.9986	5	-69.01	5	0.374	5	7 (5.33)
P-M5	0.888	1	0.2336	1	356.61	1	2.3786	2	-130.18	1	0.190	2	1 (1.33)
P-M 6	0.888	1	0.2326	1	356.61	1	2.3786	2	-130.18	1	0.192	3	2 (1.5)
P-M7	0.881	4	0.2385	3	336.30	2	2.5056	3	-125.86	2	0.189	1	5 (2.5)
P-M8	0.886	2	0.2345	2	175.28	4	2.3662	1	-127.42	3	0.190	2	4 (2.33)
P-M 9	0.882	3	0.2385	3	336.30	2	2.5056	3	-127.86	2	0.189	1	4 (2.33)
P-M10	0.888	1	0.2345	2	175.28	4	2.3662	1	-127.42	3	0.190	2	3 (2.17)
P-M11	0.888	1	0.2326	1	356.61	1	2.3786	2	-130.18	1	0.192	3	2 (1.5)

Values in the parentheses are the mean value of the statistical rankings; *RMSE* is the root mean square error, *SSE* is the sum of square error, *MAD* is the mean absolute deviation, *AIC* is the Akaike's information criterion. P-M signifies *P. kesiya*-Model.

Table 4.11. Ranking of the allometric models of *T. ciliata* based on statistical fittings.

Allometric equations	**Adjusted R^2**	**Rank**	***RMSE***	**Rank**	***F* value**	**Rank**	***SSE***	**Rank**	***AIC***	**Rank**	***MAD***	**Rank**	**Final Ranking**
T-M1	0.810	4	0.3356	4	226.85	3	5.8543	4	-113.93	5	0.249	4	5 (4)
T-M2	0.810	4	0.3356	4	226.85	3	5.8543	4	-113.93	5	0.249	4	5 (4)
T-M3	0.810	4	0.3356	4	226.85	3	5.8543	4	-113.93	5	0.249	4	5 (4)
T-M4	0.706	5	0.4173	5	128.33	5	9.0527	5	-93.90	6	0.575	5	6 (5.1)
T-M5	0.882	1	0.2642	1	397.52	1	3.6316	2	-145.08	1	0.192	1	1 (1.17)
T-M 6	0.882	1	0.2642	1	397.52	1	3.6316	2	-139.75	2	0.192	1	2 (1.33)
T-M7	0.877	3	0.2704	3	377.18	2	3.8037	3	-137.26	3	0.2	3	4 (2.83)
T-M8	0.881	2	0.2655	2	197.08	4	3.5966	1	-137.22	4	0.193	2	3 (2.5)
T-M9	0.877	3	0.2704	3	377.18	2	3.8037	3	-137.26	3	0.2	3	4 (2.83)
T-M10	0.881	2	0.2655	2	197.08	4	3.5966	1	-137.22	4	0.193	2	3 (2.5)
T-M11	0.882	1	0.2642	1	397.52	1	3.6316	2	-145.08	1	0.192	1	1 (1.17)

Values in the parentheses are the mean value of the statistical rankings; *RMSE* is the root mean square error, *SSE* is the sum of square error, *MAD* is the mean absolute deviation, *AIC* is the Akaike's information criterion. T-M signifies *T. ciliata*-Model.

Table 4.12. Ranking of the allometric models of *M. champaca* based on statistical fittings.

Allometric equations	**Adjusted R^2**	**Rank**	***RMSE***	**Rank**	***F* value**	**Rank**	***SSE***	**Rank**	***AIC***	**Rank**	***MAD***	**Rank**	**Final Ranking**
M-M1	0.839	4	0.3013	4	172.41	3	2.9054	3	-77.57	4	0.22258	4	4 (3.67)
M-M2	0.839	4	0.3013	4	172.41	3	2.9054	3	-77.57	4	0.22258	4	4 (3.67)
M-M3	0.839	4	0.3013	4	172.41	3	2.9054	3	-77.57	4	0.22258	4	4 (3.67)
M-M5	0.861	3	0.2800	3	204.76	2	2.5084	2	-82.56	3	0.19080	3	3 (2.67)
M-M6	0.861	3	0.2800	3	204.76	2	2.5084	2	-82.56	3	0.19080	3	3 (2.67)
M-M7	0.884	1	0.2558	1	251.62	1	2.0939	1	-88.73	1	0.17514	1	1 (1)
M-M8	0.880	2	0.2599	2	121.88	4	2.0939	1	-85.65	2	0.17516	2	2 (2.17)
M-M9	0.884	1	0.2558	1	251.62	1	2.0939	1	-88.73	1	0.17514	1	1 (1)
M-M10	0.880	2	0.2599	2	121.88	4	2.0939	1	-85.65	2	0.17516	2	2 (2.17)
M-M11	0.861	3	0.2800	3	204.76	2	2.5084	2	-82.56	3	0.19080	3	3 (2.67)

Values in the parentheses are the mean value of the statistical rankings; *RMSE* is the root mean square error, *SSE* is the sum of square error, *MAD* is the mean absolute deviation, *AIC* is the Akaike's information criterion. M-M signifies *M. champaca*-Model.

4.5.4. Estimation of relative error for the developed best fit models

The single variable (D), P-M1 and P-M3 models exhibited reduced (-4.06 %) relative error in *P. kesiya* (Table 4.13), and each of these models may be used to estimate *P. kesiya* aboveground biomass when just a dataset of diameter is required. When comparing the actual and projected biomass with the different models for *T. ciliata*, the model T-M3 yields a relatively low relative error (-1.12 %) compared to T-M1 (-7.45 %) and T-M2 (-1.86 %) (Table 4.14). As a result, for single predictor (D), the best fit models for *P. kesiya* and *T. ciliata* were $ln\text{AGB} = -1.1334 + 2.074\ (ln\text{D})$ and $ln\text{AGB} = -2.3351 + 0.786\ (ln\text{D}^3)$, respectively. Meanwhile, *T. ciliata* had two first-best-fit models (T-M5 and T-M11). In comparison to T-M11 (RE=-1.30 %), T-M5 underestimates aboveground biomass (RE=-5.59 %). As a result, T-M 11 was chosen as the most suitable model. For *P. kesiya* best fit model was $ln\text{AGB} = -3.7268 + 1.5908\ (ln\text{D*H})$ with R^2=0.888, whereas *T. ciliata* best fit model was $ln\text{AGB} = -2.0311 + 1.4858\ (ln\text{D*H*WD})$ with R^2 =0.882.

In addition, for *M. champaca*, the allometric model (M-M3); $ln\text{AGB} = -1.1425 + 0.704(ln\text{D}^3)$ was the most suitable for AGB when using the single variable DBH as it yielded minimum relative error (-2.78) than M-M1 (-9.73) and M-M2 (-8.34) (Table 4.15). Therefore, the M-M3 is recommended for estimating *M. champaca* AGB and C inventory when only diameter has been recorded by the investigator (Aghimien et al., 2015). Among the best performing models, the best fit model (i.e. M-M9) followed by the 2nd best fit model (i.e. M-M 8) had a low relative errors (e.g. -1.25 and -1.53%, respectively), and are supposed to most accurately estimate the AGB compared to the M-M7 and M-M10 as the later equations underestimated the biomass by -8.34% and -6.95%, respectively. However, when the wood density was incorporated as a predictor variable in D^2H in above four best fit models, the prediction error was reduced by -1.25 % from -8.34% which reflected the importance of WD in predicting the AGB of *M. champaca*. Therefore, in the present study M-M 9: $ln\text{AGB} = -2.1868 + 0.9145\ (ln\text{D}^2\text{*H*WD})$ was the best fit model for estimating AGB of *M. champaca*. The above variables (i.e. D^2, H & WD) have also been used as predictor variables in the AGB estimation of various tropical trees, e.g. *Eucalyptus camaldulensis* (Mandal et al., 2013); *Tectona grandis* (Chaturvedi and Raghubanshi, 2015); tropical forest trees (Chave et al., 2005; 2014); tropical woodlands (Aabeyir et al., 2020).

Furthermore, a relationship was established between the actual and predicted value of AGB generated from the best performing model as well as DBH based best allometric equation of the *P. kesiya* (Figure 4.11), *T. ciliata* (Figure 4.12) and *M. champaca* (Figure 4.13). The relationship was highly correlated for all the species: *P. kesiya* (R^2 of 0.843 and 0.891), *T. ciliata* (R^2 of 0.814 and 0.884) and *M. champaca* (R^2 of 0.843 and 0.887), reflecting that the models developed had high accuracy for estimating AGB of *P. kesiya*, *T. ciliata* and *M. champaca*.

Allometric models are frequently used for biomass estimation and it varies greatly between tree species and locations due to differences in tree growth rate, wood density, and floristic composition (Aboal et al., 2005). The choice of allometric models has a significant impact on biomass estimate, and using generic allometric models resulted in bias in forest biomass estimation owing to variations in tree species and stand density, forest location, and age (Kebede and Soromessa, 2018). As a result, species-specific data are critical for precisely estimating forest biomass, assessing the C content of aboveground tree components for emission trading, and assisting in sustainable forest management (Solberg, 1997). The biomass models for *Schizostachyum pergracile* were built species-specific allometric models that came across in Manipur (Thokchom and Yadava, 2017).

The allometric equation for aboveground biomass estimation of *P. kesiya, T. ciliata* and *M. champaca* was established following non-destructive approached and, employing diameter at breast height, wood density and tree height as independent variables. All the selected candidate models were highly significant ($p<0.0001$) and had adjusted R^2 range of 0.575 to 0.888, 0.706 to 0.882 and 0.839 to 0.884 respectively. The study found the best allometric model for AGB estimation of *P. kesiya* as lnAGB = - 3.7268 + 1.5908 (lnD*H) with highest R^2 of 0.888 and lower *RMSE* value of 0.2326, *SSE* of 2.3786, *MAD* of 0.190, *AIC* of -130.18 and had low relative error (-4.06%). Whereas *T. ciliata* best fit model was lnAGB = - 2.0311 +

1.4858 (*ln*D*H*WD) with highest R^2 of 0.882, *RMSE* of 0.2642, *SSE* of 3.6316, *MAD* of 0.192, *AIC* of -145.08 and relative error (-1.30%). The study found the allometric model 9 (M-M9) expressed in *ln*AGB = - 2.1868 + 0.9145 (*ln*D^2*H*WD) as the best fit model for *M. champaca* and had low relative error (-1.25%) of prediction, highest adjusted R^2 of 0.884 and lower *RMSE* value of 0.2558, *SSE* of 2.0939, *MAD* of 0.17514 and *AIC* of -88.73. Therefore, the developed allometric models for each species is appropriate for species-specific biomass estimation in the state Manipur.

Table 4.13. Best fit models of the study and models with single predictor diameter developed for estimating aboveground biomass *of P. kesiya.*

Species	**Allometric models**	**Best fit models**	R^2	**Adjusted** R^2	**RE (%)**	**CF**
P. kesiya	1st best model (P-M 5)	*ln*AGB=-3.7268+1.5908(*ln*D*H)	0.890	0.888	-4.06	1.03
	2nd best model (P-M 6)	*ln*AGB=-3.7268+0.7954{*ln*$(D*H)^2$}	0.890	0.888	-8.14	1.03
	2nd best model (P-M 11)	*ln*AGB=-2.7612+1.5908(*ln*D *H*WD)	0.890	0.888	-4.06	1.03
	Single Variable D (P-M 1, P-M 2, P-M 3)	*ln*AGB=-1.1334+2.074(*ln*D)	0.843	0.840	-4.06	1.04
		*ln*AGB=-1.1334+1.0370(*ln*D^2)	0.843	0.840	-8.13	1.04
		*ln*AGB=-1.1334+0.691(*ln*D^3)	0.843	0.840	-4.06	1.04

P-M indicate *P. kesiya* model; RE indicate the relative error of the allometric equation and CF as correction factor.

