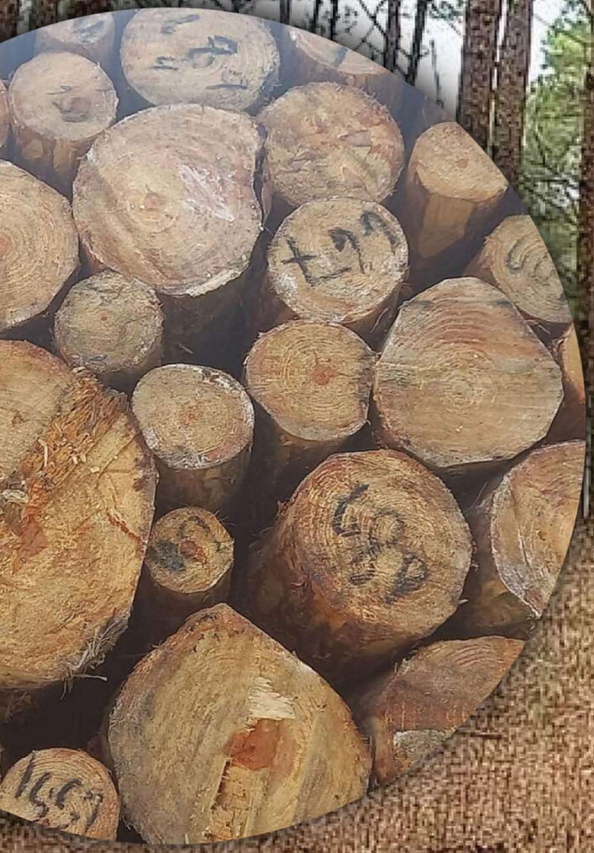
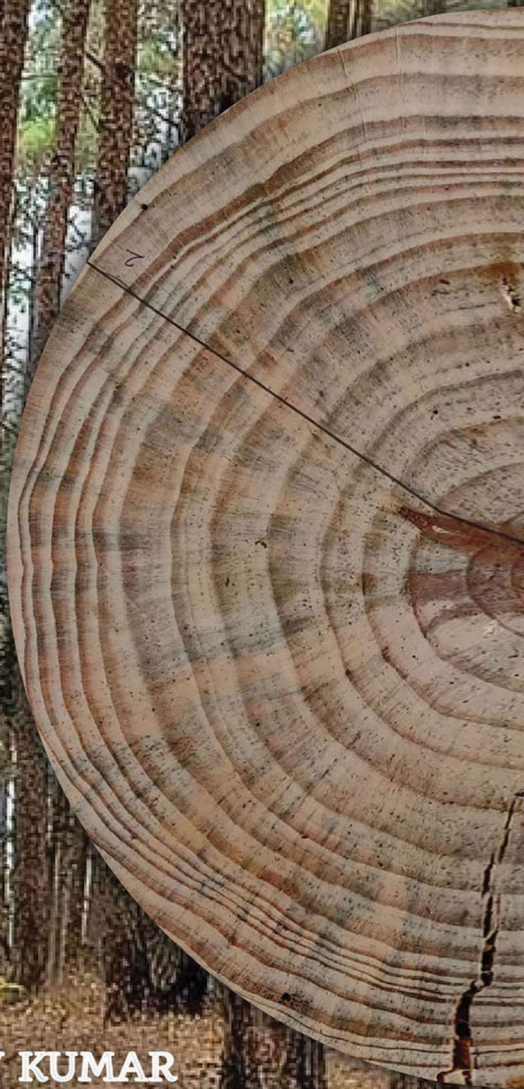
ROTATION AGE AND VOLUME ESTIMATION OF KHASI PINE IN MEGHALAYA
VOLUME-I





AJAY KUMAR
DINESH K. MEENA
HARISH C. CHAUDHARY
NITIN KULKARNI

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Ajay Kumar

Dinesh K. Meena

Harish C. Chaudhary

Nitin Kulkarni

ICFRE-RAIN FOREST RESEARCH INSTITUTE

(Indian Council of Forestry Research and Education)
Ministry of Environment, Forest and Climate Change
Government of India
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Shri Conrad K. Sangma
Hon'ble Chief Minister & Minister in-charge
Forest and Environment Department
Govt. of Meghalaya



FOREWORD

Meghalaya is blessed with a diverse range of forests. As per the India State Forest Report, 2021 more than 76% geographical area of the state is covered by forests, contributing about 2% of the total forest cover of the country. The forests in the state encompass deciduous and evergreen tropical forests, as well as sub-tropical semi-evergreen and subtropical pine forests.

These forests play a vital role in maintaining ecological balance, preserving biodiversity, and providing livelihoods for many communities. Hence, it is incumbent upon us to ensure their prudent management for the benefit of current and future generations.

Pinus kesiya (Khasi Pine) growing in and around the Shillong plateau mainly in Khasi and Jaintia Hills has economic value. It serves as a source of timber for various purposes, including construction, furniture-making, and paper production. Meghalaya is the largest supplier of Khasi Pine timber to wood-based industries in the north eastern region. However, the absence of a local volume equation for estimation and the absence of an established rotation age significantly hinder the implementation of proper sustainable management practices for Khasi Pine forests.

I am extremely pleased to learn that a collaborative effort between the Meghalaya Forest and Environment Department and the ICFRE-Rain Forest Research Institute (ICFRE-RFRI), Jorhat, Assam, has resolved this issue by developing local volume equations and calculated the rotation age. The findings are compiled into this user-friendly publication. I am sure that it will assist stakeholders in obtaining accurate volume estimations and determining the appropriate time for tree harvesting. The findings will offer a solution for the sustainable harvesting and management of Khasi Pine trees in the state.

I convey my heartiest congratulations to the Principal Chief Conservator of Forest, Working Plan, Research & Training and District Council Affairs, Forest and Environment Department, Meghalaya and Director, ICFRE-RFRI for providing desired joint leadership in this important endeavour, and compliment the entire team for timely completion of the assigned task, and commendable work done by them.

(Conrad K. Sangma)

Shri Pravin Bakshi, IAS
Commissioner and Secretary
Forest and Environment Department
Govt. of Meghalaya



MESSAGE

Khasi Pine is a crucial commercial species for Meghalaya, as its wood is utilized for timber purposes and serves as a raw material for wood-based industries. The increasing demand for timber in the region has intensified pressure on Khasi Pine forests. To alleviate this pressure and ensure the forest's sustainability, an effective management strategy is imperative.

It is evident that lack of a reliable volume estimation equation and established rotation period significantly hampers our ability to effectively manage our forest resources. These essential tools will enable us to accurately assess the quantity of timber available in our forests or determine the optimal timing for harvesting activities.

Such studies are important as such knowledge gaps may compromise the ecological integrity of our forests with negative impact on livelihoods of the communities dependent on them. Moreover, it poses a significant obstacle in our efforts to achieve long-term sustainability and resilience in the face of evolving environmental challenges.

I appreciate the joint efforts of the Working Plan, Research & Training wing, Forest and Environment Department, Meghalaya and ICFRE-Rain Forest Research Institute for equipping us with accurate volume estimation equations and well-defined rotation periods of Khasi Pine.

I hope that this collaborative effort will serve the purpose of planning and management of Khasi Pine in the state more effectively.

(Pravin Bakshi)

Shri R. S. Gill, IFS
Principal Chief Conservator of Forest & Head of Forest Force
Forest and Environment Department
Govt. of Meghalaya



MESSAGE

As stewards of our precious natural resources, it is incumbent upon us to ensure that our forest management practices are guided by sound scientific principles and best practices. Central to this endeavor is the development of a local volume equation, tailored to the unique characteristics of our forests, which will enable us to accurately estimate the volume of timber available for harvest.

Additionally, the establishment of a rotation period is essential for determining the optimal timing for harvesting activities, ensuring the long-term health and productivity of our forests.

The work of preparing a local volume equation and calculation of rotation age of *Pinus kesiya* (Khasi Pine) has been completed through collaborative efforts, leveraging the expertise of ICFRE-Rain Forest Research Institute scientists, and officials of Meghalaya Forest and Environment Department. By pooling our knowledge and resources, robust methodologies have been developed, grounded in empirical data which will reflect the ecological dynamics of our Khasi Pine forests.

I congratulate the ICFRE-RFRI team for dedication and commitment to this important work and the Working plan, Research & Training wing of our department. I look forward to more such collective efforts and making a positive impact on the management and sustainability of Khasi Pine and other forests in the State.

(R. S. Gill)

Shri Harish C. Chaudhary, IFS
Principal Chief Conservator of Forest, Working Plan,
Research & Training and District Council Affairs
Forest and Environment Department
Govt. of Meghalaya



MESSAGE

It is essential to implement sustainable forest management practices that prioritize the conservation of biodiversity, soil health, carbon sequestration, sustainability along with the well-being of local communities.

To initiate planning for the harvesting and management of any species, certain information such as regeneration, rotation age, yield, threats, economics, etc., is required, which has not been available for all tree species.

Pinus kesiya is a fast-growing evergreen tree species of pine native to Southeast Asia, dominant in the eastern and central part of the Meghalaya state. It is commercially important, utilized in various industries such as construction, furniture making, and paper production. However, the department faces challenges in accurately measuring the volume of growing stock, estimating carbon stock, and managing the demand and supply of Khasi Pine timber due to the lack of a local volume equation. Similarly, the absence of a rotation age criterion for Khasi Pine complicates sustainable harvesting practices. According to the norms of the Ministry of Environment, Forest and Climate Change, Government of India, the state can renew or issue new licenses to wood-based industries only based on the availability of timber, which necessitates data on growing stock, rotation age, harvesting limit etc. To address these challenges, the Forest and Environment Department, Meghalaya has approached ICFRE-RFRI, Jorhat for the development of a local volume equation and calculation of rotation age.

I appreciate the work of the ICFRE-RFRI for the successful completion of the task and bringing up a comprehensive user friendly document on Khasi Pine local volume table, Current Annual Increment (CAI), Mean Annual Increment (MAI), rotation age and maximum girth of rotation specific to the site in the state. This, I am sure, will go a long way in exploring further scope of joint and collaborative works.

(Harish C. Chaudhary)

सत्यमेव जयते

Dr. Nitin Kulkarni
Director

भा. वा. अ. शि. प. - वर्षा वन अनुसंधान संस्थान
ICFRE-RAIN FOREST RESEARCH INSTITUDE
भारतीय वानिकी अनुसंधान एवं शिक्षा परिषद्
Indian Council of Forestry Research & Education
पर्यावरण, वन और जलवायु परिवर्तन मंत्रालय , भारत सरकार
(Ministry of Environment, Forest & Climate Change, Govt. of India)
देववन, जोरहाट - 785001, असम / Deovan, Jorhat-785010 (Assam)



PREFACE

As custodians of our forests, it is incumbent upon us to ensure their long-term health and vitality. Effective management of our forest resources requires that our forest managers must equip ourselves with the necessary tools and methodologies.

A local volume equation tailored to the unique characteristics of our forests will enable us to accurately estimate timber volumes, facilitating informed decision- making in harvesting and resource allocation. Likewise, establishing a rotation period is essential for maintaining forest productivity and biodiversity, ensuring that future generations can continue to benefit from these invaluable ecosystems.

The collaborative efforts of the Meghalaya Forest and Environment Department and Scientists team of our ICFRE-RFRI have enabled us to develop a robust and scientifically sound local volume equation and find out the rotation period for Khasi Pine. This will be a significant step towards advancing sustainable Khasi Pine forest management practices. It demonstrates our commitment to conservation, biodiversity preservation, and the well-being of our communities.

It is a matter of great privilege and pride on our part to be involved in preparation of local volume equations and calculation of rotation period of Khasi Pine. I thank everyone involved in this venture for their significant contributions that ensured timely completion of the task leading to publication in the best possible form.

(Dr. Nitin Kulkarni)

वर्षा वन अनुसंधान संस्थान
RAIN FOREST RESEARCH INSTITUTE
भारतीय वानिकी अनुसंधान एवं शिक्षा परिषद्
Indian Council of Forestry Research & Education
(पर्यावरण, वन एवं जलवायु परिवर्तन मंत्रालय, भारत सरकार के अधीन एक स्वायत्त परिषद्)
देववन, जोरहाट - 785001, असम
(An Autonomous body of Ministry of Environment, Forests & Climate Change, Govt. of India)
Deovan, Jorhat- 785001, Assam



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(Dinesh K. Meena)

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Acronyms

AIC	Akaike's Information Criterion
CAI	Current Annual Increment
DBH	Diameter at Breast Height
DCA	District Council Affairs
EC	Electrical Conductivity
FAO	Food and Agriculture Organization
FIPI	Forest Inventory and Planning Institute
FSI	Forest Survey of India
GBH	Girth at Breast Height
IBM	International Business Machines
ICFRE	Indian Council of Forestry Research and Education
IFS	Indian Forest Service
ISFR	India State of Forest Report
MAD	Mean Absolute Deviation
MAI	Mean Annual Increment
MAPE	Mean Absolute Prediction Error
NBSS & LUP	National Bureau of Soil Survey and Land Use Planning
PCCF	Principal Chief Conservator Of Forest
RFRI	Rain Forest Research Institute
RMSE	Root Mean Square Error
R&T	Research and Training
SOC	Soil Organic Carbon
SPSS	Statistical Package for the Social Sciences
TOF	Trees Outside Forest
WP	Working Plan

EXECUTIVE SUMMARY

Forests play a critical role as ecosystems, offering ecological, economic, and social benefits. However, their sustainable management necessitates careful consideration, particularly in estimation of growing stock and determining rotation age. Rotation age indicates a forest stand's maturity for harvest, a decision pivotal in forestry management due to its multifaceted nature and varying maturity standards. Various rotations have been identified over the years, with biological rotation, which maximizes volume production, being the most applicable. This age is easily discerned from growth curves, marking the point of intersection between current annual increment (CAI) and mean annual increment (MAI) curves. The importance of rotation age spans timber production optimization, sustainable forest management, ecosystem health, and biodiversity conservation. It synchronizes harvesting with tree species' needs, ensuring a sustainable supply of high-quality timber while regulating timber extraction to prevent overexploitation, biodiversity degradation, and ecosystem service erosion.

Pinus kesiya, a dominant species in Meghalaya, exemplifies the importance of rotation age. Its economic and ecological significance in timber production, bioenergy, medicinal compounds, and carbon sequestration underscores the need for sustainable management. However, unsustainable harvesting practices prevail due to insufficient data on growth dynamics and optimum rotation age. To address this knowledge gap, the present research study was designed to estimate the relationship between tree diameter and stump diameter, assess growth increments, calculate rotation age, and prepare volume tables specific to *Pinus kesiya* in Meghalaya. This endeavour aligns with the overarching goal of achieving economic and sustainability objectives while preserving forest ecosystems, enabling informed decision-making for sustainable forest management. Embracing the principles of rotation age sets stakeholders on a path toward a future where forests prosper, biodiversity thrives, and the enduring benefits of nature are secured for generations to come.

Meghalaya, known as the 'abode of clouds' is a hilly state in Northeast India, bordered by Assam to the north and Bangladesh to the south. Home to the Khasi, Jaintia, and Garo tribes, it comprises three Autonomous District Councils – Khasi Hills, Garo Hills, and Jaintia Hills, with Shillong serving as the capital in the East Khasi Hills district. Covering 22,429 km^2, Meghalaya ranges in latitude from 25˚00’00’’N to 26˚10’00’’N and longitude from 89˚45’00’’E to 92˚45’00’’E. The altitude varies from 150 to 1961 meters above sea level. Meghalaya experiences a humid subtropical climate with high rainfall during summers, influenced by the Northeast winter and Southwest monsoon, with temperatures ranging from

2ºC to 36ºC. Rainfall is exceptionally high, with areas like Cherrapunji and Mawsynram receiving up to 14,189 mm annually. Soils in Meghalaya are classified into four types: Red Loam or Hills soils, Lateritic soils, and new and old alluviums, each with distinct characteristics. Forest cover spans 17,118.79 km^2, accounting for 76.32% of the state's geographical area, with a recorded forest area covering 9,496 km^2. The top five species found inside recorded forest area, the top five are *Schima wallichii, Pinus kesiya, Shorea robusta, Ficus* spp., and *Artocarpus heterophyllus* while in trees outside forests (TOF) are *Pinus kesiya, Pinus roxburghii, Schima wallichii, Areca catechu,* and *Pinus patula*. Forests in Meghalaya are classified into categories such as Tropical Wet Evergreen, Tropical Semi-Evergreen, Tropical Moist Deciduous, and Montane Subtropical Forests.

The study was conducted in West Jaintia Hills district focused on forests dominated by the Assam Subtropical Pine Forest type, with two types of sites selected for analysis. Soil nutrient status was assessed through systematic soil sampling, while *Pinus kesiya* trees were sampled destructively for measurements of diameter at breast height (DBH), height, and volume estimation. Soil analysis involved determining pH, electrical conductivity (EC), organic carbon, available potassium, nitrogen, phosphorus, sulfur, boron, and cationic micronutrients. For volume estimation of trees, frustums were sectioned and measured to calculate the volume of each sampled tree. Regression analysis was carried out to establish relationships between volume and DBH, and height in the form of volume equations, which were used in preparation of both local and general volume equations. Statistical comparisons were made to identify the best-fit models. Current annual increment (CAI) and mean annual increment (MAI) of *Pinus kesiya* trees were calculated to assess growth rates, with rotation age determined by plotting CAI and MAI curves using MS Excel software. Overall, data analysis involved SPSS version 26 statistical package and Microsoft Excel spreadsheet software, with a meticulous approach to soil and tree sampling, measurement, and analysis to understand the pine dominated forest dynamics in Meghalaya.

The study conducted in two pine forest bearing sites with different site quality or ecological settings, focused on assessing the characteristics and nutrient status of soil, as well as the growth dynamics of *Pinus kesiya* trees. The soil analysis revealed variations in soil depth, texture, and nutrient composition across different sites. In Site Quality-I, soil depths ranged from moderately shallow to moderately deep, spanning 60 to 100 cm, with gently to moderately sloping hills. The presence of rock fragments increased with depth, influencing soil texture, which ranged from loamy sand to sandy clay loam. Co-dominant tree species in

this site included *Myrica esculenta*, *Schima wallichii*, and others. Site Quality-II exhibited shallower soil depths, ranging from very shallow to shallow, with exposed rocks on the surface in many areas. Soil texture resembled loamy sand to sandy loam, with sparse distribution of tree species like *Myrica esculenta* and *Castanopsis* spp. Soil nutrient status analysis revealed acidic soil conditions at both sites, with pH ranging from 4.18 to 4.63, and low electrical conductivity indicating non-saline soil. Soil organic carbon content decreased with depth, with Site Quality-I exhibiting higher organic matter due to its finer texture and dense canopy cover. Available nitrogen decreased with depth, with higher uptake observed at Site Quality-I's upper surface soil due to high ground flora density. Phosphorus levels showed no significant difference between sites, while available potassium concentration was higher in Site Quality-I, possibly due to higher uptake by trees and lower organic matter in Site Quality-II. Significant differences were observed for micronutrients such as copper, boron, and magnesium at all depths.

Thirty-eight sample trees of *Pinus kesiya* were felled, with varying diameters at breast height (DBH) and heights recorded. Regression analysis established relationships between DBH and stump diameter, with the quadratic model proving to be the best fit. Local and general volume equations were developed to estimate tree volume based on DBH and height, with power models demonstrating the highest accuracy. Current annual increment (CAI) and mean annual increment (MAI) of *Pinus kesiya* trees were calculated, revealing variations based on site quality. Site Quality-I, considered a good site, exhibited lower rotation age and higher growth rates compared to Site Quality-II, classified as a poor site. The biological rotation age of trees in Site Quality-II was estimated to be 48 years, while in Site Quality-I, it was 27 years. Rotation girth at breast height was also estimated, with Site Quality-I showing a higher rotation girth compared to Site Quality-II. By integrating the findings of this research with existing knowledge and published studies, forest managers and policymakers can make informed decisions regarding forest management practices in Meghalaya. However, the study also highlights the need for further research incorporating long-term growth data and additional environmental variables to refine our understanding of *Pinus kesiya* growth dynamics and optimize forest management strategies for sustainable resource utilization. Overall, the research contributes valuable insights into the sustainable management of Pine-dominated forests in Meghalaya, facilitating informed decision-making and conservation efforts in the region.

Chapter 1
INTRODUCTION

1.1 Background

Forests, the lungs of our planet, are complex ecosystems that provide a myriad of ecological, economic and social benefits. Sustainable forest management is essential for maintaining these benefits and a key component of this management is to determine the rotation age of trees within a forest stand. The rotation age, pivotal in forestry, signifies the point at which a stand of trees reaches maturity for harvest, posing a longstanding challenge in sustainable forest management. This age reflects the culmination of efforts to determine the optimal time for harvesting forests to achieve maximum sustained output. Forestry's multifaceted nature, coupled with varying management objectives, results in diverse maturity standards based on factors such as size, age, and growth vigor of trees. Considered by forest economists as the foremost decision in management plans, the rotation age defines the period from stand establishment to final felling, typically measured in years (Bettinger and Li, 2009). With the continuous efforts made by many foresters over the past century, diligent efforts by foresters have identified various rotation types, including physical, silvicultural, technical, biological, rotations for maximizing income, and optimal economic rotation. Each rotation type represents a nuanced approach to forest management, reflecting ongoing endeavours to balance economic, ecological, and social objectives while ensuring the long-term sustainability of forest ecosystems.

The most applicable rotation in forestry, the biological rotation or the rotation of maximum volume production, which yields a maximum annual quantity of material is indicated by the age at which the mean annual increment (MAI) culminates. This rotation will yield the largest volume per unit area per annum and hence plays a significant role in the forestry sector. The biological rotation age can be easily determined from the age and growth curves in which the point of intersection of the current annual increment (CAI) and MAI is identified as the rotation age. The rotation of the highest income (revenue) and optimum economic rotation are the other rotations, especially described in terms of economic returns. The former is estimated irrespective of the capital value of the forest in which the age at which the mean annual net revenue per unit area of the forest is maximum is the rotation of the highest income. The financial or optimum economic rotation age yields the

highest net return on the invested capital at a particular rate of interest under which soil expectation value is expected to be the maximum (Prakash, 1986).

Estimation of rotation age is crucial for the proper management of forests and for moving the structure of a forest from an irregular state to a "normal" state. Although normal forests are rarely found in practice, the concept of a normal forest is often acknowledged in forest planning efforts and used to guide the development of forest plans (Bettinger and Li, 2009).

1.2 Importance of rotation age in forest management

Rotation age is the age at which a stand of trees reaches maturity and becomes eligible for harvesting. It is a dynamic parameter varying across different tree species, environmental conditions, and management objectives. The determination of rotation age involves a delicate interplay of ecological considerations, economic factors and social dimensions. Importance of rotation age determination can be summarized under following heads:

1.2.1 Optimizing Timber Production

The primary role of rotation age is evident in its impact on timber production. Harvesting trees at the right age is crucial for optimizing both the quantity and quality of wood. Premature harvesting can lead to suboptimal wood quality, while delayed harvesting may result in diminished economic returns. The dynamic nature of rotation age allows foresters to synchronize harvesting with the specific needs of different tree species ensuring a sustainable supply of high-quality timber (Prakash, 1986).

1.2.2 Sustainable Forest Management

Sustainable forest management is the cornerstone of responsible forestry practices. Rotation age serves as a linchpin in this paradigm by regulating the rate of timber extraction in harmony with the natural regeneration capacity of the forest. Striking this balance prevents overexploitation, degradation of biodiversity, and the erosion of ecosystem services (FAO, 2012). Sustainable forest management, guided by rotation age principles, safeguards the health and resilience of forest ecosystems for future generations.