Table 4.14. Best fit models of the study and models with single predictor diameter developed for estimating aboveground biomass *of T. ciliata.*

Species	**Allometric models**	**Best fit models**	***R^2***	**Adjusted *R^2***	**RE (%)**	CF
T. ciliata	1st best model (T-M 5)	*ln*AGB= -3.2747 + 1.4858(*ln*D*H)	0.884	0.882	-5.59	1.04
	1st best model (T-M 11)	*ln*AGB= -2.0311+1.4858 (*ln*D*H*WD)	0.884	0.882	-1.30	1.04
	2nd best model (T-M 6)	*ln*AGB=-3.2747+0.7429{*ln*(D*H)^2}	0.884	0.882	-7.45	1.04
	Single variable D (T-M1, T-M2, T-M 3)	AGB=-2.3351+2.3585 (*ln*D)	0.814	0.810	-7.45	1.06
		*ln*AGB=-2.3351+1.1793(*ln*D^2)	0.814	0.810	-1.86	1.06
		*ln*AGB=-2.3351+0.786(*ln*D^3)	0.814	0.810	-1.12	1.06

T-M indicates *T. ciliata* model; RE indicate the relative error of the allometric equation and CF as correction factor.

Table 4.15. Best fit models of the study and models with single predictor diameter developed for estimating aboveground biomass *of M. champaca*.

Species	**Allometric models**	**Best fit models**	R^2	**Adjusted** R^2	**RE (%)**	CF
M. champaca	1st best model (M-M 7)	$lnAGB=-2.6033+0.9145(lnD^{2}*H)$	0.888	0.884	-8.34	1.04
	1st best model (M-M 9)	$lnAGB=-2.1868+0.9145(lnD^{2}*H*WD)$	0.888	0.884	-1.25	1.03
	2st best model (M-M 8)	$lnAGB=-2.5998+1.8302(lnD)+0.9115(lnH)$	0.888	0.880	-1.53	1.04
	2st best model (M-M 10)	$lnAGB=0.9151+0.9151(lnWD*D^{2})+0.9115(lnH)$	0.888	0.880	-6.95	1.03
	Single Variable D (M-M 1, M-M 2, M-M 3)	$lnAGB=-1.1425+2.1109(lnD)$	0.843	0.839	-9.73	1.05
		$lnAGB=-1.1425+1.0554(lnD^{2})$	0.843	0.839	-8.34	1.05
		$lnAGB=-1.1425+0.704(lnD^{3})$	0.843	0.839	-2.78	1.05

M-M indicate *M. champaca* model; RE indicate the relative error of the allometric equation and CF as correction factor.

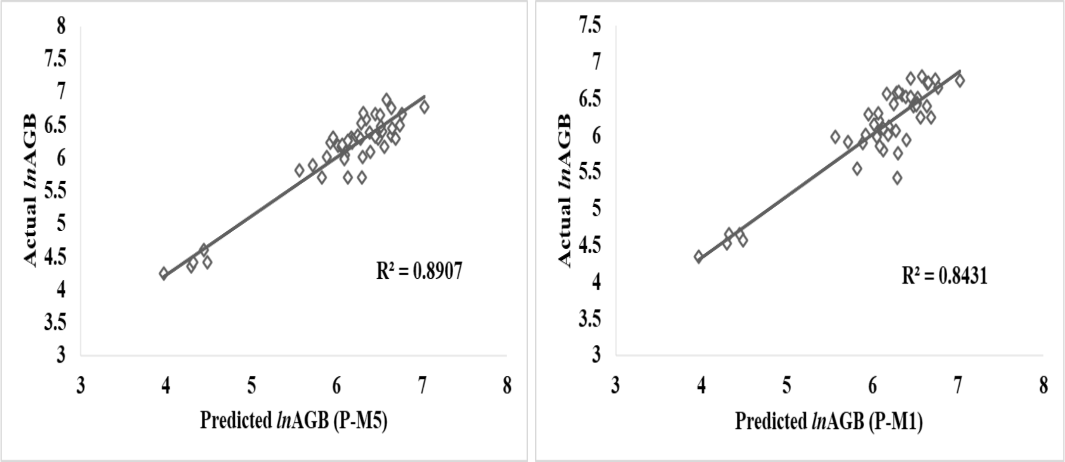


Figure 4.11. Relationship between the actual and predicted aboveground biomass (*ln*AGB) of *P. kesiya* generated from our best fit model (P-M5) and model using diameter alone (P-M1).

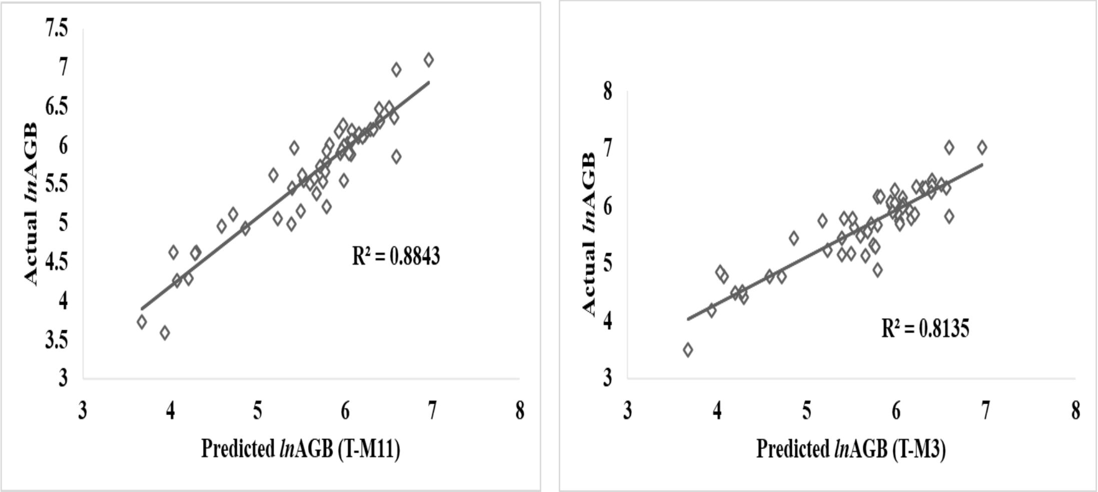


Figure 4.12. Relationship between the actual and predicted aboveground biomass (*ln*AGB) of *T. ciliata* generated from our best fit model (T-M11) and model using diameter alone (T-M3).

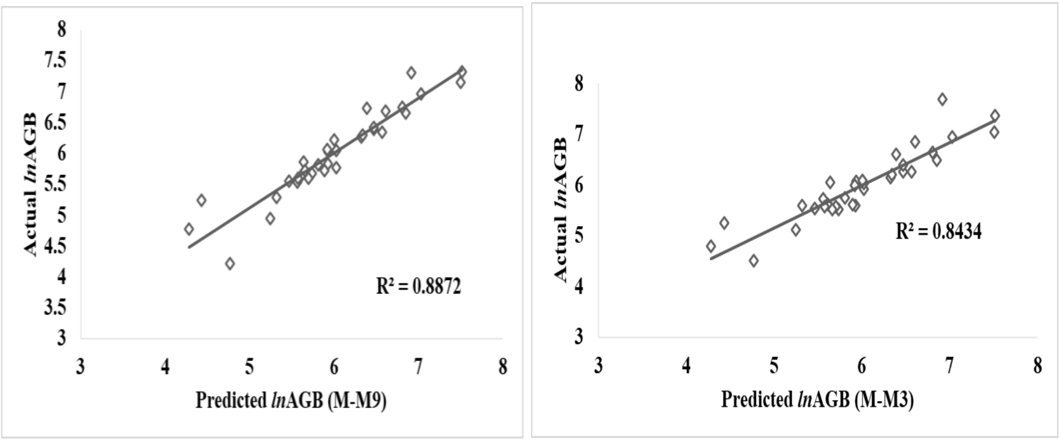


Figure 4.13. Relationship between the actual and predicted aboveground biomass (*ln*AGB) of *M. champaca* generated from our best fit model (M-M9) and model using diameter alone (M-M3).

4.6. Carbon sequestration potential for different tree species of Manipur

4.6.1. Estimation of Carbon (C) content

The C content of the studied trees (viz. *P. kesiya*, *T. ciliata* and *M. champaca*) analysed using the CHN analyser showed lower C contents 42.05 %, 36.75 % and 38.8 % for *P. kesiya*, *T. ciliata* and *M. champaca,* respectively, compared to C estimation using ash method (Table 4.16). The C contents in the present obtained using CHN was slightly lower compared to the previous reported values in various studies based dry ashing method but was comparable to the C analysed using ash method. Choudhary et al. (2014) reported 46.39% and 45.52% of C content in stem wood and as a whole of *P. kesiya* in their study in Arunachal Pradesh, Northeast India. Nagar et al. (2021) reported C content of 45.99% in *T. ciliata*. Further, different studies emphasis that the plant biomass contains 45% to 50% of C (Ravindranath et al., 1997; Bhaisya and Barik, 2011; Choudhary et al., 2014; Potadar and Patil, 2017). However, the dry ashing method had estimated the C content of 46.4%, 45.8% and 46% for *P. kesiya*, *T. ciliata* and *M. champaca* respectively, and these values were closer to the previously reported values (Choudhary et al., 2014; Nagar et al., 2021) and general acceptable C content i.e. 45 % to 50 %. The higher values of C concentration obtained by ash content method are possibly because of the variations in elemental concentrations which adds source of error. However, the low values of C concentration obtained by CHN would possibly be because of the detection of C in gaseous form. However, the values of C content estimated from dry ashing method were used for further analysis to compare the results obtained with the previous studies.

Table 4.16. Carbon concentrations for *P. kesiya*, *T. ciliata* and *M. champaca*.

Method used	**Carbon concentration (%)**		
	P. kesiya	*T. ciliata*	*M. champaca*
CHN analyser	42.05	36.75	38.8
Dry ashing method	46.4	45.8	46

4.6.2. Above Ground Biomass (AGB) estimation

Tree ring analysis revealed that the mean annual ring width does not differ significantly among and within the tree species and sites (Table 4.17, 4.18 and 4.19) and were in the range of 0.95 mm year^{-1} to 0.99 mm year^{-1}, with the lowest in *P. kesiya* of Senapati site and highest in *M. champaca* of Tengnoupal site. This annual ring width values were used to estimate the AGB through the employment of suitable published allometric model for the region and as well as allometric model developed in this study.

4.6.2.1. Above Ground Biomass (AGB) estimation using model developed earlier

The AGB of *P. kesiya* estimated using the equation developed by Nath et al. 2019 was higher (5.96 kg year^{-1} tree^{-1}) in the Senapati site as compared to the Chandel site (5.71 kg year^{-1} tree^{-1}). Similarly, the AGB of *T. ciliata* were recorded higher in Senapati, followed by Chandel and Tengnoupal sites with the values of 6.53 (kg year^{-1} tree^{-1}), 6.08 (kg year^{-1} tree^{-1}) and 5.38 (kg year^{-1} tree^{-1}), respectively. In the case of *M. champaca*, the higher AGB (6.33 kg year^{-1} tree^{-1}) were estimated from Tengnoupal compared to Chandel site. Among the tree species for the Chandel site, *T. ciliata* and *M. champaca* had comparatively more AGB than *P. kesiya*. Similarly, *T. ciliata* had higher AGB than *P. kesiya* in the Senapati site. However, in the Tengnoupal site, *M. champaca* had higher AGB than *T. ciliata* which is also the lowest AGB reported in this study. It was also observed that there was no significant difference in the AGB of the studied tree species for the same site and among the sites. However, the AGB of the *T. ciliata* when compared among the sites, varied significantly ($P<0.05$) between the two sites (Senapati and Tengnoupal) (Table 4.18).