1.2.3 Ecosystem Health and Dynamics

Forests, as intricate ecosystems, rely on a dynamic interplay of flora, fauna and environmental conditions. Rotation age influences the structural and functional aspects of the forest ecosystem. By strategically determining the age at which trees are harvested, foresters can shape the successional stages of the forest, influencing habitat availability

and ecological niches (Ashton and Kelty, 2018). This approach contributes to the overall health of the ecosystem supporting processes such as nutrient cycling, water purification, and carbon sequestration.

1.2.4 Biodiversity Conservation

Biodiversity, the hallmark of a healthy ecosystem finds support in the concept of rotation age. Different species thrive at various stages of forest development. By implementing rotation age strategies, foresters create a mosaic of stands at different successional stages, fostering diverse habitats for a wide array of plant and animal species (Koskela et al., 2007). This not only preserves biodiversity but enhances the resilience of the ecosystem to environmental changes. The careful consideration of rotation age in economic planning contributes to the long-term viability of forestry enterprises (Nghiem, 2014).

Rotation age in forest management is a testament to our ability to coexist with nature, recognizing that our well-being is intricately linked to the health of the ecosystems that surround us. By embracing the principles of rotation age, we embark on a journey towards a future where forests thrive, biodiversity flourishes, and the benefits of nature are perpetuated for generations to come.

1.3 Tree Volume Equations

Tree volume equations are the regression models depicting average volume of standing trees for specific species. Foresters and researchers usually estimate the total volume of tree stands or forest coupe for better management and assessment of site quality. For this, they require the average volume of a tree having dimensions within specified range. Through providing average volume of a standing tree, the volume equations provide great help to foresters and researchers in estimating total volume of trees in forest stands or TOF. Volume equations can be prepared for either total wood including branches or volume of merchantable timber part of trees. Volume equations can be prepared by measuring standing trees with the help of modern forestry tools or by measuring trees after felling. Most of the volume equations, in 19th and 20th centuries, were prepared by felling of trees which is a destructive procedure apart from being capital and labour consuming. Therefore, nowadays volume equations are being developed using non-destructive methods. On the basis of applicability, both volume equations are of the following two kinds:

1.3.1 Local volume equations

These equations are based on single variable i.e. DBH (Diameter at breast height) only. In these equations, volume is estimated by using DBH only. These equations are applicable to a small area where locality factors do not differ significantly; therefore, trees of the same diameter usually have the same height.

1.3.2 Regional/general volume equations

Being based on two variables i.e. DBH and height of trees, in these equations volume is estimated by using DBH and height. These are applicable to a large area where locality factors differ significantly, thereby leading to trees with the same diameter having different heights.

1.4 *Pinus kesiya* Royal ex Gordon

Pinus kesiya Royal ex Gorden, a member of the Pinaceae family, is commonly recognized as Khasi pine in the North East region of India. This rapidly growing pine characterized by three needles, stands out as the most prevalent subtropical Asian species within the Pinus genus. Its distribution spans across China, India, Laos, Myanmar (Burma), the Philippines, Thailand, and Vietnam thriving at altitudes ranging from 300 to 2700 meters above sea level (Armitage and Burley, 1980). In the Indian context, this species is naturally found in the eastern Himalayan regions, particularly in the northeastern states of Meghalaya, Arunachal Pradesh, Nagaland, and Manipur. Meghalaya, in particular, boasts an extensive subtropical pine forest concentrated in the central highlands of the state. Within this region, a narrow belt of pine forest extends along the high reaches of Khasi and Jaintia Hills, showcasing a pure association of *Pinus kesiya*. This association is complemented by scattered broad-leaved tree species including *Schima wallichii, Myrica esculenta, Alnus nepalensis, Emblica officinalis,* and *Quercus* sp.

Pinus kesiya exhibits a preference for shade-intolerant environment and thrives in wet subtropical to temperate climates with distinct dry and rainy seasons, maintaining humidity levels not less than 70%. Its adaptability extends to poor soils, provided they are well-drained. Natural regeneration is particularly robust on mineral soils (FIPI, 1996). As a tall tree with a straight cylindrical trunk, *Pinus kesiya* attains heights of 20-30 meters. The bark is characterized by thickness, appearing dark brown with deep longitudinal fissures, while the branches exhibit robustness and take on a red-brown hue from the second year. The needle-like leaves are dark green, typically arranged in fascicles of three, each measuring 15-20 cm in length. The fascicle sheath, persistent and 1-2 cm long, adds to the

distinct features of this species. Cones of *Pinus kesiya* are ovoid, measuring 5-9 cm in length and often curving downwards occasionally exhibiting slight distortion. The winged seeds, 6-7 cm long with a 1.5-2.5 cm wing, result from pollination in mid-spring, with cones maturing over an 18–20-month period (LeMay, 1996).

1.4.1 Utilization Potentials of *Pinus kesiya*

The economic and ecological significance of *Pinus kesiya* cannot be overstated. Valued for its timber of high quality and resin, this species also finds utility in charcoal production, fuelwood, essential oil extraction, and the re-vegetation of degraded lands. Its multifaceted contributions underscore its importance in various sectors, making it a key component of sustainable forest management in the regions it inhabits.

1.4.1.1 Timber and Wood Products

The timber from *Pinus kesiya* is highly valued for its quality and versatility. Its wood is used in construction, furniture manufacturing, and paper production. Research has focused on wood properties, such as density and fiber characteristics, to optimize its utilization in different industries (Missanjo and Matsumura, 2016).

1.4.1.2 Bioenergy and Biomass

Pinus kesiya has potential applications in bioenergy production and biomass utilization. Studies have explored the calorific value of its wood and its suitability for energy generation. As the demand for sustainable and renewable energy sources rises, *Pinus kesiya*'s role in bioenergy may become increasingly significant (Kataki and Konwer, (2002).

1.4.1.3 Medicinal and Aromatic Compounds

Beyond its role in traditional forestry products, *Pinus kesiya* has been investigated for its medicinal and aromatic properties. Essential oils extracted from different parts of the tree have shown potential applications in pharmaceuticals and aromatherapy. This diversification of use adds an extra layer of value to the species (Govindarajan *et al*., 2016).

1.4.1.4 Carbon Sequestration and Climate Change Mitigation

Pinus kesiya contributes to carbon sequestration and climate change mitigation through its ability to capture and store atmospheric carbon dioxide. Understanding its role in carbon dynamics is crucial for incorporating *Pinus kesiya* into climate change mitigation strategies and sustainable forestry practices (Patricioand Tulod, 2010; Chaudhary *et al*., 2014).

1.5 Problem statement

Pinus kesiya is reported to be harvested by the local communities without considering the age of maximum return of timber volume, which is leading to its pre-mature unsustainable harvesting. This is because there is no information available on growth dynamics, opportunity cost of premature harvesting and optimum biological rotation age for Khasi Pine growing in Meghalaya. The calculation of rotation age is necessary to achieve the economic and sustainability goals of the harvester. Issue on the same was raised by Shri H.C. Chaudhary, IFS, PCCF (WP, R&T and DCA), Meghalaya during his visit to ICFRE-RFRI on 23.01.2023. He sought technical assistance from ICFRE-RFRI for local volume tables and calculation of biological rotation age by stem and stump analysis. In response to the same, a present research project was developed for preparation of volume table and calculation of rotation age of *Pinus kesiya* in Meghalaya State.

1.6 Objectives of the project

1. To estimate relationship between DBH and stump diameter of *Pinus kesiya*
2. To estimate the current annual increment and mean annual increment of *Pinus kesiya*
3. To calculate rotation age of *Pinus kesiya*
4. To prepare local and general volume tables for *Pinus kesiya*

Chapter 2

METHODOLOGY

2.1 State of Meghalaya

Meghalaya, literally meaning the '*abode of clouds*' is a hilly state situated in the Northeastern region of India. The state is bounded on the North by Assam and on the South by Bangladesh. It is the homeland of three indigenous hill tribes, namely the *Khasi*s, the *Jaintias* and the *Garo*s. The state is divided into three divisions, twelve districts and eight Sub-divisions. The whole State is covered by 46 Community Development Blocks. The state has three Autonomous district councils set up under the provisions of Sixth Schedule to the Constitution of India, namely the Khasi Hills Autonomous District Council, Garo Hills Autonomous District council and Jaintia Hills Autonomous District Council. Shillong is its capital located in the East Khasi Hills district.

2.1.1 State profile

2.1.1.1 Geographical Extent

Meghalaya covers a geographical area of 22,429 km^2 and lies between the latitudes of 25˚00'00''N to 26˚10'00''N and the longitudes of 89˚45'00''E to 92˚45'00''E (Fig. 2.1). The altitude of the Meghalaya Plateau ranges from 150 to 1961 meters above mean sea level, the Khasi Hills having the highest altitude, followed by Jaintia Hills in the East. Garo Hills are basically plain, and its highest peak is Nokrek Peak with an elevation of 1515 meters.

2.1.1.2 Climate

Altitude has a distinctive impact on the climate of Meghalaya that broadly can be classified as a humid subtropical climate, characterized by high rainfall mostly during summer. The climate of Meghalaya is directly influenced by the Northeast winter and Southwest monsoon. The temperature ranges from 2°C to 36°C based on the altitude. Meghalaya is considered as one of the highest rainfall areas in the world with average annual rainfall of about 2600 mm over Western Meghalaya, between 2500 to 3000 mm over Northern Meghalaya and about 4000 mm over South-Eastern Meghalaya. Rainfall in Cherrapunji and Mawsynram is quite heavy and ranges from 11,995 mm to 14,189 mm.

2.1.1.3 Soil

As per the traditional system of classification, broadly the soils of Meghalaya can be classified into four types namely Red Loam or Hill soils, the Lateritic soils and new and old alluviums. The Red soil is confined to the entire foot hills region along the East and Western belt of the state. These soils are generally acidic in nature, sandy to silty texture, rich in silica, high organic matter, and low base saturation. Laterite soil is found in the Northern face of the central upland and in the Western section of the Garo hills regions.

2.1.1.4 Forest Cover

Forest Cover of Meghalaya is 17,118.79 km^2 which is 76.32 % of the state's Geographical area. The tree cover of the state is 710 km^2 which is 3.16% of the state's Geographical area**.** The total forest and tree cover in the State thus stands 79.48% covering 17,828.79 km^2 which contributes to 2.20% of India's Forest and Tree Cover. The recorded forest area of the state is 9,496 km^2 which is 42.34% of its geographical area. Out of the total forest area, reserved forests cover 11.72%, Protected forests cover 0.13% and unclassed forest cover 88.15%. In terms of forest canopy density classes, the state has 488.98 km^2 area under very dense forest, 9,267.29 km^2 area under moderately dense forest and 7,362.52 km^2 area under open forest (Fig 2.1 and Table 2.1).

Table 2.1 Forest and Tree Cover (km^2) of Meghalaya

Very Dense Forest	Moderately Dense Forest	Open Forest	Total Forest	Tree Cover	Total Forest and Tree Cover
560.16	9,159.89	7362.02	17,046.07	698	17,744.07
					(Source: FSI, 2021)

Total growing stock in the state is 55.36 million cum including both recorded forest area and trees outside forests (TOF). The total carbon stock of forests in the State including the TOF patches is 183.39 million tonnes (674.43 million tonnes of Co_2 equivalent) which is 2.55% of total forest carbon stock of the country (FSI, 2021). The forest cover of the state has decreased by 72.72 km^2 while the tree cover has decreased by 12 km^2 as compared to ISFR, 2019.

Pinus kesiya, *Pinus roxburghii*, *Schima wallichii*, *Areca catechu* and *Pinus patula* are the top five species found in ToF in Meghalaya while *Schima wallichii*, *Pinus kesiya*, *Shorea robusta*, *Ficus* spp. and *Artocarpus heterophyllus* are the top five tree species inside recorded forest area.