4.6.2.2. Estimation of C stock and sequestration rate

The mean annual C stock for the studied tree species did not vary significantly between the tree species. Similar to the AGB, the C stock of *T. ciliata* differ significantly ($P<0.05$) between Senapati and Tengnoupal sites. In this study, the highest (2.99 kg year^{-1} tree^{-1}) and lowest (2.46 kg year^{-1} tree^{-1}) mean annual C stock was found in *T. ciliata* at Senapati and Tengnoupal sites (Table 4.18). The mean annual C stock of *P. kesiya* was 2.65 kg year^{-1} tree^{-1} and 2.78 kg year^{-1} tree^{-1} for Chandel and Senapati sites, respectively (Table 4.17). The C stock of *M. champaca* for Chandel and Tengnoupal were 2.78 kg year^{-1} tree^{-1} and 2.91 kg year^{-1} tree^{-1}, respectively (Table 4.19). It is found that greater C stock of both *P. kesiya* and *T. ciliata* were recorded from Senapati sites as compared to Chandel and Tengnoupal sites. In *M. champaca*, greater C stock was found in Tengnoupal than the Chandel site.

The annual C sequestration rate of *T. ciliata, P. kesiya and M. champaca* were presented for various study sites (Figure 4.14, 4.15 and 4.16). C sequestration rate ($p > 0.05$) did not vary significantly among tree species and/or sites. The mean annual C sequestration rate of *T. ciliata* for each study site (viz. Chandel, Senapati and Tengnoupal) was 0.037 kg year^{-1}, 0.038 kg year^{-1} and 0.029 kg year^{-1} respectively. The lowest C sequestration rate was noticed in the Tengnoupal site. The minimum and maximum C sequestration rate was recorded as 0.001 kg year^{-1} from Senapati site and 0.126 kg year^{-1} from Chandel site in the calendar year 1989 and 2014, respectively. Similarly, *P. kesiya* from both Chandel and Senapati sites had comparable value of mean annual C sequestration rate with 0.027 kg year^{-1} and

0.028 kg year^{-1}. In case of *M. champaca*, the mean annual C sequestration rate was higher in Tengnoupal site with 0.041 compared to Chandel site with a value of 0.03. Further, the maximum annual C sequestration rate was found as 0.172 in the calendar year 1975.

In the present study, biomass and C stock of *P. kesiya* were higher in the Senapti site than Chandel site which may be due to the nature of forest type. *P. kesiya* of the Senapati were of pure stand plantation and had greater biomass and C stock than Chandel site which were mixed stand with the presence of few broad-leaved species. In Philippines, Patricio and Tulod (2010) reported that *P. kesiya* plantation had higher biomass density than mixed *P. kesiya* and other broad-leaved species of similar age. Chen et al. (2016) revealed that planted *P. massoniana* in China had greater biomass C stock densities when compared to natural pine forests. Similarly, forest productivity, C stocks and sequestration rates were much higher in the planted forests than in natural forests (Guo and Ren, 2014; Huang et al., 2008). The higher biomass and C stocks in Planted *P. kesiya* may be attributed to the management practice in this forest, particularly, control burning of the forest floor for preventing wild fire in the site and the susceptible nature of the pine to fire. The practice of floor burning usually resulted in removing the understory growth and affects the regeneration of seedlings. Pornleesangsuwan (2012) found that fire disturbance had affected the regeneration of broad-leaved trees in the *P. kesiya* plantations in Thailand. It has been demonstrated that greater management effort increased biomass yield and C storage (Wade et al., 2010). Also, the removal of understory in the forests affected the tree growth and increased the C stock density (Wu et al., 2013)

In comparison of the sites, more biomass is allocated in the Senapati than Chandel and Tengnoupal sites which may be due to lower environmental temperature as a result of higher altitude of the former than later. Altitude and slope aspect determined the governing temperature of any sites which affects the forest composition as a whole, and the plant biomass increased at higher altitude with change in temperature and precipitation which also enhance the C stock in the soil

(Choupanian et al., 2012). Several studies reported the increase of biomass C with higher altitude (Zhu et al., 2010; Gairola et al., 2011; Feyissa et al., 2013; Yohannes et al., 2015). For example, Yohannes et al. (2015) study in Gedo forest of Ithopia found less AGB and C values of 296.89 t C ha^{-1} and 338.69 t ha^{-1} at low elevation (2279m - 2420m) and greater AGB and C values of 324.05 t C ha^{-1} and 545.80 t ha^{-1} at high elevation (2421m - 2549m).

However, higher biomass and C stocks in *M. champaca* from Tengnoupal may be because of the presence of larger trees in girth as well as older age of the sample trees in this region. Big trees contribute a significant part in small-scale C accumulation and storage that determine the stand level dynamics (Yoda et al., 1965; Köhl et al., 2017). Similarly, mature trees forming the upper crown canopy are more likely to accumulate higher C in the forests (Köhl et al., 2017). And greater availability of mature trees in the stands can possibly enhance the capacity of the C storage in the forest ecosystem since biomass accumulation are higher with stand age and is one factor that control the forest ecosystem biomass (Chen et al., 2016). Ko¨rner (2009) highlighted that the C capital of forests is control by the tree longevity instead of growth rate. Köhl et al. (2017) found in their studies that higher C accumulation rates were allocated at the older age of *Cedrela odorata*, *Hymenaea courbaril* and *Goupia glabra*, and stress the role of older trees to the C capital of forests, where tree longevity by maintaining and through their constant growth simultaneously enhance the C capital. Authors recommended that old tropical growth trees don’t simply support to C accumulations through extensive C resistance times but rather sustain greater C accumulation rates at their older stages of their timespan. Das and Ramakrishnan (1987) study suggested that the biomass and nutrient contents of *P. kesiya* in different stand age ranged from 1 to 22 years in the Meghalaya, Northeast, India. He found an increased rate of biomass with older stand age, the biomass for stand age 1 and stand age 22 were: 2.09 kg ha^{-1} x 10^{3} and 308.72 kg ha^{-1} x 10^{3}, respectively.

In this study, *T. ciliata* and *M. champaca* had greater biomass and C stocks than that of *P. kesiya*, which may be due to the differences in their girth and age.

This was also supported by Terakunpisut et al. (2007), stating that C sequestration of forests relied on forest types, tree girth size and their age of the tree or stand. Compared to small trees of less than 8 cm diameter, healthy tree species with diameter more than 77 cm sequestered more than 90 times C (Nowak, 1994; Potadar and Patil, 2017). Gogoi et al. (2020) studied the tree diversity and C stock in a subtropical broad-leaved forest and subtropical pine forest growing in comparable elevation of Meghalaya, north-eastern India, and found that the broad-leaved forest stands i.e. Mawnai broad-leaved forest and Nongkrem broad-leaved forest had significant greater tree biomass C stock (140.4 Mg C ha^{-1} and 133.6 Mg C ha^{-1}) than the pine forest stands i.e. Mawnai Pine forest and Nongkrem Pine forest (74.7 Mg C ha^{-1} and 63 Mg C ha^{-1}). Similarly, Thong et al. (2020) found *Antidesma acidum* and *Rhus chinensis* having more living woody biomass C than *P. kesiya* in the Urkhrul district of Manipur. However, the same authors reported highest living woody biomass C in various fallow periods for *T. ciliata* and *P. kesiya* in Chandel district of Manipur. Joshi et al. (2021) had reported higher C sequestration in *P. roxburghii* stand (4.83 Mg C ha^{-1} year^{-1}) as compared to the stands of *Shorea robusta* (4.63 Mg C ha^{-1} year^{-1}), mixed Oak (4.47 Mg C ha^{-1} year^{-1}), and *Quercus leucotrichophora* (3.99 Mg C ha^{-1} year^{-1}) in the central Himalaya. This may be due to the altitudinal variations of these forest stands and slow growing nature of the species compared to pine. In spite of this, Rai et al. (2021) had suggested *M. champaca* as the significant commercial timbers for the Eastern Himalayan region since the forest dominated by *M champaca* was found to have the highest amount of litter production and decomposition as compared to the *Tectona grandis*, *Shorea robusta* and *Lagerstroemia parviflora* dominated forests, which may greatly contribute in greater forest C sink.

4.6.2.3. Aboveground Biomass (AGB), C stock and sequestration rate

The values of AGB, C stock and sequestration rate estimated using the allometric model developed in this study were higher for *P. kesiya* and *M. champaca* than the values estimated using the Nath et al. (2019). However, *T. ciliata* had estimated lower values in their AGB, C stock and sequestration rate using this developed allometric model. The mean AGB values for *P. kesiya* were 9.32 kg year^{-1} tree^{-1} and 9.76 kg year^{-1} tree^{-1} for Chandel and Senapati sites. The mean AGB values for Chandel, Senapati and Tengnoupal sites for *T. ciliata* were 1.92 kg year^{-1} tree^{-1}, 2.06 kg year^{-1} tree^{-1} and 1.70 kg year^{-1} tree^{-1}, respectively. *M. champaca* had mean AGB values of 9.20 kg year^{-1} tree^{-1} and 9.59 kg year^{-1} tree^{-1} for Chandel and Tengnoupal sites, respectively. The mean C stock of *P. kesiya* was 4.32 kg year^{-1} tree^{-1} and 4.53 32 kg year^{-1} tree^{-1} for Chandel and Senapati sites. However, for *T. ciliata* mean annual C stocks were 0.88 kg year^{-1} tree^{-1}, 0.94 kg year^{-1} tree^{-1} and 0.78 kg year^{-1} tree^{-1} for Chandel, Senapati and Tengnoupal sites, respectively. *M. champaca* had 4.23 kg year^{-1} tree^{-1} and 4.41 kg year^{-1} tree^{-1} for Chandel and Tengnoupal sites, respectively. Similarly, the mean annual C sequestration rate of *P. kesiya* was 0.043 and 0.045 for Chandel and Senapati sites, respectively. However, mean annual C sequestration rate of *T. ciliata* was 0.013 kg year^{-1}, 0.013 kg year^{-1} and 0.010 kg year^{-1} for Chandel, Senapati and Tengnoupal sites, respectively. *M. champaca* had 0.049 kg year^{-1} and 0.056 kg year^{-1} for Chandel and Tengnoupal sites, respectively.

The allometric model developed by Nath et al. (2019) for biomass estimation was based on mixed species pool for the Northeast region of India. However, the allometric model developed in this study is a species-specific developed in the region of Manipur which will more suitable and applicable for the estimation of biomass and C sequestration rates in Forests of Manipur, India. As observed from the table 4.17 and 4.19, using the allometric equation of Nath et al. (2019), the AGB of *P. kesiya* and *M. champaca* in the present study was underestimated and that of *T. ciliata* was overestimated in comparison to species-specific model used from this study in Manipur. This is because of the use of various species pooled data from different part of northeastern region and changes soil and environmental conditions that caused variation in tree either in the radial growth, wood density or tree heights. Rahman et al. (2021) studied the biomass of mangrove forest biomass using the general and species-species allometric model and found that the generic allometric models overestimated the AGB from 22% to 167% compared to the species-specific models at the individual tree level. The species-specific allometric model encapsulate the trees variations in their height, diameter and wood density which are caused by ecological and management intervention which the mixed-species and pan-tropical models may not capture (Maulana et al., 2016; Mahmood et al., 2019; Hossain et al., 2020). Nogueira et al. (2008) indicated that allometric models developed in infertile soils of forests in central Amazonia causes overestimates of biomass when used to trees in the open forests of Southern Amazon. Further, they also revealed the allometric models developed by Higuchi et al. (1998), Chambers et al. (2001) and da Silva (2007) overestimating the biomass of small trees while underestimating the biomass of large trees. As such, the overestimation and underestimation of AGB in the present study when using the developed model in the present study and Nath et al. (2019) may have been resulted from the environmental changes, forest types as well as variation in the tree size that affected the estimation of tree biomass.

This is the first study in Manipur to describe the biomass C stock using a tree rings approach at the individual tree level. Pompa-Gracia et al. (2018) studied the C accumulation dynamic using the dendrochronological approach in two pine species (*P. arizonica* and *P. cembroides*). The C accumulation of *P. arizonica* and *P. cembroides* are 4.80 kg year^{-1} and 4. 84 kg year^{-1} respectively, which are greater than our estimated C stock values ranging from 2.46 kg year^{-1} to 2.99 kg year^{-1} (estimated using Nath et al., 2019) and 0.78 kg year^{-1} to 4.53 kg year^{-1} (estimated using the study develop model). This may be attributed to the difference in the radial growth rate, age, diameter, allometric models and regional with different environmental conditions since biomass and C are greatly influence by these factors. Sanogo et al. (2016) had estimated the C sequestration rates of *Vitellaria paradoxa* in different land used types, and reported its average C sequestration rate of 0.112 C ha^{-1} year^{-1}

and 0.068 C ha^{-1} $yearr^{-1}$ in parkland, 0.075 C ha^{-1} $year^{-1}$ and 0.053 C ha^{-1} $year^{-1}$ in fallows with respect to the site Yanfolila and Koutiala, West Africa.

Table 4.17. Mean ring width (RW), above ground biomass (AGB) and carbon (C) stock of *P. kesiya* from Chandel and Senapati sites.

Species	***P. kesiya***	
Sites	**Chandel**	**Senapati**
RW (mm $year^{-1}$)	0.98 ± 0.03^a	0.95 ± 0.02^a
Min/Max	0.64/1.32	0.72/1.22
Time span	1982-2018	1989-2018
Nath et al. (2019)		
Mean AGB (kg $tree^{-1}$)	5.71 ± 0.35^a	5.96 ± 0.32^a
Min/Max	2.21/10.24	3.26/ 10.07
Mean C stock (kg $year^{-1}$)	2.65 ± 0.16^a	2.78 ± 0.14^a
Min/Max	1.02/4.85	1.51/4.67
Developed model		
Mean AGB (kg $tree^{-1}$)	9.32 ± 0.55^a	9.76 ± 0.50^a
Min/Max	3.75/16.67	5.47/16.17
Mean C stock (kg $year^{-1}$)	4.32 ± 0.27^a	4.53 ± 0.23^a
Min/Max	1.74/7.73	2.54/7.50

Values are in annual mean ± 1SE (n=37 and 30 for *P. kesiya* in Chandel and Senapati sites). Different superscript letters indicated significantly difference (P<0.05). C=carbon, Min =minimum, Max=maximum.

Table 4.18. Mean ring width (RW), above ground biomass (AGB) and C stock of *T. ciliata* from Chandel, Senapati and Tengnoupal sites.

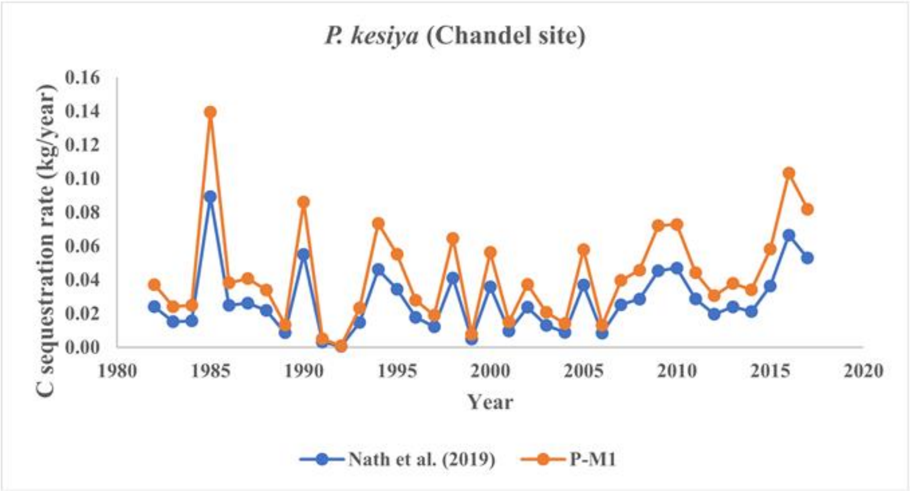
Species	***T. ciliata***		
Sites	**Chandel**	**Senapati**	**Tengnoupal**
Mean RW (mm year^{-1})	0.97 ± 0.33^{a}	0.97 ± 0.29^{a}	0.98 ± 0.30^{a}
Min/Max	0.46/1.29	0.58/1.26	0.50/1.29
Time span	1984-2018	1981-2018	1984-2019
Nath et al. (2019)			
Mean AGB (kg tree^{-1})	6.08 ± 0.40^{a}	6.53 ± 0.39^{ab}	5.38 ± 0.33^{ac}
Min/Max	1.15/10.46	2.05/11.08	1.21/9.37
Mean C stock (kg year^{-1})	2.79 ± 0.19^{a}	2.99 ± 0.18^{ab}	2.46 ± 0.15^{ac}
Min/Max	0.52/4.93	0.94/5.07	0.55/4.29
Developed model			
Mean AGB (kg tree^{-1})	1.92 ± 0.14^{a}	2.06 ± 0.81^{ab}	1.70 ± 0.11^{ac}
Min/Max	0.31/3.56	0.58/3.64	0.33/3.09
Mean C stock (kg year^{-1})	0.88 ± 0.06^{a}	0.94 ± 0.06^{ab}	0.78 ± 0.05^{ac}
Min/Max	0.14/1.63	0.26/1.67	0.15/1.42

Values are in annual mean ± 1SE (n=35,38 and 36 for *T. ciliata* in Chandel, Senapati and Tengnoupal sites). Different superscript letters indicated significantly difference ($P<0.05$). C=carbon, Min =minimum, Max=maximum.

Table 4.19. Mean ring width (RW), above ground biomass (AGB) and C stock of *M. champaca* from Chandel and Tengnoupal sites**.**

Species	***M. champaca***	
Sites	**Chandel**	**Senapati**
RW (mm year^{-1})	0.97±0.03^{a}	0.99 ± 0.05^{a}
Min/Max	0.60/1.31	0.39/1.87
Time span	1981-2018	1974-2019
Nath et al. (2019)		
Mean AGB (kg tree^{-1})	6.05 ± 0.40^{a}	6.33 ± 0.60^{a}
Min/Max	2.01/11.02	0.76/22.40
Mean C stock (kg year^{-1})	2.78 ± 0.19^{a}	2.91 ± 0.28^{a}
Min/Max	0.93/5.7	0.35/10.30
Developed model		
Mean AGB (kg tree^{-1})	9.20±0.60^{a}	9.59 ± 0.88^{a}
Min/Max	3.14/16.57	1.21/3.10
Mean C stock (kg year^{-1})	4.23 ± 0.28^{a}	4.41 ± 0.41^{a}
Min/Max	1.45/7.62	0.56/15.23

Values are in annual mean ± 1SE (n=38 and 46 for *M. champaca* in Chandel and Tengnoupal sites). Different superscript letters indicated significantly difference (P<0.05). C=carbon, Min=minimum, Max=maximum.



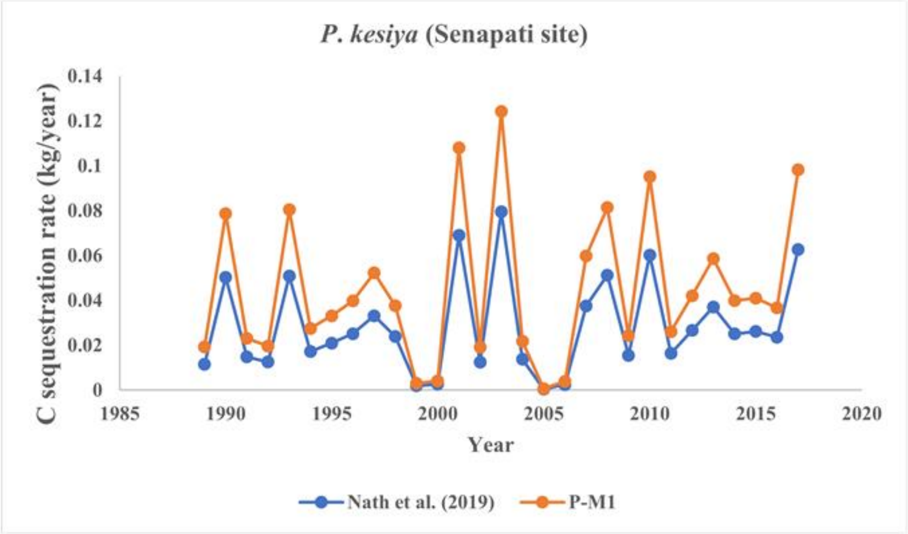


Figure 4.14. Annual C sequestration rate of *P. kesiya* for Chandel and Senapati study sites at various time span, C=carbon.

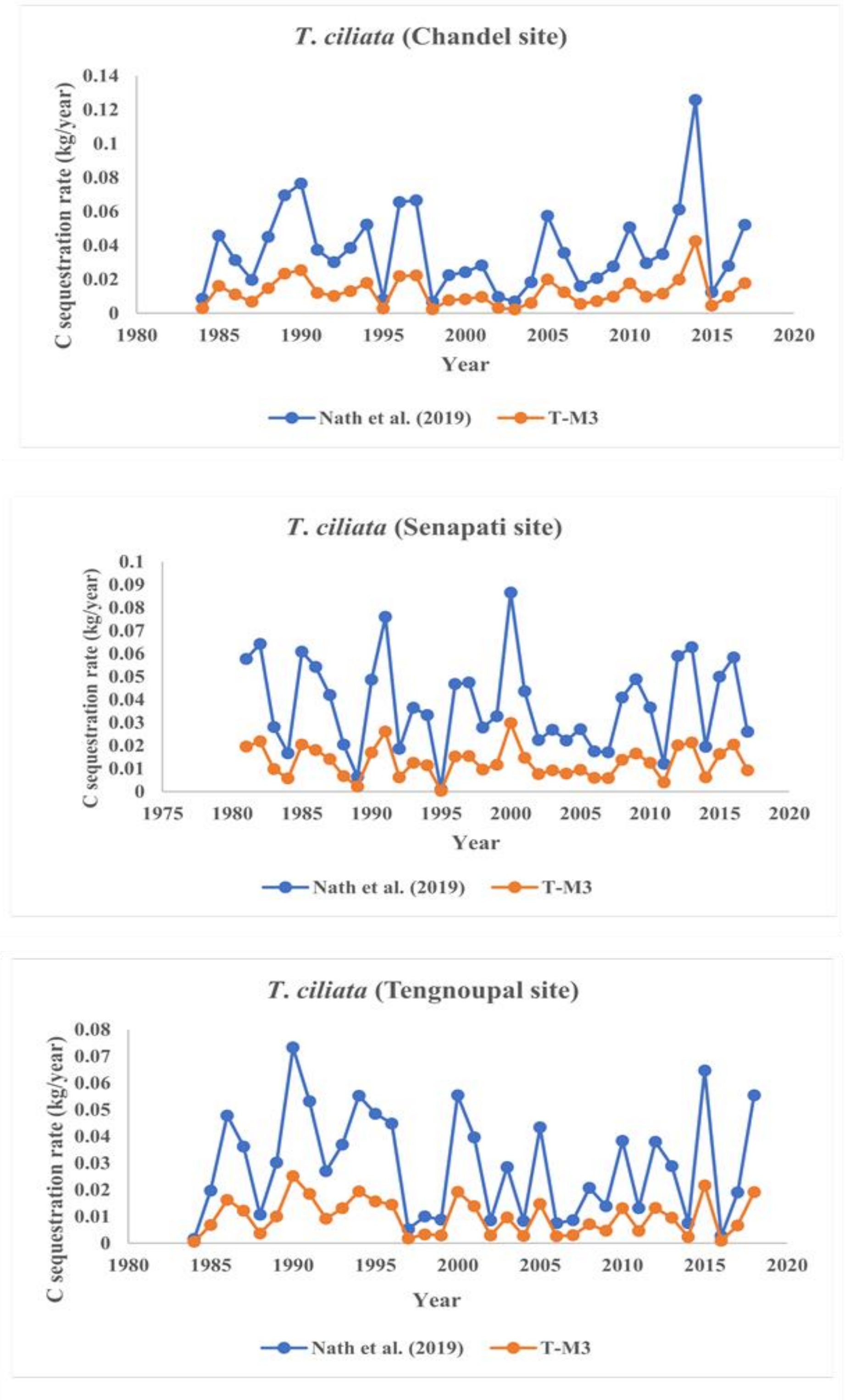
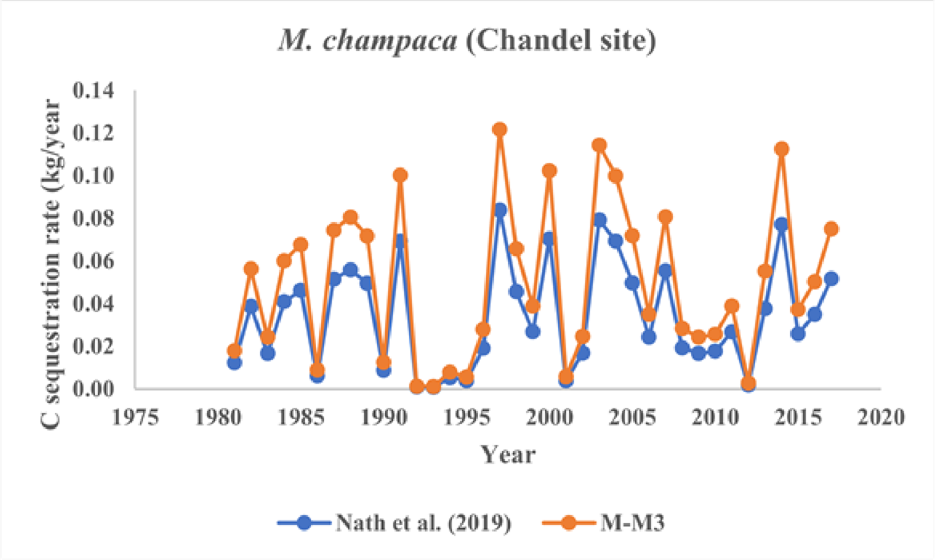