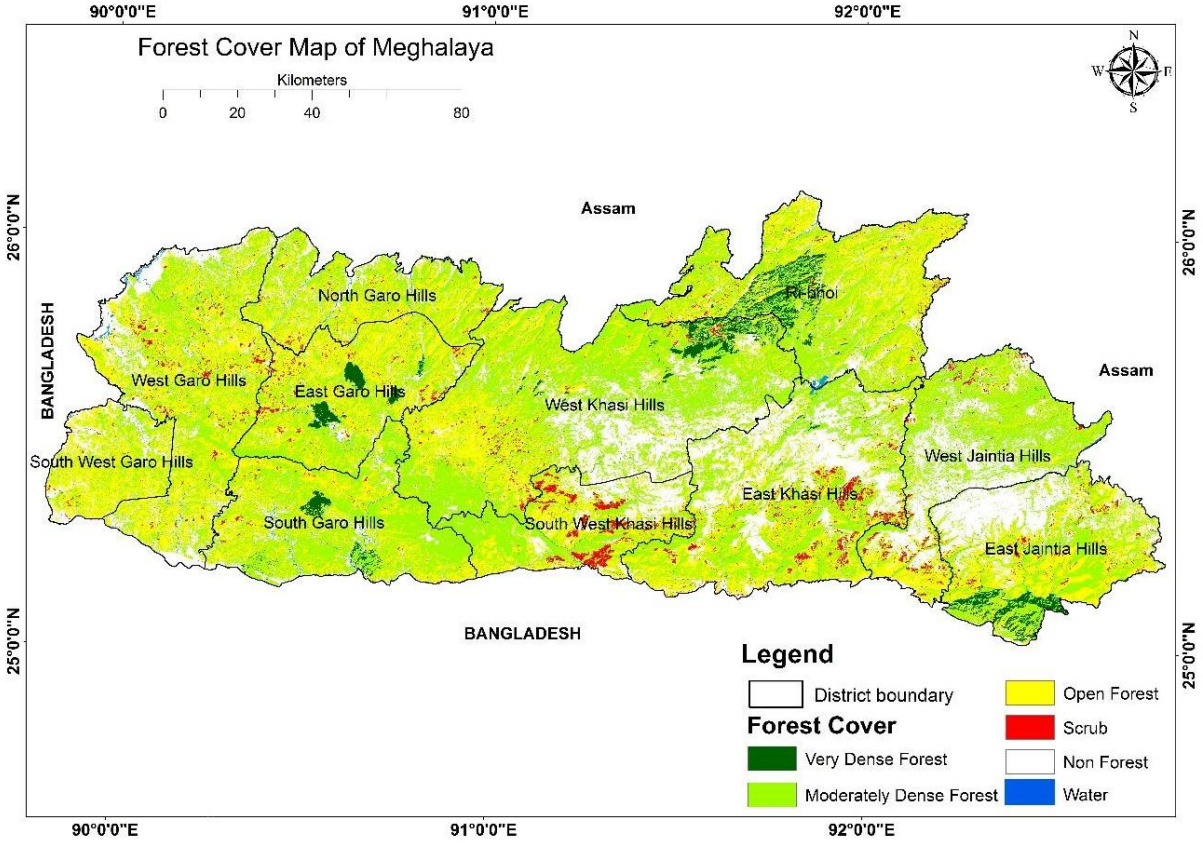


Fig 2.1 Forest cover Map of Meghalaya (Source: FSI, 2019)

2.1.1.5 Forest Type

As per the classification of Champion and Seth (1968), the Forests of Meghalaya can be categorized into following categories:

Tropical Wet Evergreen

a. Cachar Tropical Evergreen Forest (1B/C3)
b. Pioneer Euphorbiaceae Scrub (1B/2S1)

Tropical Semi-Evergreen Forests

a. Assam Alluvial Plains Semi-Evergreen Forest (2B/C1a)
b. Secondary Moist Bamboo Brakes (2/2S1)

Tropical moist deciduous Forests

a. Khasi Hill Sal Forest (3C/C1a(ii))
b. 3C/C3b East Himalayan Moist Mixed Deciduous Forest

Montane Subtropical Forests

a. 8B/C2 Khasi Subtropical Wet Hill Forest
b. 9/C2 Assam Subtropical Pine Forest

2.2 Study Sites

The study was conducted in West Jaintia Hills district of Meghalaya. Forests of the district are mostly dominated by the Assam Subtropical Pine Forest type. A total of five pine forest dominated sites were selected in West Jaintia Hills for the present study. These include pine dominated locations of Mookyndur, Nonglatem, Mynsngat, Nartiang and Sabahmuswang (Sabah) forests. As per the National Bureau of soil survey and land Use Planning (NBSS & LUP) soil of the sampling site falls under: -

Typic Kandihumults (dominant covers 174.9 thousand hector area): These type of soils are deep, excessive drained, fine texture on moderately sloping side (slope of hills) and possessing a loamy surface and a modest risk of erosion

Typic Dystrochrepts (covers only 7.8 thousand hector area): are associated with moderately deep soil, excessively drained, the texture is coarse-loamy on gently sloping hill tops possessing very severe erosion hazard and strong stoniness.

Out of these sites, Mookyndur forests characterized with shallow soil depth, open forest cover with less than 40% of canopy cover and southern aspect with 20–30-degree slope (Fig 2.3). Biotic pressure was also evident at this site. While other sites are having quite deep soil depth, moderately dense pine forest and northern aspect with less than 10 degree slope. All sites are falling in 1000-1500 msl elevation class. Based on the characteristics of Mookyndur forest was termed as Site Quality-II and other remaining forests as Site Quality-I.

2.3 Data collection

2.3.1 Sampling for soil quality assessment

Determining soil nutrient status is fundamental for sustainable yield, efficient resource management, environmental protection and long-term soil health and productivity. A systematic approach in the following manner was followed to determine the soil nutrient status.

The soil samples were collected from each location. From each location, at least 4 composite samples were obtained. These composite samples were collected using the zigzag sampling method, maintaining a minimum distance of 100 m between each sample. Soil samples were collected from three depths: 0-30 cm, 30-60 cm, and 60-90 cm, using a soil auger.

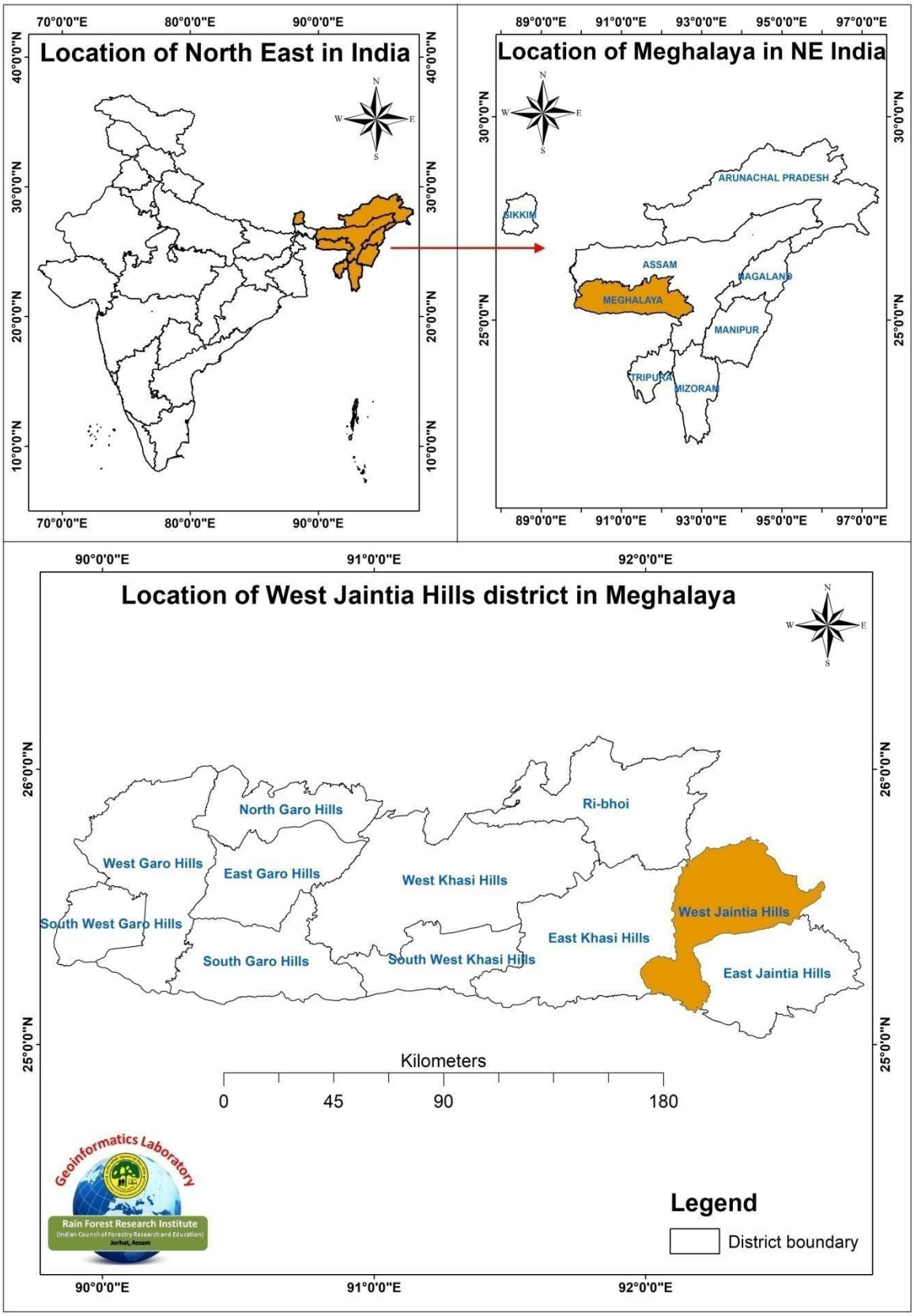


Fig 2.2 Location map of study site

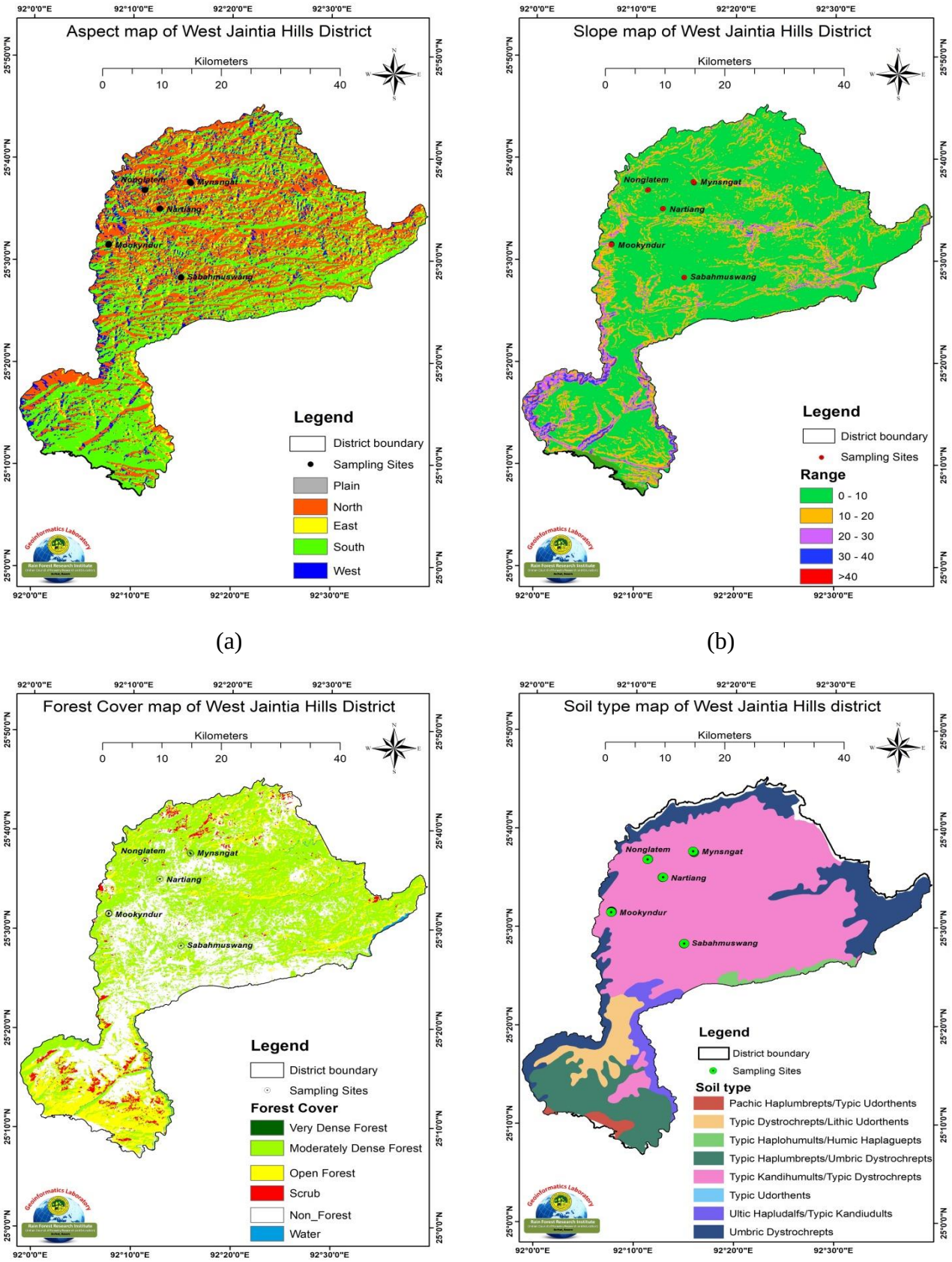


Fig 2.3 Map of sampling sites showing (a) Aspect (b) Slope (e) Forest Cover (f) Soil type (Source: FSI, 2019 and NBSS & LUP)