Figure 4.15. Annual C sequestration rate of *T. ciliata* for Chandel, Senapati and Tengnoupal study sites at various time span, C=carbon.



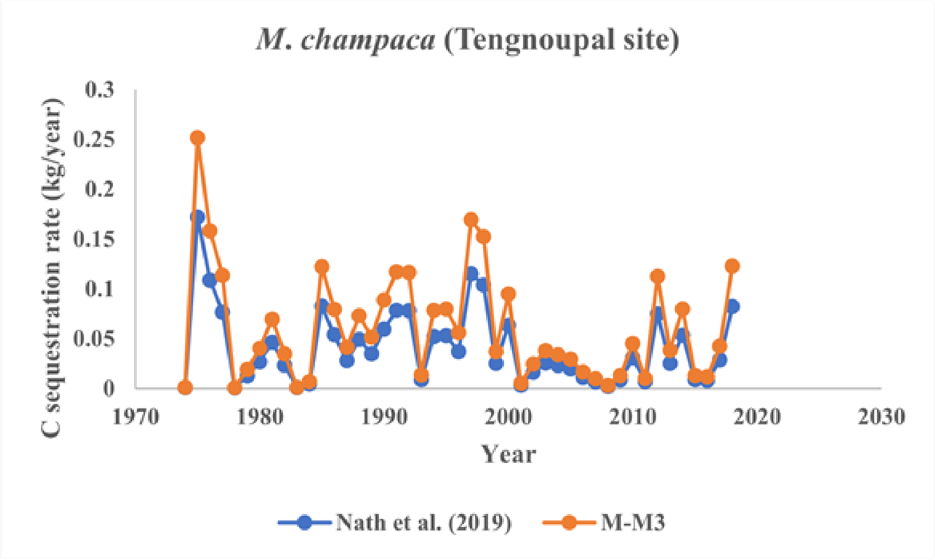


Figure 4.16. Annual C sequestration rate of *M. champaca* for Chandel and Tengnoupal study sites at various time span, C=carbon.

CHAPTER 5

Summary and conclusions

Forests play a crucial part in reducing the rising concentration of atmospheric CO_2 by sequestering in the living biomass, and they store higher amount carbon than any other terrestrial ecosystems. Since C sequestration rates vary with individual tree species and forest and therefore all species do not respond to environmental change at the same rate in space and time. Generally, trees are sensitive to climatic variables, and fluctuates in their ring width growth from season to season because of the direct or indirect effects of environmental factors. This yearly variation in growth provides a basis for monitoring past climatic and biological events. Moreover, tree ring studies help us to understand the effects of climate change on tree growth. Further, it is helpful for determining tree growth pattern which are crucial for C sequestration. Therefore, it is important to identify the important tree species for its potential in C accumulation in order to enhance sustainable forest management for future development strategies and help in mitigating global warming.

In the present study, the potential sites were selected in three districts (namely Tengnoupal, Chandel and Senapati at different altitudes ranging from ca. 400 m to 1300 m amsl) of Manipur. Due to variation in elevations, these sites had different climatic conditions. Annual growth of a tree is a significant criterion for dendrochronological studies. Selection of the tree species for this study was based on distinct growth forming rings, for example, *P. kesiya, T. ciliata* and *M. champaca.* The sampling sites for *P. kesiya* were selected from Chandel and Senapti districts; *T. ciliata* from Chandel, Senapati and Tengnoupal; and sampling sites for *M. champaca* were selected from Chandel and Tengnoupal districts.

A total of 62 cores from 31 trees were collected for *P. kesiya* from each sampling site i.e., Chandel and Senapati sites. For *T. ciliata,* 40 cores from 20 trees were collected from Tengnoupal site while 54 cores from 27 trees were collected each from Chandel and Senapati sites. And for *M. champaca,* 44 cores from 22 trees and 40 cores from 20 trees were collected from Chandel and Tengnoupal sites, respectively. These collected cores were processed following the procedure of Stokes and Smiley (1968) by mounting the cores on wooden grooves using glue. The surface of the core was flattened with the razor blade and polished the surface using various grades of sandpapers for clarity/visibility of the rings. The processed sample cores were analysed visually under the microscope and manually dated to the calendar year by counting the rings and marking a single dot for every decade count. Further, the ring width measurement was taken using the Windendro Software. Using the program COFECHA, the cross-dating measurements were verified. The COFECHA results showed high inter-series corelation with the master series for all the tree species of different sites. The SIC of *P. kesiya* were 0.350 and 0.367 for Chandel and Senapati sites; *T. ciliata* revealed a SIC of 0.397 (Chandel site), 0.336 (Senapati site) and 0.342 (Tengnoupal site) respectively; while *M. champaca* showed a SIC of 0.334 and 0.366 from Chandel and Tengnoupal sites, respectively.

In addition, tree ring width chronologies of each species from different sites were developed using the program Arstan by standardising the raw tree width series which removes age related biological growth trend and stand dynamics while preserving the climatic variables. A total of seven tree ring-width chronologies were developed using the Arstan program which were: *P. kesiya* of Chandel site (37 years: 1982-2018 C.E.); *P. kesiya* of Senapati site (30 years: 1989-2018 C.E.); *T. ciliata* of Chandel site (35 years: 1984-2018 C.E.); *T. ciliata* of Senapati site (38 years: 1981-2018 C.E.); *T. ciliata* of Tengnoupal site (36 years: 1984-2019 C.E.); *M. champaca* of Chandel site (38 years: 1981-2018); *M. champaca* of Tengnoupal site (46 years: 1974-2019), respectively. All these tree ring chronologies had a Mean Sensitivity (MS) value closer to 0.2. The MS value of *P. kesiya* was 0.196 and 0.152, respectively from Chandel and Senapati sites, whereas the MS value of *T. ciliata* was 0.265, 0.253 and 0.223 from Chandel, Senapati and Tengnoupal sites. The MS value of *M. champaca* was 0.226 and 0.326 from Chandel and Tengnoupal sites, respectively. Since the MS value around 0.2 reflects the tree sensitivity to climate change, and thus, the studied trees had the potential for dendrochronological studies.

Age of the trees were directly estimated by counting the rings from the tree cores extracted from the breast height. The studied tree samples from various sites had a varying age ranging from 6 to 46 years. The age range of *P. kesiya* from

Chandel and Senapati sites were 16 to 37 years and 11 to 30 years, respectively. For *T. ciliata*, the age range were 13 to 35 years, 6 to 38 years and 10 to 36 years for Chandel, Senapati and Tengnoupal sites. Similarly, age range of *M. champaca* from Chandel and Tengnoupal sites were found as 10 to 38 years and 11 to 46 years, respectively. These results imply that the studied trees are of young age. In community owned forest, mature trees are usually log mainly for its timber values for construction purpose. As a result, more young trees are ample in this forest types as compared to the forest under reserved by Forest department.

The growth pattern of the trees was estimated based on basal area increment (BAI) following the method of Biondi (1999). The BAI analysis shows that growth trend of *P. kesiya* of Chandel site showed an increasing trend over time while *P. kesiya* of Senapati site showed increasing trend at the initial stage and then gradually declined over time which may be attributed to the competition of resources among the trees due to increasing tree age and sharing the same niche in the study site.

The BAI trend of *T. ciliata* observed an increasing trend over the years though highest growth at the initial age followed by sharp declined in Chandel and Tengnoupal sites. Similarly, the BAI trend of *M. champaca* at Chandel site was found to increase over the years. However, *M. champaca* at Tengnoupal site observed gradual decreased in growth trend and later rises progressively in their common period. The increase in BAI in the initial stage may be due to the less core samples representing the initial BAI series as well as extracting cores from breast height might affected on wood formation of early years and other potential climatic factors and human disturbances might resulted in BAI fluctuations. The result of the BAI analysis showed that *T. ciliata* had a higher growth compared to other species because of its fast-growing nature that out compete the other species in growth. Also, *T. ciliata* revealed its fastest growth in the Chandel site. All the species from various sites shows gradual increase in growth trend in their common period which indicates that the trees are still young and at their growing stage. Forests are dynamic ecosystems that are delicately balanced through the interaction of many different ecological components and processes and thus, they are vulnerable to changes in both abiotic and biotic disturbances. This study suggests for future research into the growth-restricting environmental variables, human influence, and radial growth and BAI for these species so as to better understand the growth dynamics of the species. The knowledge will be useful for a better understanding of the species capacity to store C in the changing climate condition.

Best fit allometric model was developed for the estimation of aboveground biomass of *P. kesiya, T. ciliata* and *M. champaca* through non-destruction method using the correlation and regression method between aboveground biomass (AGB) and DBH, tree height and wood density. A total of thirteen (13) allometric models developed using single predictor variables (DBH or height alone) and multiple predictor variables (i.e. DBH in combination with tree height and wood density). These models were subjected to statistics test in order to select the best fit model. The models having a value of greater coefficient of determination (adjusted R^2), lower value of sum of square error, root mean square error, Akaike's information criterion and mean absolute deviation were the best fit model. In addition, percentage of the relative errors were calculated to validate the accuracy of the model. All these statistical tests and relative errors provided the best fit model for each tree species to assess the aboveground biomass. The most suitable best fit allometric model for the estimation of biomass of *P. kesiya* was: $ln\text{AGB}=-3.7268+1.5908\ (ln\text{D}*\text{H})$ with adjusted R^2 of 888, *SSE* of 2.3786, *RMSE* of 0.2326, *AIC* of -130.178, *MAD* of 0.1896 and relative error (-4.06%). However, best fit model for *T. ciliata* was: $ln\text{AGB}= -2.0311+1.4858\ (ln\text{D}*\text{H}*\text{WD})$ with adjusted R^2 of 882, *SSE* of 3.6316, *RMSE* of 0.2642, *AIC* of -145.079, *MAD* of 0.191696 and relative error (-1.30%). And the best fit model for *M. champaca* was: $ln\text{AGB}=-2.1868+0.9145\ (ln\text{D}^2*\text{H}*\text{WD})$ with adjusted R^2 of 0.884, *SSE* of 2.0939, *RMSE* of 0.2558, *AIC* of -88.7259, *MAD* of 0.175141 and relative error (-1.25%). The selected best fit models for each species in this study were highly significant ($p<0.001$) statistically. Therefore, they can be used as species-specific allometric models to assess the aboveground of *P. kesiya, T. ciliata and M. champaca* for the region. The development of species-specific allometric models represents a substantial improvement over using general allometric models developed for other species to estimate the biomass of a species accurately. Such species-specific models will be helpful in analysing and tracking the global C cycle.