Fig 2.4 Soil samples collection in the field

Soil depth beyond 60 cm was not found in Site Quality-II locations, therefore soil samples from these sites were collected from only two depths. All collected samples were packed into poly bags along with aluminium tags bearing unique IDs and transported to the ICFRE-RFRI soil laboratory for analysis. The collected soil samples were air-dried, ground, and sieved using a 2mm mesh. The processed samples were then stored in a dry, moisture-free environment.

2.3.2 Sampling of *Pinus kesiya* trees

Destructive approach was followed for measurement of sampled trees. A total of 38 trees of *Pinus kesiya* were purposely selected for the present study. Out of these, 28 trees were from the Site Quality-I whereas 10 were from the site of Site Quality-II. These trees were felled and sectioned using the mechanized chainsaw. DBH and height of sampled felled trees were measured in centimeter with the help of measuring tape. Total height (in meters) of the standing trees was measured with the help of Nikon Forestry Pro Laser Rangefinder. Under bark and over bark girth and diameter of both ends of each section of stem were measured (Fig 2.5). A disk of 5-10 cm thickness was also separated out at the stump height and brought to the ICFRE-RFRI laboratory to process further for ring counting and determination of age of sampled trees (Fig 2.6).



Fig 2.5 Research team taking measurements of felled tree

Diameter at one-meter interval (frustum of one meter) up to merchantable top end diameter (up to 16cm) of the stem was also measured using the Criterion RD1000® Optical Dendrometer (LTI, 2006) coupled to a professional photographic tripod. This non-destructive data was taken for the same trees which were felled later for destructive sampling.



(a) (b)

Fig 2.6 Showing the representative stumps of trees of (a) Site Quality-I and (b) Site Quality-II

2.4 Data Analysis

2.4.1 Soil Analysis

The dried soil samples were analyzed for pH and EC in a 1:2.5 soil/water suspension by thermo Scientific PCTestr 35-meter Multi-Parameter Pocket Tester. Soil organic carbon was analyzed by wet digestion method (Walkley black,1934), available potassium was extracted with 1M NH_4 OAc (pH 7.0) and then measured by flame photometer, available nitrogen was determined by Alkaline permanganate method as per the Subbiah and Asija (1956), available phosphorus by Bray P-1 (Bray and Kurtz, 1945), available sulfur by Turbidimetric method (Chesnin and Yien, 1950), available boron was extracted by hot water and determine by spectrophotometer using coloured stabling reagent Azomethine-H (Gupta, 1967) and cationic micronutrient by DTPA-micronutrient soil test (Lindsay and Nrvell, 1978) using atomic absorption spectrophotometer.

2.4.2 Preparation of local and general volume tables for *Pinus kesiya*

2.4.2.1 Computation of volume of trees

Volumes of all felled trees were estimated by taking girth measurement of each section (frustum) of main bole. The volume of frustums other than bottom frustum was calculated using Smalian's formula based on cross sectional area of both the ends of frustum. Volume of lower most frustum or bottom frustum was calculated using Newton's formula keeping in view the neiloid form of bottom frustum.

Smalian's formula, $V_f = \frac{S_1+S_2}{2} l$

Newton's formula, $V_f = \frac{S_1+S_m+S_2}{6} l$

where,

$S_1 = \pi r_1^2$; the cross-sectional area of large end of the frustum

$S_2 = \pi r_2^2$; the cross-sectional area of smaller end of the frustum

$S_m = \pi r_m^2$; the cross-sectional area of mid-section of the frustum

l = length of the frustum

r_1, r_2 and r_m are the radii (cm) of larger end, smaller end and middle.

The total volume (V) of the tree was calculated by summing up the volume of the stem plus that of all the segments in the crown.

$$V = V_{f1} + V_{f2} + \ldots\ldots\ldots\ldots + V_{fn} + V_{br}$$

The above procedure was followed for calculating the volume of each of the 38 sampled trees. This volume obtained was then subjected to model fitting and finding the best fit model.

2.4.2.2 Development of local volume equation

Regression analysis was carried out to estimate the relationship under bark Volume and over bark DBH. The regression models based on under bark volume (m^3) as dependent variable and over bark DBH (cm) as independent variable were established using calculated volume and DBH values of 38 sampled trees. Five functional forms *viz*, linear, quadratic, power, logarithmic and exponential regression models were tested to select the best fit model for development of local volume equation:

1. Linear model $V = a + bD$
2. Quadratic model $V = a + bD + cD^2$
3. Power model $V = aD^b$ or $lnV = lna + blnD$
4. Logarithmic model $V = a + blnD$
5. Exponential model $lnV = a + bD$ or $V = 10^{a+bD}$

Where:

V – Volume (m^3),

D – Over bark DBH (cm)

a and b – regression coefficients

2.4.2.3 Development of general volume equation

The regression models for general volume equation based on calculated volume (m^3) as dependent variable and two independent variables i.e., over bark DBH (cm) and height (m) was established using calculated volume, DBH and height values of 38 sampled trees. Six functional forms *viz*, linear, quadratic (3 forms), power and logarithmic were tested to select the best fit model to predict volume using DBH:

1. Linear model $V = a + bD + cH$
2. Quadratic model (1) $V = a + bD + cD^2H$
3. Quadratic model (2) $V = a + bD^2H$
4. Quadratic model (3) $\sqrt{V} = a + bD + cH$ or $V = (a + bD + cH)^2$
5. Power model $V = aD^bH^c$ or $lnV = lna + blnD + clnH$
6. Logarithmic model $V = a + blnD + clnH$

2.4.2.4 Statistical comparison and identification of best fit models

All regression models used in development of local and general volume equations fitted and regression coefficients were estimated using IBM SPSS version 26 statistical software through Levenberg-Marquardt minimisation method under non-linear regression analysis. The adjusted coefficient of determination (r^2_{adj}) was calculated and used to determine the quality of fitness of each equation. r^2_{adj} shows the proportion of the total variance that is explained by the model adjusted for the number of model parameters. Every regression model was statistically compared and best fit models for local and general volume equations were identified based on criteria indicators *i.e.*, adjusted r^2, lowest root mean square error (RMSE), mean absolute prediction error (MAPE) and Akaike's Information Criterion difference (AIC_d) (Tewari and Kumar, 2003; Tiwari and Singh, 2006; Tiwari and Singh, 2018; Islam and Chowdhury, 2017; Thangjam et al., 2019).). The mathematical expressions of these criteria are given below:

- Root mean square error $RMSE = \sqrt{\frac{\sum (V_o - V_p)^2}{n-1-p}}$
- Mean absolute prediction error $MAPE = \frac{\sum |V_o - V_p|}{n} * 100$
- Akaike's information criterion $AIC = n\ ln\ ln\ \hat{\sigma}^2 + 2p$

where, $\hat{\sigma}^2 = \sum_{i=1}^{n} \frac{(V_o - V_p)^2}{n}$

Where, V_o – Observed volume; V_P– predicted volume; n – total number of observations; p - number of model parameters

Developed equations were used for the preparation of local volume tables.

2.4.2.5 Estimation of the relationship between DBH and stump diameter of trees

Like DBH and Volume relationship *i.e.* local volume equation, regression analysis was carried out to estimate the relationship between stump diameter (under bark) and DBH (over bark), and similarly five functional forms *viz,* linear, quadratic, power, logarithmic and exponential models were tested to select the best fit model to predict DBH from stump diameter.

1. Linear model $D = a + bS$
2. Quadratic model $D = a + bS + cS^2$
3. Power model $D = aS^b$ or $lnD = lna + blnS$
4. Logarithmic model $D = a + blnS$

5. Exponential model $lnD = a + bS$ or $D = 10^{a+bS}$

Where:

S – under bark stump diameter (cm)

a and b – regression coefficients

These models were statistically compared and the best fit model was identified using the same criteria indicators as in local and general volume equations.

2.4.3 Estimation of the current annual increment and mean annual increment

Stump analysis was carried out to find out the stump diameter at different ages of the tree. It was the analysis of a stump cross-section by counting and measuring the annual growth rings in order to estimate the age of the tree and its past rates of radial growth. Distance from pith to rings corresponding to the age was measured in the four directions on the cross section of disk (Fig 2.7). By this way, we had 4 values of radius for each year. By taking the mean of all four radii, the mean value of radius was calculated and by multiplying by two, stump diameter at different ages was estimated. The estimated age of each sample was adjusted by adding two years to account for the time it takes for the pine sapling to reach stump height. DBH at different ages of trees were calculated using the DBH-stump diameter relationship model developed under the present study. Then the volume of trees of different ages was calculated by using the local volume equation developed under the present study. Mean volume increment during a particular year was estimated of dominant representative trees with fairly large DBH. Under aged trees were not included in this exercise.

The growth that takes place in a particular year is called the Current Annual Increment for that year. The volume of a tree is built up by the annual increments that the tree puts on in successive years. The CAIs vary from year to year. The average of all CAIs is the Mean Annual Increment of pine trees which denotes average annual rate of growth up to any given age. MAI is thus defined as the total increment up to a given age divided by that age.

CAI at the age of n years = $V_n - V_{n-1}$

MAI at the age of n years = $\frac{V_n}{n}$

Where,

V_{n-1} = volume in (n-1) years, i.e. volume at the age of (n-1) years;

V_n = volume in n years, i.e. volume at the age of n years

CAI and MAI for pine trees were calculated separately for the Site Quality-I and Site Quality-II (Mookyndur forest) as growth of trees was varying considerably at sites with poor and good site quality.

2.4.4 Calculation of rotation age of *Pinus kesiya*

Rotation age was calculated by plotting the Current Annual Increment (CAI) and Mean Annual Increment (MAI) curves using MS Excel software. The age where the curves of CAI and MAI culminate is known as the biological rotation age, beyond which it is not biologically viable to retain the tree at the site.

All data analysis was done using SPSS version 26 statistical package and Microsoft Excel spreadsheet software.

2.4.5 Calculation of rotation girth of *Pinus kesiya*

Similar to the rotation age, rotation girth was calculated by plotting CAI and MAI. The girth at which curves of CAI and MAI culminate is considered as rotation girth at biological rotation age.



Fig 2.7 Scientists measuring the annual ring width on *Pinus kesiya* stumps

Chapter 3

RESULTS

3.1 Characteristics and Nutrient status of Soil

3.1.1 Soil physical characteristics

Soil characteristics were analyzed separately for each type of sites.