The standardized tree ring widths developed using Arstan programme were used for estimation of aboveground biomass and C stock by employing the suitable allometric model. Allometric model develop for NE, India (Nath et al., 2019) and the model generated in present study were used for estimation of aboveground biomass. The tree diameter was estimated from the annual radial growth of the tree cores following the method proposed by Pompa-Garcia et al. (2018). The values of AGB, C stock and sequestration rate estimated using the allometric model (model using the diameter alone) developed in this study were higher for *P. kesiya* and *M. champaca* to the values estimated using the Nath et al. (2019). However, in case of *T. ciliata* the estimated values were lower for AGB, C stock and sequestration rate using the allometric model developed in this study.

The estimated mean C stock using the study developed model for *P. kesiya* are: 4.32 kg year^{-1} tree^{-1} (Chandel site) and 4.53 32 kg year^{-1} tree^{-1} (Senapati site); for *T. ciliata* are: 0.94 kg year^{-1} tree^{-1} (Senapati site), 0.88 kg year^{-1} tree^{-1} (Chandel site) and 0.78 kg year^{-1} tree^{-1} (Tengnoupal site); and for *M. champaca* are: 4.23 kg year^{-1} tree^{-1} (Chandel site) and 4.41 kg year^{-1} tree^{-1} (Tengnoupal site). The equation given by Nath et al. (2019) estimated mean AGB for *P. keisiya* are: 2.65 kg year^{-1} tree^{-1} for Chandel site and 2.78 kg year^{-1} tree^{-1} for Senapati site; and AGB for *T. ciliata* are: 2.99 kg year^{-1} tree^{-1} for Senapati site, 2.79 kg year^{-1} tree^{-1} for Chandel site and 2.46 kg year^{-1} tree^{-1} for Tengnoupal site; and AGB for *M. champaca* are: 2.78 kg year^{-1} tree^{-1} for Chandel site and 2.91 kg year^{-1} tree^{-1} for Tengnoupal site, respectively. The mean AGB and C stock of *P. kesiya* and *M. champaca* were underestimated while that of *T. ciliata* were overestimated when using the equation of Nath et al. (2019) when compared with the equation developed for species-specific in the present study which may be due to the changes in soil and environmental conditions causing variation in the tree radial growth.

The study observed that the aboveground biomass and C stock of *T. ciliata* was higher in the Senapati site than Chandel and Tengnoupal sites. Though the differences between Chandel and Senapati sites were not significant, however, significance ($P \leq 0.05$) difference was observed between the Senapati and Tengnoupal sites. The significant differences in these two districts may be because of the variation in altitude and climatic conditions which affects the tree growth rate. Further, the AGB and C stock of *P. kesiya* were higher in the Senapati site than the Chandel site. The higher biomass and C stock in the former may be because of the management practices like control fire of understory vegetation to make the availability of the nutrients locked into plant biomass. Any management efforts taken up enhances the biomass yield and C storage and burning of understory affects the tree growth and surges the C stock density (Wade et al., 2010; Wu et al., 2013).

The AGB and C stock of *M. champaca* were found lower in the Chandel site as compared to Tengnoupal site. The presence of large and older trees and favorable environmental conditions in the Tengnoupal site has largely contributed to significantly higher biomass and C accumulation. In the present study, *T. ciliata* and *M. champaca* had greater biomass and C stocks than that of *P. kesiya*. This is because of the fast-growing nature of the former compared to later.

This is the first study in Manipur to use the tree rings approached to describe the aboveground biomass C accumulation at the individual trees level. Tree ring studies provide historical tree growth information at spatio-temporal resolution, and the information is potentially useful to produce better estimates of the magnitude and stock of C and nutrients. This study is useful in enhancing better management strategies for the sustainable management of forests and help in mitigation of the climate change. This study is helpful to the forest managers and policy makers to project C budget in these forest ecosystems and manage them more effectively in changing climate.

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PHOTO PLATES

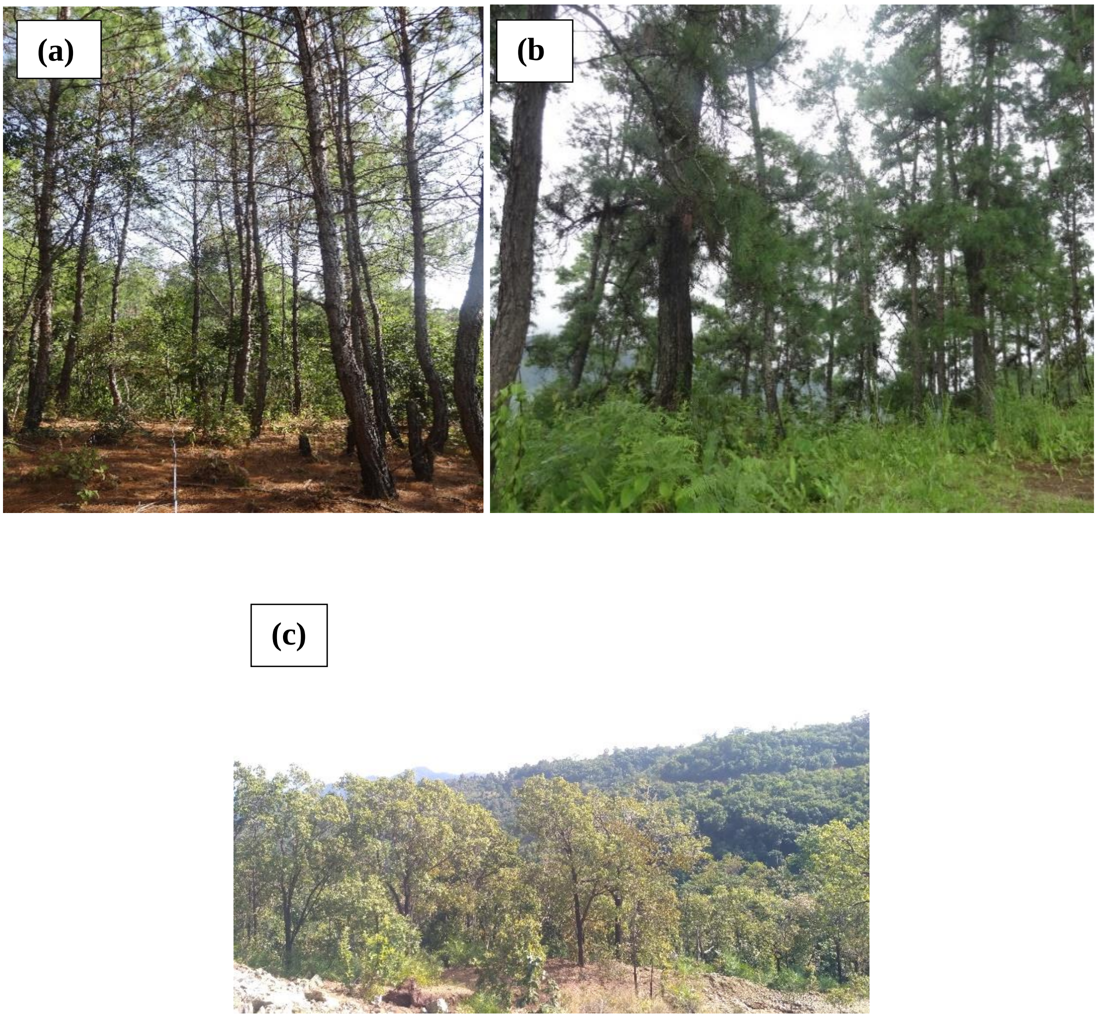

Photo plate 1: Study areas: (a) Chandel site, (b) Senapati site and (c) Tengnoupal site

Photo plate 2: Coring of the sample trees using the Haglof Increment borer.

Photo plate 3: Extracted cores of the sample trees.

Photo plate 4: Extracted cores kept in labelled plastic straw.

Photo plate 5: Mounting of cores on the wooden groove using the water base glue.

Photo plate 6: Flattening and sanding of the cores.

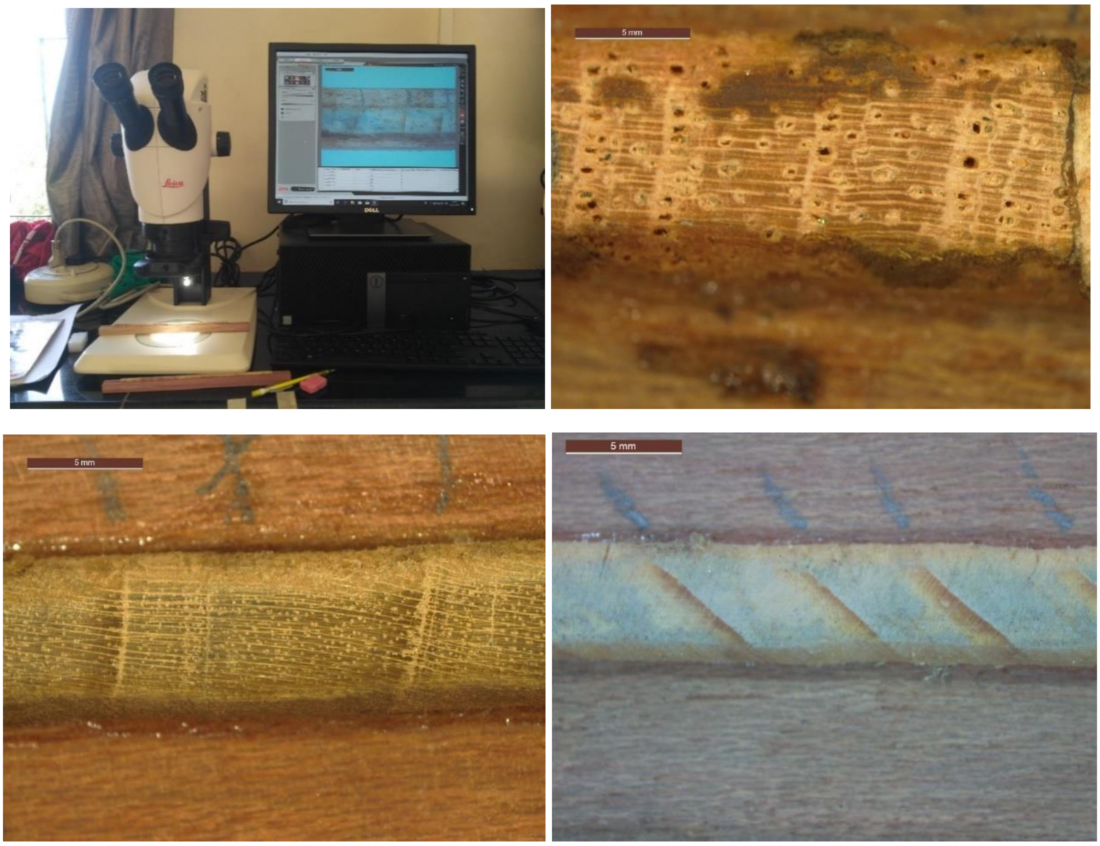

Photo plate 7: Tree cores under leica microscope.