Site Quality-I

The depth of the soil in all locations of Site Quality-I ranges from moderately shallow to moderately deep, spanning from 60 to 100 cm (Fig 3.2). In general, these sites feature gently to moderately sloping hills. The presence of rock fragments is less than 15% of the total volume in the upper surface soil (0-30 cm), while deeper down, between 60 and 90 cm, the volume of rock fragments increases to 35-60% and 60-80%, respectively (Fig 3.1). Soil texture resembles loamy sand to sandy loam and sandy clay loam. *Myrica esculenta, Schima wallichii*, *Castanopsis* spp., *Duabanga* spp., *Erythrina* spp. and *Terminalia* spp. are the main co-dominant tree species found in these sites.

Site Quality-II

The soil depths in Site Quality-I range from very shallow to shallow varying between 0 to 50 cm, with rocks (boulders) exposed on the surface in many places (Fig 3.2). The soil atop the hills, steep slopes, and ridges has a depth of less than 25 cm, while in the lower parts of the hills or less steep areas, it reaches a depth of 50 cm. Rock fragments in a form of gravel appear in the upper soil surface (0-30 cm) and comprise 60-90% of the total volume (Fig 3.3). By feeling the soil, it resembles loamy sand to sandy loam texture. These sites have sparse distribution of *Myrica esculenta*, *Castanopsis* spp., *Duabanga* spp. and *Terminalia* spp. are the main co-dominant tree species along with shrubs like *Rubus* spp.

3.1.2 Soil nutrient status

Results of soil nutrient status of Site Quality-I and II are summarized in Table 3.2.

pH: The soil at both sites are acidic in nature, with pH ranging from 4.18 to 4.63, showing no significant difference among the sites even at different depths.

Table 3.1 Details of physico-chemical properties of soil in sites

Parameters	Site Quality-I			Site Quality-II		
	Soil depth classes			Soil depth classes		
	0-30	**30-60**	**60-90**	**0-30**	**30-60**	**60-90**
Mean depth	30.00	57.62	85.67	19.19	42.54	-
Stoniness (Rock fragments) (%)	<15	35-60	60-80	60-80	60-80	-
pH	4.23±0.04a	4.29±0.01a	4.26±0.06a	4.54±0.04a	4.50±0.06a	-
EC (dS/m)	0.03±0.00a	0.02±0.00a	0.02±0.00a	0.02±0.00a	0.02±0.00a	-
Organic Carbon (%)	1.35±0.11a	0.71±0.03b	0.54±0.07b	0.71±0.11b	0.26±0.04c	-
Available Nitrogen (kg/ha)	208.77±6.29a	172.72±2.70b	150.53±13.96bc	217.95±9.13a	147.39±4.25c	-
Available Phosphorus (kg/ha)	17.04±1.54a	19.60±0.68a	18.48±1.43a	21.77±3.21a	14.98±0.57a	-
Available Potassium (kg/ha)	115.38±18.14a	73.30±3.62b	77.20±13.64b	65.11±8.02b	39.19±4.68c	-
Available Sulphur (ppm)	4.11±0.32a	3.78±0.10a	3.89±0.79a	4.26±0.37a	5.08±0.65a	-
Available Iron (ppm)	28.54±2.35a	22.86±1.52a	17.12±3.78a	29.52±4.92a	34.43±8.38b	-
Available Manganese (ppm)	2.84±0.27a	1.42±0.09b	2.80±1.18a	1.90±0.41b	0.63±0.13b	-
Available Boron (ppm)	0.76±0.18a	0.68±0.04a	0.90±0.33a	0.90±0.20a	1.10±0.27a	-
Available Zinc (ppm)	0.31±0.05a	0.24±0.02a	0.25±0.11a	0.64±0.10b	0.54±0.05b	-
Available Copper (ppm)	0.42±0.06a	0.24±0.02b	0.19±0.07b	0.06±0.01c	0.002±0.00c	-

The alphabetical notations signify statistically significant differences between the respective means ($P < 0.05$).

Electrical conductivity (EC): Both sites exhibit low EC (>2dS/m) indicating non-saline soil with no significant difference ($p<0.05$) observed between the sites and depths. This similarity may be attributed to both sites falling within the same climatic zone and the soils originating from the same parent material.

Soil organic carbon (SOC): Soil organic carbon percentage ranges from 0.26 to 1.35 and follows a normal trend, decreasing with soil depth at both sites with a significant difference ($p<0.05$) observed between the depths of Site Quality-I & Site Quality-II. The soil texture of Site Quality-I is finer than that of Site Quality-II and it has a gentle to moderate slope with dense canopy cover, promoting high organic matter.

Nitrogen: A similar trend was observed for available nitrogen decreasing with soil depth at both sites but no significant difference ($p<0.05$) was found at the depth of 0-30 cm soil, while a significant difference ($p<0.05$) was observed at lower depths. This may be attributed to low pH, leading to low nitrogen availability. Additionally, due to high ground flora density (seedlings, saplings, shrubs and herbs) at Site Quality-I compared to Site Quality-II, nitrogen uptake by plants at the upper surface soil is higher at Site Quality-I, reducing the nitrogen stock. This trend reverses when going deeper, i.e., at 30-60 cm. Due to the shallow depth (43 cm) of Site Quality-II, the roots of pine spread in this strata and uptake nitrogen from this zone, while in the case of Site Quality-I the soil depth in most of the sampled areas is more than 90 cm promoting deep root penetration and uptake from different soil depths.

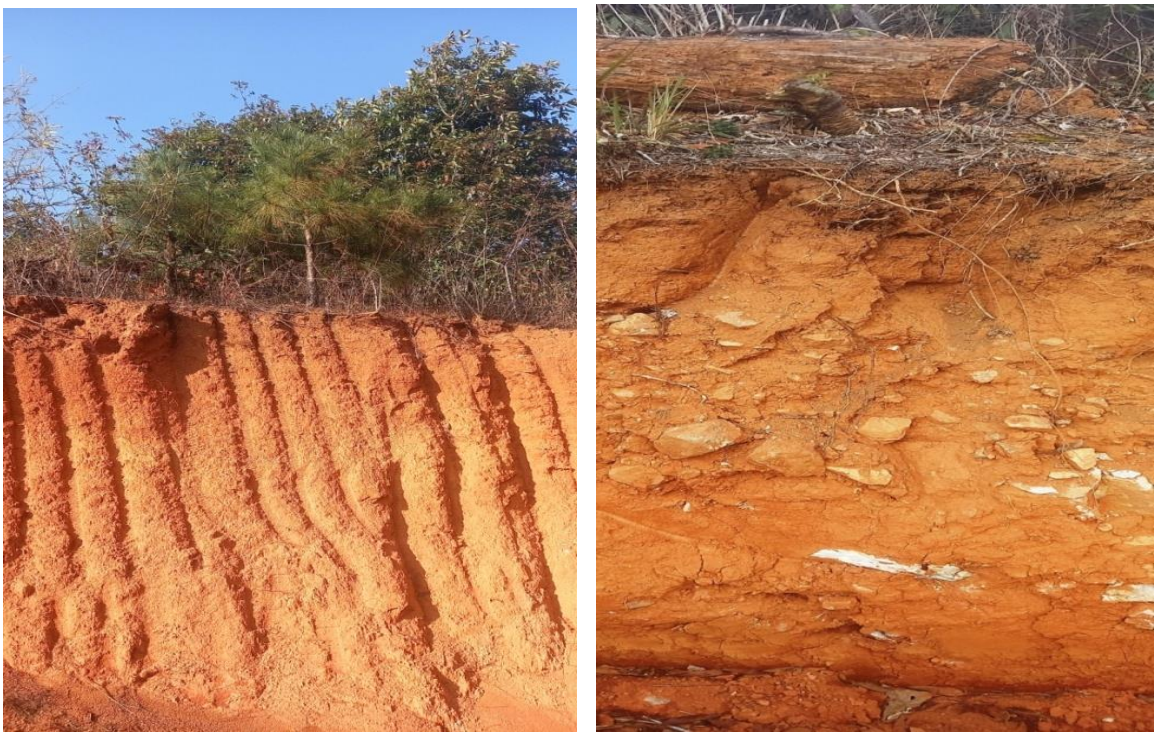
Phosphorus: In the case of phosphorus, there is no significant difference ($p<0.05$) between sites.

Potassium: The concentration of available potassium is higher in Site Quality-I compared to Site Quality-II, and this difference is highly significant. This disparity may be due to the high uptake of potassium by the Khasi pine from the shallow soil of Site Quality-II and low organic matter.

Micronutrients: Among the micronutrients, a significant difference was observed for copper, boron, and magnesium at all depths.



Fig 3.1 *Pinus kesiya* natural stand in Site Quality-I



(a) (b)

Fig 3.2 Two different road cut profiles near the Site Quality-I: (a) showing depth soil; (b) showing volume of fragment of rocks with 35-60% below 50-60cm soil depth



Fig 3.3 *Pinus kesiya* natural stand with exposed rocks in Site Quality-II



(a) (b)

Fig 3.4 Two different roads cut profiles near the Site Quality-II: (a) showing very shallow depth; (b) showing the 60-90 % of volume rock fragment in soil

3.2 Summary statistics of felled sample trees of *Pinus kesiya*

As mentioned in the methodology section, a total of 38 sample trees in both sites were felled. DBH of sampled trees was varying from 19.10cm to 56.50cm, whereas height was varying from 13.8m to 28.2m. The mean DBH and height of the dataset (n=38) was 37.67cm and 20.64cm respectively. Summary statistics of the dataset is presented in Table 3.2.

Table 3.2 Summary statistics of sample trees of *Pinus kesiya*

Statistics	DBH (cm)	Height (m)	Stump diameter (cm)	Total Stem Volume (m^3)
Mean	37.67	20.64	36.52	0.936
Std. Error	1.49	0.63	1.52	0.089
Median	39.09	20.46	37.85	0.889
Std. Deviation	9.16	3.87	9.38	0.546
Kurtosis	-0.37	-0.71	-0.01	0.811
Skewness	-0.23	0.14	0.13	0.745
Minimum	19.10	13.82	18.59	0.124
Maximum	56.50	28.29	60.39	2.580
Count	38	38	38	38

3.3 Relationship between DBH and stump diameter of *Pinus kesiya*

Estimated regression coefficients along with their standard error and fit statistics for all five models tested for estimation of DBH using stump diameter are presented in Table 3.3.The statistical analysis revealed maximum adjusted r^2, minimum Root Mean Square Error (RMSE), Mean Absolute Prediction Error (MAPE) and Akaike Information Criterion (AIC) values for quadratic model $D = -7.92272 + 1.56988 * S - 0.00827 * S^2$. Therefore, this functional form is proved to be the best fit model to calculate over bark DBH using stump diameter as an independent variable. Fig.3.5 demonstrates the predicted DBH by the best fit model and measured DBH against stump diameter.

Table 3.3 Values of coefficients and fit statistics for different regression model for DBH based on stump diameter

Model No.	**Estimated Coefficients**			**Adj. r^2**	**RMSE**	**MAPE**	**AIC**
	a	***b***	***c***				
1	2.75541 *(0.95596)*	1.27537 *(0.03385)*		0.954	1.879	3.906	53.946

2	**-7.92272** ***(3.25141)***	**1.56988** ***(0.17810)***	**-0.00827** ***(0.00237)***	**0.966**	**1.618**	**2.867**	**42.569**
3	1.17369 *(0.11822)*	0.96432 *(0.28187)*		0.956	1.889	3.580	54.330
4	-79.95300 *(3.85566)*	33.00748 *(1.07894)*		0.961	1.740	3.440	48.091
5	13.48402 *(0.69278)*	0.02724 *(0.00136)*		0.886	3.223	6.224	94.947

(Standard errors of coefficients are given in parenthesis)
*Best fit model is highlighted in bold.

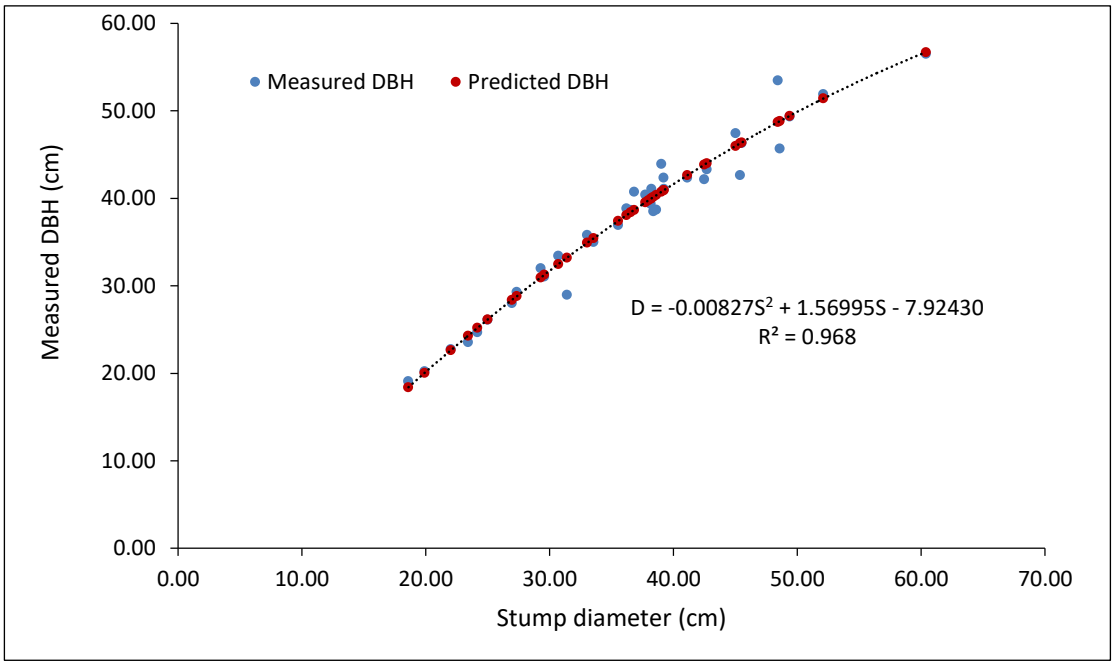


Fig 3.5 Scatter plot of the measured DBH and predicted DBH against stump diameter by selected model for *Pinus kesiya*

3.4 Local and general volume tables for *Pinus kesiya*

3.4.1 Local volume equation

Estimated regression coefficients along with their standard error and fit statistics for all five models tested for the estimation of volume using DBH are presented in Table 3.4. The statistical analysis revealed maximum adjusted r^2, minimum RMSE, MAPE and AIC values for power model $V = 0.0000485 * D^{2.68565}$. Therefore, this functional form is proved to be the best fit model to calculate the volume of trees using DBH. The linearized form of this model can also be written as $lnV = -9.933395 + 2.6565 * lnD$. Fig 3.5 demonstrates the

predicted volume by the best fit model and measured volume against DBH. Local volume table was developed using the DBH based best fit local volume equation (Annexure -I).

Table 3.4 Values of coefficients and fit statistics for different regression model for local volume equation

Model No.	Estimated Coefficients			Adj. r^2	RMSE	MAPE	AIC
	a	***b***	***c***				
1	-1.20641 (0.11440)	0.05688 (0.00295)		0.907	0.1602	22.365	-133.19
2	0.29873 (0.24446)	-0.03057 (0.01361)	0.00119 (0.00018)	0.956	0.1083	10.011	-161.28
3	**0.0000485 (0.00001)**	**2.68565 (0.07355)**		**0.958**	**0.1078**	**9.491**	**-162.97**
4	0.04197 (0.00519)	0.07687 (0.00319)		0.822	0.2209	32.282	-108.75
5	-5.77771 (0.50458)	1.86682 (0.13993)		0.92	0.2032	14.123	-115.11

(Standard errors of coefficients are given in parenthesis)
*Best fit model is highlighted in bold.

3.4.2 General volume equation

Estimated regression coefficients along with their standard error and fit statistics for all six models tested for estimation of volume using DBH and height are presented in Table 3.4. The statistical analysis revealed the maximum adjusted r^2, minimum RMSE, MAPE and AIC values for power model $V = 0.0000465 * D^{2.096774} * H^{0.72342}$. Therefore, this functional form is proved to be the best fit model to calculate tree volume of trees using DBH and height as independent variables. $lnV = -9.976488 + 2.2096774 * lnD + 0.72342 * lnH$ is the linearized form of this model. Fig 3.6 demonstrates the predicted volume by the best fit general volume equation and measured volume against DBH. The general volume table was developed using the DBH and height based best fit general volume equation.

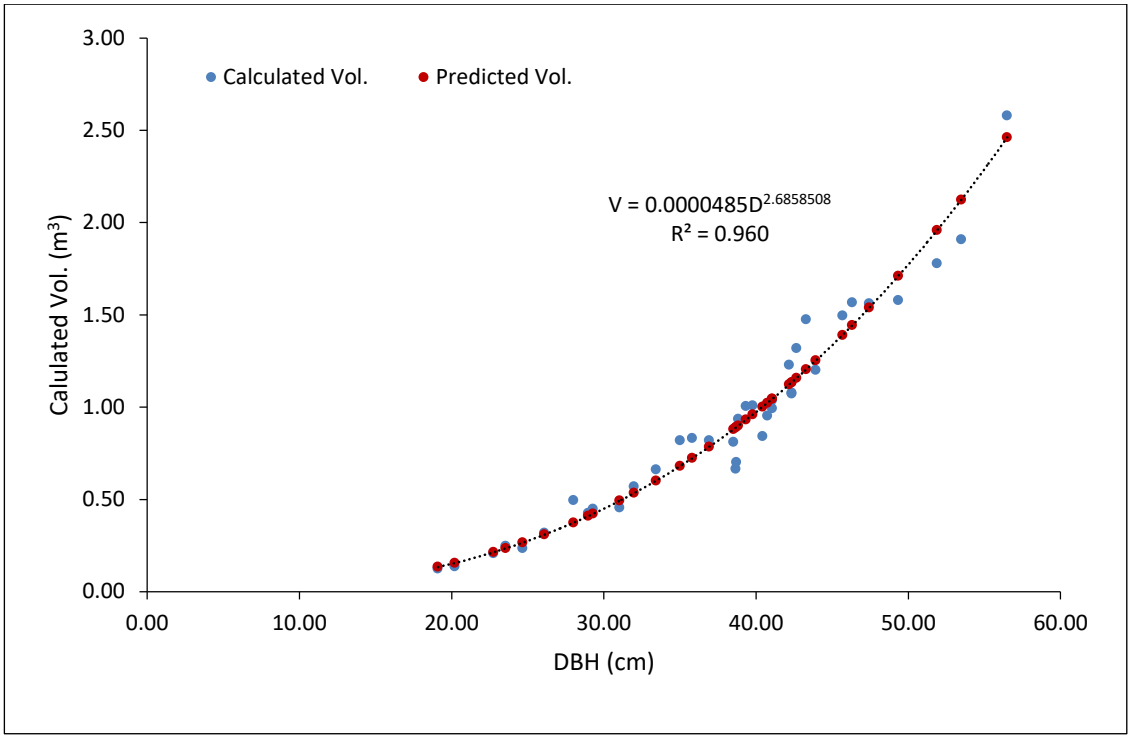


Fig 3.6 Scatter plot of the calculated volume and predicted volume against DBH by selected model for local volume equation

Table 3.5 Values of coefficients and fit statistics for different regression model for general volume equation

Model No.	Estimated Coefficients			Adj. r^2	RMSE	MAPE	AIC
	a	***b***	***c***				
1	-1.469409 *(0.135284)*	0.042785 *(0.005385)*	0.038475 *(0.012765)*	0.924	0.1427	20.065	-139.95
2	-0.153421 *(0.129770)*	0.008004 *(0.005521)*	0.000024 *(0.000003)*	0.972	0.0863	7.575	-178.23
3	0.030013 *(0.029684)*	0.000027 *(0.000001)*		0.971	0.0888	8.335	-178.01
4	-0.414121 *(0.050735)*	0.026100 *(0.001687)*	0.017045 *(0.003732)*	0.923	0.2674	33.951	-92.25
5	**0.0000465 *(0.000016)***	**2.096774 *(0.133934)***	**0.723420 *(0.158065)***	**0.973**	**0.0852**	**5.755**	**-179.20**
6	-6.601906 *(0.535946)*	1.171750 *(0.267163)*	1.104436 *(0.373533)*	0.817	0.6931	89.349	-19.86

(Standard errors of coefficients are given in parenthesis)
*Best fit model is highlighted in bold.

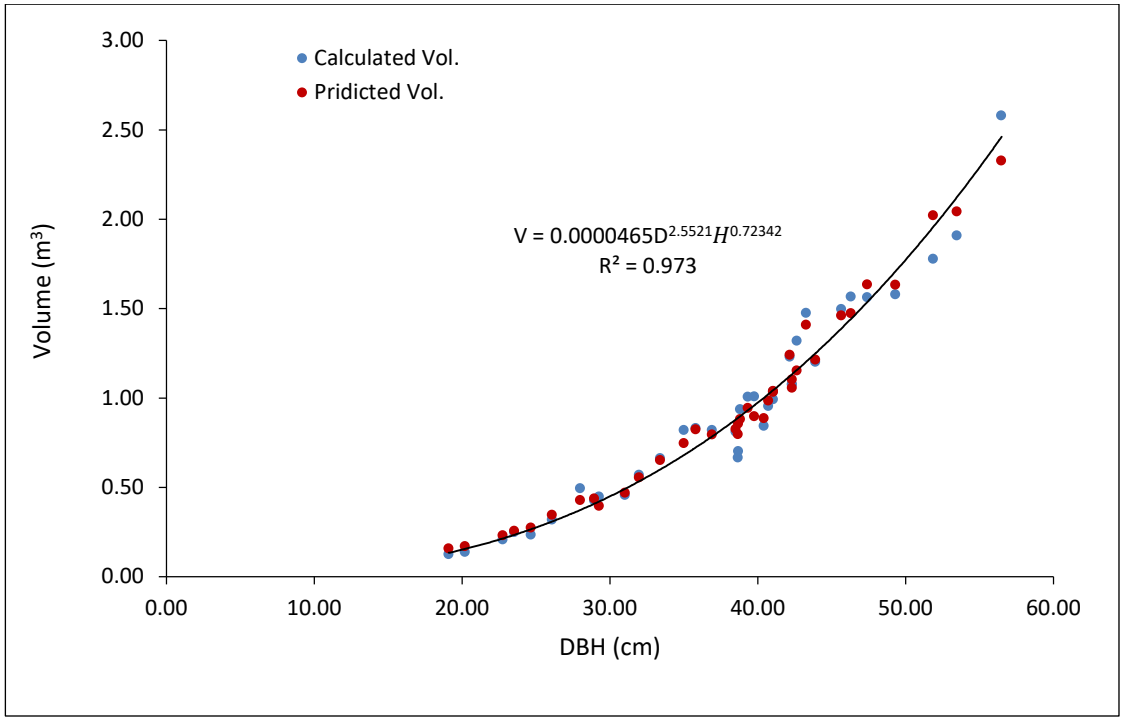


Fig 3.7 Scatter plot of the observed volume and predicted volume against DBH by selected model for general volume equation

3.5 Current annual increment and mean annual increment of *Pinus kesiya*

CAI and MAI depend on the growth rates of individual trees and the growth rate is highly affected by the site quality. As discussed earlier, the site qualities of both sites vary greatly. Site Quality-I was considered as a good site whereas Site Quality-II as a poor site. Therefore, CAI and MAI were calculated separately for pine trees growing in forest with poor site quality and good site quality. The maximum age of sampled trees in poor site quality forest was 68 years, whereas it was 49 years for the sampled trees of good site quality. Maximum DBH for Site Quality-II and Site Quality-I forest was 43.9 cm and was 56.5 cm respectively. It shows that the trees growing in Site Quality-I are attaining bigger DBH at lesser age in comparison to the forest of Site Quality-II. It proves that the growth rate of *Pinus kesiya* trees was considerably less in the forest of poor site quality.