Photo plate 8: Soil sample analysis for carbon estimation.

Photo plate 9: Ash of the cores for estimation of carbon concentration using dry ashing method.

Photo plate 10: Climbing trees for measuring the diameter at different heights of the tree.

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LIST OF PUBLICATIONS

1. Monsang, N. P., Upadhyay, K. K. and Tripathi, S. K. (2023). Dendrochronology based growth pattern analysis of *Toona ciliata* M. Roem in Northeast India. Environment and Ecology 41 (1C): 659-665.
2. Monsang, N. P., Upadhyay, K. K. and Tripathi, S. K. (2023). Girth-volume based allometric model for biomass estimation of Magnolia champaca (L.) Baill. ex Pierre in Manipur, Northeast India. Vegetos: 1-9.
3. Monsang, N. P., Singh, N. S., Upadhyay, K. K. and Tripathi, S. K. (2023). Changes in Soil Physico-Chemical Properties in different Land Use Systems of Manipur, Northeast India. Indian Journal of Ecology 50(4): 918-925.
4. Monsang, N. P., Lalremsang, P. and Upadhyaya, K. (2019). Allelopathic effect of *Dendrocalamus longispathus* Kurz and *Schizostachyum dullooa* gamble on maize and soyabean crops. Journal of Experimental Biology and Agricultural Sciences, 7(6): 536-544.

Publication in Book Chapter

1. Monsang, N. P. and Tripathi, S. K. (2019). Studies on Ethno-medicinal Plants used by Tribes of Chandel District, Manipur, pp. 195-201. Eds. S.K. Tripathi, Kalidas Upadhyay and Nagaraj Hegde, Medicinal Plants of India: Conservation and Sustainable Use. Today and Tomorrow's Printers and Publishers, New Delhi.
2. Monsang, N. P., Tripathi, S. K., Singh, N. S. and Upadhyay, K. K. (2021). Climate Change and Mizoram: Vulnerability Status and Future Projections, pp. 33-40. Ed. Sati, V. P., Mizoram: Environment, Development, and Climate Change.Today and Tomorrow's Printers and Publishers, New Delhi.

PAPER PRESENTED IN CONFERENCE/SEMINAR

1. Changes in soil carbon and nutrients under different forests in Manipur, Northeast India. International conference on "Novel approaches in Life Sciences-2022. Organized by Department of Botany and IQAC Organizes,

Guru Nanak Khalsa College of Arts, Science & Commerce, Matunga, Mumbai.

2. Assessing carbon sequestration in *Pinus kesiya* Royle ex Gordon from Manipur, Northeast India. National seminar (Hybrid Mode) on Strengthening Environment Health: Role of Society, Science & Technology-2022. Organized by Department of Rural Technology and Social Development, Guru Ghasidas Vishwavidyalaya, Bilaspur (C. G.).
3. Determining growth pattern of Pinus kesiya using dendrochronology in Manipur, Northeast India. International conference on biodiversity, biogeochemistry and ecosystem sustainability in changing environment-2023. Jointly organized by Department of Forestry, Mizoram University, Aizawl and Indian Ecological Society.

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Approval of Research Proposal

1.	Departmental Research Committee	: 22.03.2019
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3.	School Board	: 26.04.2019

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ABSTRACT

DETERMINING CARBON SEQUESTRATION POTENTIAL OF IMPORTANT TREE SPECIES FROM DIFFERENT ECOLOGICAL REGIONS OF MANIPUR USING DENDROCHRONOLOGY

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

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DECEMBER, 2023

ABSTRACT

DETERMINING CARBON SEQUESTRATION POTENTIAL OF IMPORTANT TREE SPECIES FROM DIFFERENT ECOLOGICAL REGIONS OF MANIPUR USING DENDROCHRONOLOGY

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Introduction

Dendrochronology is the science which analyse the annual growth patterns of tree rings and infer useful information about tree age, annual growth rate, past abiotic and biotic events. A. E Douglass is known as the father of dendrochronology (Schweingruber, 1988). He was the first to use cross-dating, a technique that assigns specific calendar year for each tree ring by matching similar ring-width patterns among various trees (Studhalter, 1956). Dendrochronology has been widely applicable in assessing the historical state of environment and vegetation pattern because of the ability of tree rings to preserve historical events. In addition, dendrochronology has been used in various fields of studies viz. archeological studies emphasising wooden dating from archeological sites, climatologic studies understanding the past climatic variations and geomorphological studies to analyse the geomorphological processes related to flood, landslide, river associated vegetation developments (Shikangalah, 2020). Dendrochronology has achieved increased prominence in the field of research with due appreciation to the efforts and contributions made by Douglass and his students together with European equivalents like Bruno Huber, Walter Liese, Bernd Becker, Dieter Eckstein, and Fritz Schweingruber (Speer, 2010). (Speer, 2010).

Dendrochronological studies are limited to those tree species with growth rings. Trees develop one growth ring per year, which represents the growth of the same year, including early and latewoods that vary in thickness and density according to the effect of many internal and external causes (Sajad and Ahmed, 2021). The analysing of tree ring offers significant information on the diameter growth rates, stand age, and longevity, which is used to develop long-term sustainable forest management plans (Xu et al., 2019; Baral et al., 2022). For example, lifespan of the spruce stands of boreal forests is required to understand the growth patterns, mortality mechanisms, and natural succession (Castagneri et al., 2013). Dendrochronological methods, which count the annual rings in increment cores or stem cross sections, as well as other approaches like repeated diameter measurements and radiocarbon dating, can be used to estimate the age of trees.

However, the latter attempts were not successful to offer reliable results for age dating except for dendrochronology revealing the most dependable and accurate method for age dating in presence of tree annual rings (Worbes, 2002). A tree ring width series may be utilised in recognising signature rings which aid to determined tree age (Ogden, 1981) and growth pattern of aged tree which play a crucial purpose in carbon (C) accumulation (Lanner and Connor, 2001; Johnson and Abrams, 2009; Köhl et al., 2017). The estimation of tree age is a potential strategy for identifying suitable time for harvesting trees and regeneration which will aid ecologists on acquiring forest age structure and time for germination at individual tree species level. Further, forest stand age holds an important measure for development of tree growth model, effective time for management events and harvesting that together providing invaluable data for sustainable forest management and conservation strategies (Schumacher et al., 2020).

Tree ring studies have been used to produce long-term growth data in order to identify the pattern of tree growth changes as they can potentially produce annual growth data dating back to when a tree was first planted (Bowman et al., 2013; Upadhyay and Tripathi, 2019). Ecological factors including precipitation, temperature, latitude, altitude, and even the species type have a considerable impact on the establishment of annual rings in trees (Ols et al., 2018; Sajad and Ahmed, 2021). Absolute stand growth values expressed as basal area increment (BAI) that would help researchers to better grasp how temperature impacts radial development in trees. BAI is crucial in ecological and physiological research as it explains the changes in biomass accumulation rates along bioclimatic gradients. It is also used to forecast forest yield and determine the best silvicultural practises for forest management (Bowman et al., 2013; Sanchez-Huerta and Pompa-García, 2014). The tree ring analysis for the determination of tree age and growth is very economical, rapid and reliable method which is useful for forest management **(**Boninsegna et al., 1989)**.** As a result, numerous dendrochronological investigations have been carried out to track the growth pattern of trees across time.

Ecosystem net primary productivity, carbon and nutrient cycling are all significantly impacted by plant biomass, which is a crucial component of ecological processes (Ostadhashemi et al., 2014; Nyamjav et al., 2020). Further, it is crucial for reducing the global C cycle by storing atmospheric carbon dioxide (CO2) for a longer time (Brahma et al., 2021). Allometric equations are most widely used and appropriate method of biomass estimation because they are effective, economical, and non-destructive (McClaran et al., 2013; Han and Park, 2020). Various local and general allometric models based on multi-species, species-specific, or site-specific data have been developed for various forests and ecological zones. General allometric equations are typically inappropriate as they may result in large errors in biomass calculations in comparison to regional or local equations (Chave et al., 2005; Heiskanen, 2006). In addition, allometric models also differed by region and species, and these variations were influenced by a variety of variables, including topographic circumstances, soil types, tree ages, species composition, and climate fluctuations (Gentry, 1982; Alexandrov, 2007, Brown and Lugo, 1992; Laurance et al., 1999; Slik et al., 2010; Baraloto et al., 2011; Macauley et al., 2009). As such, it is desirable to employ species-specific allometric models to avoid significant mistakes brought on by species.

Radial growth of a tree is an indication of its health which indicates C flow into forest ecosystems. The tree growth rate may vary over time due to many internal and external causes, and it decreased with aged (Sullivan et al., 2016). As a result, variations in the growth rates of forest trees may significantly affect the global C cycle because these variations influence their net C intake or loss (Zuidema et al., 2020). Annual C sequestration rate can be determined either by the tree ring analysis or repeated measurement of tree diameter over time through the set up of long-term research plots. Further, tree ring analysis are more efficient than repeated measurement of tree diameter over time by having easy access to information on forests' radial growth, carbon stock and sequestration rates (Fritts, 1976; Chhukan, et al., 2018) and aids to reduce the high transaction costs associated with maintaining long-term research plots (Gebrekirstos et al., 2014). Recently, tree rings have been used to analyse C sequestration trends in addition to their earlier usage to study trends in aboveground net primary productivity (Acher et al., 2002; Liu et al., 2012). Many dendrochronological researches are being conducted in India with an emphasis on historical reconstruction of tree growth rates and the relationship between climate and growth; however, there are no studies to determine the potential of dendrochronology in assessing C sequestration rates. As such, this study employing dendrochronology for assessing annual C stock and sequestration rate will be helpful in gaining knowledge on developing strategies to boost forest resilience in the face of anticipated climate change. Dendrochronology methods that offer annual growth rate will be useful in assessing the health and productivity of individual trees and their potential to sequestration C. Further, the developed allometric model will be helpful in precise estimation of tree species-specific biomass and C stock which ultimately help in the sustainable forest management.

Objectives

The objectives of the study are given as below:

1. To determine age and growth patterns of the important tree species using dendrochronology.
2. To develop allometric models relating girth and biomass for the selected tree species for the estimation of above ground biomass and carbon stock.
3. To assess carbon sequestration potential of important trees from different ecological regions of Manipur using dendrochronology.

Materials and methods

Study sites

The study was carried out at the forests of Japhou in Chandel district; Maram in Senapati district and Saibol in Tengnoupal district of Manipur. The Tengnoupal district is south-eastern region of Manipur, whereas, Chandel and Senapati are in the southern and northern regions of the state, respectively. The study site of the Chandel is located at 24˚19`05``N, 24˚19`58``N latitude and 94˚00`31``E, 94˚00`30``E Longitude. Study area of Maram in Senapati district is located at 25˚23`51``N, 25˚24`43``N latitude and 94˚05`52``E, 94˚06`15``E longitude. The other study site of Tengnoupal district is situated at 24˚28`31``N latitude and 94˚21`04``E longitude.

Present study sites were selected based on climatic variability mainly on the variations in mean temperature. The mean annual temperature variations in these sites were: 2-3 ˚C with a marginal annual precipitation difference of about 40 mm between Chandel and Senapati sites and about 150-200 mm between Tengnoupal and Chandel and Senapati sites. The soils of the study sites were analysed for its physico-chemical properties. The soil texture was analysed using following the method prescribed by Bouyoucos (1962), soil moisture content (SMC) by Verstraeten et al. (2008), soil pH was measured using a digital pH metre (Bandyopadhyay et al., 2012). Soil organic carbon (SOC) was assessed through Walkley and Black method (1934). Available nitrogen (N) was determined following (Subbiah and Asija, 1956), available phosphorus (P) was estimated using the Bray and Kurtz technique (1945), and exchangeable potassium (K) was following (Jackson, 1973).

Sampling and analysis of the tree and cores

Using the Haglof increment corer, cores from healthy trees of *M. champaca*, *T. ciliata* and *P. kesiya* were randomly collected at breast height (1.37 m) with typically two cores per tree. There were 62 cores collected from 31 trees of *P. kesiya* from each Chandel and Senapati sites, respectively. And 50 cores from 25 trees, 54 cores from 27 trees and 40 cores form 20 trees of *T. ciliata* were collected from Chandel, Senapati and Tengnoupal sites, respectively. Further, 44 cores from 22 trees and 40 cores from 20 trees of *M. champaca* were collected for Chandel and Tengnoupal sites, respectively. The cores were immediately placed in the plastic straw pipe after being properly given labelled. The sample cores were processed and analysed using a standard dendrochronological method (Speer, 2010). The ring widths were measured using the Windendro Software with accuracy of the nearest 0.001 mm. Using the quality control computer application COFECHA, the errors in the cross-dating were examined for those measured ring width (Holmes, 1983; Grissino-Mayer, 2001). Each raw ring width series was standardised using the computer programme ARSTAN (Cook, 1985), which also preserved the climate and environmental variables while removing the age-growth trend and stand dynamics that appeared as noise in the dendrochronological analysis (Fritts, 1976).

Estimation of tree age and growth pattern

The age of trees was directly estimated from cores by counting the number of rings from the inner pith, which was counted as 1 year age from the pith to the bark. Further, measured ring width data were calculated into tree BAI following the equation given in Biondi (1999) and Baral et al. (2022) for estimation of growth pattern

Modelling of allometric equations

Allometric equations were developed through regression analysis. Variables of both axes (x represent aboveground biomass) and (y representing DBH, wood density and tree height) were log natural (*ln*) transformed to avoid heteroscedasticity in the regression analysis. Best fit allometric equations were selected based on level of significance of correlation coefficients and later the best fit selection models were based on highest co-efficient of determination (adjusted R^2 closer to 1) and other parameters [i.e. high *F* value, lower value of root mean square error (*RMSE*), sum of square error (*SSE*), mean absolute deviation (*MAD*) and akaike's information criteria (*AIC*)]. The prediction error of the best fitted models was examined using the percentage of relative error (RE%).

Dendrochronology approach for estimating tree biomass, C stock and sequestration

Tree biomass were estimated using the allometric equation given by Nath et al. (2019) and as well as using the model developed in the present study. In order to estimate diameter from the tree ring, the annual radial growth value was multiplied by 2, taking into account that stems are perfectly round (Pompa-Garcia et al., 2018). The C concentration was estimated using CHN analyser and ashing method. C stock was estimated by multiplying the biomass and C concentration. The annual C sequestration rate was calculated as the difference of total C content between two consecutive years divided by their corresponding age. Descriptive statistical tools were employed to calculate mean and standard deviation of the datasets. One-way ANOVA and t- test were performed to compare for significant differences ($p < 0.05$) of biomass, C stock and C sequestration rate for various tree species between the sites.

Results and discussion

The soils of the study sites were sandy loam to loamy sand in texture and had acidic soil with a pH ranged from 4.3 to 5.3. The highest value (1.04 g cm^3) of BD was observed in the Chandel Lithocarpus Forest (CLF) and Senapati Quercus Forest (SQF) while the lowest (0.85 g cm^3) was found in Tengnoupal Dipterocarp Forest (TDF). Soil moisture content was highest (37.25%) in TDF and lowest (29.66%) in Chandel site of Mixed Pine Forest (CMPF). The WHC ranged from 55.5 to 84.9%, with Senapati site Pine plantation (SPP) and CLF recording the highest and lowest WHC, respectively. SPP had the highest value (30.2 Mg ha$^{–1}$), whereas CMPF had the lowest value (6.6 Mg ha$^{–1}$) of SOC. The available N ranged from 282.81 to 438.65 kg ha^{-1} to 30 cm soil depth. High P concentrations were observed at SPP (37.64 to 54.75 kg ha^{-1}) and low P was in SQF (12.74 to 15.14 kg ha^{-1}). The highest K values were observed at CLF (187.13 to 236.20 kg ha^{-1}) which may be due to the input of high amount of leaf litter from very deep trees.

The COFECHA result showed high correlation with the master series of each species and/or site, with high series inter–correlation (SIC) that is above conventional threshold limit of 0.321. The value of SIC for *P. kesiya* was 0.350 and 0.367 for Chandel and Senapati sites, respectively. SIC for *T. ciliata* was 0.397, 0.336 and 0.342 for Chandel site, Senapati site and Tengnoupal site, respectively. The SIC value for *M. champaca* was 0.334 and 0.366 for Chandel and Tengnoupal sites, respectively. The ring width chronologies developed using the arstan programme indicated 30-46 years chronologies for different species (i.e. *P. kesiya*, *T. ciliata* and *M. champaca*). These results showed the studied trees were young, and had higher variation in their radial growth. The subsample signal strength (SSS) value for *P. kesiya* is 0.882 and 0.927 for Chandel and Senapati sites, and 0.888, 0.856 and 0.856 for *T. ciliata* of Chandel, Senapati and Tengnoupal sites, respectively. However, the SSS values for *M. champaca* for Chandel and Tengnoupal sites were 0.885 and 0.858, respectively.

The maximum age was observed as 46 years in *M. champaca* from Tengnoupal site followed by 38 years in both *T. ciliata* and *M. champaca* from Senapati and Chandel sites, respectively. The minimum age was recoded as 6 years in *T. ciliata* from Senapati site. Tree age analysis indicates that the trees were still in juvenile phase of their growth. In addition, younger age of tree ring chronologies was observed in various trees reported from North-eastern forests of India. Thomte et al. (2020) observed 39 years tree-rings chronologies (1980-2018 C.E.) of *P. kesiya*, obtained from Sielmat, Manipur (Thomte et al., 2020). In BAI analysis, the growth of the *P. kesiya*, *T. ciliata* and *M. champaca* showed an increasing trend in their growth over the time. In addition, BAI trend of all this species showed a consistent growth increment in their common period with slight fluctuations. This increasing BAI growth trend in this study showed that the trees in the present sites were in juvenile states of their growth. Since the young trees usually show increasing growth rate which reach a plateau formation during maturity with a subsequent fall with age (Castagneri et al., 2013).

Following a non-destructive methodology, an allometric equation for estimating the aboveground biomass of *P. kesiya*, *T. ciliata*, and *M. champaca* was developed, using diameter at breast height, tree height, and wood density as independent variables. The best allometric model for AGB estimation of *P. kesiya* was: $ln\text{AGB} = -3.7268 + 1.5908\ (ln\text{D*H})$ with highest R^2 of 0.888 and lower *RMSE* value of 0.2326, *SSE* of 2.3786, *MAD* of 0.190, *AIC* of -130.18 and had low relative error (-4.06%). The best fit model for *T. ciliata* was: $ln\text{AGB} = -2.0311 + 1.4858\ (ln\text{D*H*WD})$ with highest R^2 of 0.882, *RMSE* of 0.2642, *SSE* of 3.6316, *MAD* of 0.192, *AIC* of -145.08 and relative error (-1.30%). Furthermore, the best fit model for *M. champaca* was: $ln\text{AGB} = -2.1868 + 0.9145\ (ln\text{D}^2\text{*H*WD})$ with highest adjusted R^2 of 0.884 and lower *RMSE* value of 0.2558, *SSE* of 2.0939, *MAD* of 0.17514 and *AIC* of -88.73 and relative error (-1.25%).

The values of AGB, C stock and sequestration rate estimated using the developed allometric model in this study were higher for *P. kesiya* and *M. champaca* than the values estimated using the Nath et al. (2019). However, *T. ciliata* had estimated lower values in their AGB, C stock and sequestration rate using this developed allometric model. This is because of the use of various species pooled data from different part of northeastern region and changes soil and environmental conditions that caused variation in tree either in the radial growth, wood density or tree heights. Model developed in the present study estimated a mean C stock for *P. kesiya* as 4.32 kg year^{-1} tree^{-1} and 4.53 32 kg year^{-1} tree^{-1} for Chandel and Senapati sites. The mean annual C stocks for *T. ciliata* was 0.88 kg year^{-1} tree^{-1}, 0.94 kg year^{-1} tree^{-1} and 0.78 kg year^{-1} tree^{-1} for Chandel, Senapati and Tengnoupal sites, respectively. However, mean annual C stocks for *M. champaca* was 4.23 kg year^{-1} tree^{-1} and 4.41 kg year^{-1} tree^{-1} for Chandel and Tengnoupal sites, respectively. Similarly, the mean annual C sequestration rate of *P. kesiya* was 0.043 and 0.045 for Chandel and Senapati sites, respectively. However, mean annual C sequestration rate of *T. ciliata* was 0.013 kg year^{-1}, 0.013 kg year^{-1} and 0.010 kg year^{-1} for Chandel, Senapati and Tengnoupal sites, respectively. Mean annual C sequestration rate for *M. champaca* was 0.049 kg year^{-1} and 0.056 kg year^{-1} for Chandel and Tengnoupal sites, respectively. In comparison, equation using Nath et al. (2019) estimated mean annual C stock of *P. kesiya* as 2.65 kg year^{-1} tree^{-1} and 2.78 kg year^{-1} tree^{-1} for Chandel and Senapati sites, respectively. The mean annual C sequestration rate of *T. ciliata* for each study site (viz. Chandel, Senapati and Tengnoupal) was 0.037 kg year^{-1}, 0.038 kg year^{-1} and 0.029 kg year^{-1} respectively. In addition, mean C stock of *M. champaca* was 2.78 kg year^{-1} tree^{-1} and 2.91 kg year^{-1} tree^{-1} for Chandel and Tengnoupal sites, respectively. Similarly, *P. kesiya* from both Chandel and Senapati sites had comparable value of mean annual C sequestration rate i.e. 0.027 kg year^{-1} and 0.028 kg year^{-1}, respectively. In case of *M. champaca*, the mean annual C sequestration rate was higher in Tengnoupal site with 0.041 kg year^{-1} compared to Chandel site with a value of 0.03 kg year^{-1}.

Conclusion

The present study concluded that the studied trees were young and at growth phase. The growth pattern analysis based on BAI revealed a consistent growth increase over time suggesting healthy growth of trees in the area. Furthermore, observing fluctuations in BAI trend suggested that the growth may be sensitive to the climatic factors since tree ring chronology revealed the young age stand which are highly sensitive to changes in climatic conditions. The choice of allometric models has a substantial impact on biomass estimate. Generic allometric models led to bias in the calculation of forest biomass because of changes in tree species and stand density, forest location, and forest age. As such, the allometric model developed in the present study for each species is appropriate for species-specific biomass estimation in the state Manipur. This is because species-specific allometric model provide accurately estimate forest biomass, evaluate the C content of aboveground tree components for emission trading, and support sustainable forest management.

This is the first study in Manipur to describe the biomass C build up at the individual tree level using the tree-rings approach. Tree ring studies provide historical tree growth information at spatio-temporal resolution, and the information is potentially useful to produce better estimates of the magnitude and stock of C and nutrients. In present study, *T. ciliata* and *M. champaca* had greater biomass and C stocks than that of *P. kesiya*. Furthermore, in comparison of the sites, more biomass is allocated in the Senapati than Chandel and Tengnoupal sites which may be attributed to lower environmental temperature as a result of higher altitude of the former than later. Therefore, *T. ciliata* and *M. champaca* act as the species having greater potential for C sequestration. These species under well manage and given proper silviculture approaches will enhance its capability for greater C sink. This study is useful in enhancing better management strategies for the sustainable management of forests and help in mitigation of the climate change. This study is helpful to the forest managers and policy makers to project C budget in these forest ecosystems and manage them more effectively in changing climate.

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