Table 3.5 shows the CAIs of average pine trees growing in Site Quality-I and II respectively. CAI and MAIs for Site Quality-I were calculated up to 49 years, whereas the same were calculated up to 68 years in Site Quality-II. CAIs of pine trees in both types of sites were not uniform during different years of growth, which shows that there are significant variations in

climatic conditions in different years which affects the mean growth rate of trees growing in these sites.

Table 3.6 CAI and MAI of pine trees growing in the forests of Site Quality-I and II

Age (years)	Site Quality-I		Site Quality-II	
	CAI (m^3)	MAI (m^3)	CAI (m^3)	MAI (m^3)
10	0.04237	0.03285	0.00764	0.00687
11	0.04474	0.03455	0.00933	0.00769
12	0.04460	0.03581	0.01176	0.00871
13	0.04996	0.03738	0.01162	0.00929
14	0.04915	0.03856	0.01353	0.01000
15	0.04336	0.03899	0.01479	0.01068
16	0.05129	0.04002	0.01460	0.01117
17	0.05093	0.04086	0.01731	0.01185
18	0.05408	0.04180	0.02002	0.01267
19	0.05773	0.04286	0.01873	0.01322
20	0.05791	0.04380	0.01836	0.01365
21	0.05695	0.04458	0.02063	0.01418
22	0.05119	0.04494	0.01672	0.01437
23	0.04004	0.04469	0.02094	0.01480
24	0.03969	0.04444	0.02250	0.01529
25	0.04081	0.04426	0.01944	0.01553
26	0.04385	0.04425	0.02400	0.01600
27	0.04053	0.04408	0.02128	0.01628
28	0.03552	0.04373	0.01962	0.01645
29	0.03636	0.04343	0.02066	0.01665
30	0.03717	0.04319	0.02486	0.01702
31	0.03751	0.04298	0.02420	0.01733
32	0.03402	0.04266	0.02254	0.01755
33	0.03314	0.04233	0.02364	0.01779
34	0.04944	0.04257	0.01970	0.01787
35	0.03798	0.04242	0.02500	0.01813
36	0.03077	0.04206	0.02499	0.01837
37	0.02964	0.04168	0.02463	0.01859
38	0.03574	0.04151	0.02148	0.01869
39	0.03302	0.04126	0.02402	0.01886
40	0.02704	0.04087	0.02021	0.01890
41	0.02312	0.04039	0.02028	0.01894
42	0.02761	0.04005	0.01796	0.01891
43	0.03178	0.03984	0.01832	0.01890
44	0.02436	0.03945	0.01990	0.01893
45	0.02692	0.03915	0.02080	0.01898
46	0.02543	0.03882	0.02091	0.01903
47	0.01892	0.03836	0.02259	0.01912
48	0.01008	0.03772	0.02305	0.01922
49	0.01275	0.03716	0.01839	0.01920

50	-	-	0.01580	0.01912
51	-	-	0.02407	0.01923
52	-	-	0.01593	0.01916
53	-	-	0.02069	0.01919
54	-	-	0.01896	0.01918
55	-	-	0.01735	0.01915
56	-	-	0.01134	0.01898
57	-	-	0.01265	0.01885
58	-	-	0.01092	0.01870
59	-	-	0.01178	0.01856
60	-	-	0.00911	0.01838
61	-	-	0.00940	0.01821
62	-	-	0.00955	0.01805
63	-	-	0.00730	0.01785
64	-	-	0.00669	0.01765
65	-	-	0.01047	0.01753
66	-	-	0.01012	0.01740
67	-	-	0.01023	0.01728
68	-	-	0.00942	0.01715

3.6 Rotation age of *Pinus kesiya*

The biological rotation age can be estimated by analyzing age and growth curves, where the point of intersection between the current annual increment (CAI) and mean annual increment (MAI) indicates the rotation age. CAI and MAI values were plotted against the corresponding age of attaining the respective CAI and MAI. Best fit curves were estimated using MS Excel software for both type of study sites (Fig. 3.8 and 3.9).

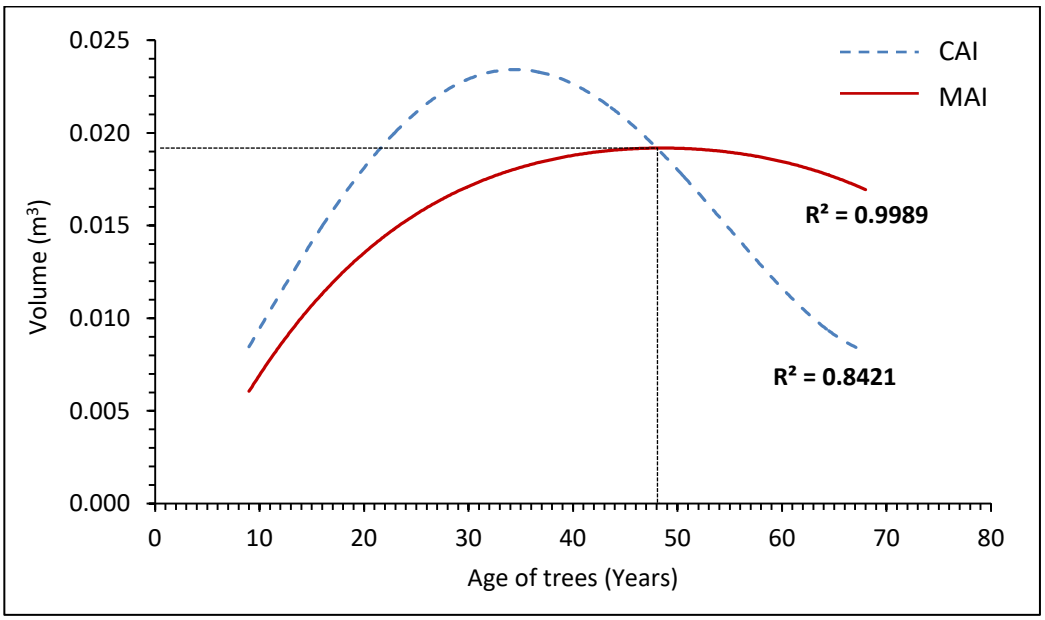


Fig 3.8 MAI and CAI in volume curves estimated for Site Quality-II

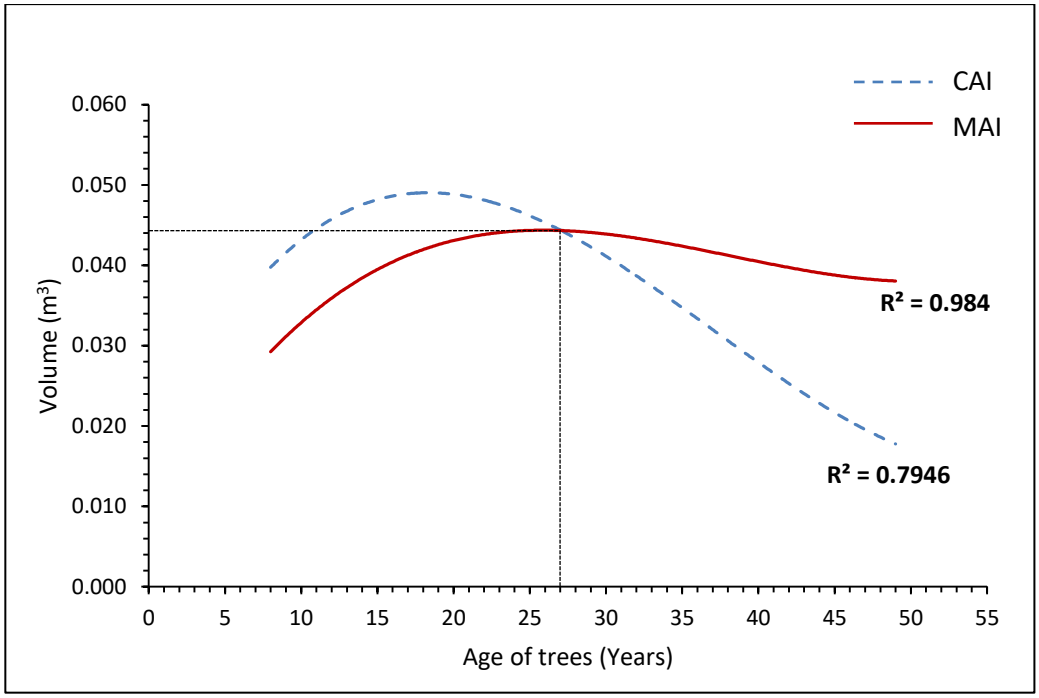


Fig 3.9 MAI and CAI in volume curves estimated for Site Quality-I

CAI and MAI curves for the pine trees of Site Quality-II (poor site quality) culminate at the age of 48 years. For Site Quality-I, they culminate at 27 years. This means that the average biological rotation age of pine trees growing in Site Quality-II and Site Quality-I are 48 years and 27 years respectively. Trees should be felled at this age and new crops of pine should be planted to utilize the maximum potential of forest land. This difference in the rotation age shows that there is great influence of the site quality on the growth rate of the trees which directly impacts the rotation age. Trees grow relatively quickly on good quality sites, reaching their biological maturity at an earlier stage compared to trees on poor quality sites.

3.7 Rotation girth of *Pinus kesiya*

Similar to the rotation age, estimated rotation girth at breast height for Site Quality-I and II based on CAI and MAI intersection is 127cm and 118 cm respectively (Fig. 3.10). Although GBH was estimated from CAI and MAI, it is advised to consider rotation GBH ranging from 127-135cm for Site Quality-I and 118-125cm for Site Quality-II. The biological rotation girth may not necessarily match the desired girth size sought by the timber industry, as timber industry requirements are governed by market demand.

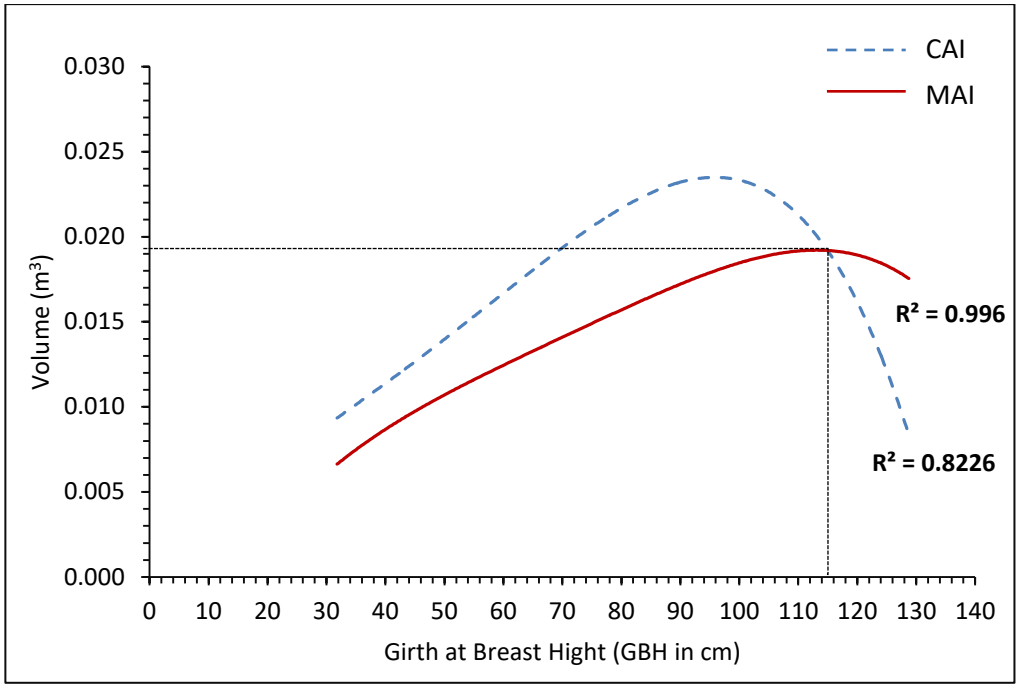


Fig 3.10 MAI and CAI volume intersection and rotation girth at breast height estimated for Site Quality-II

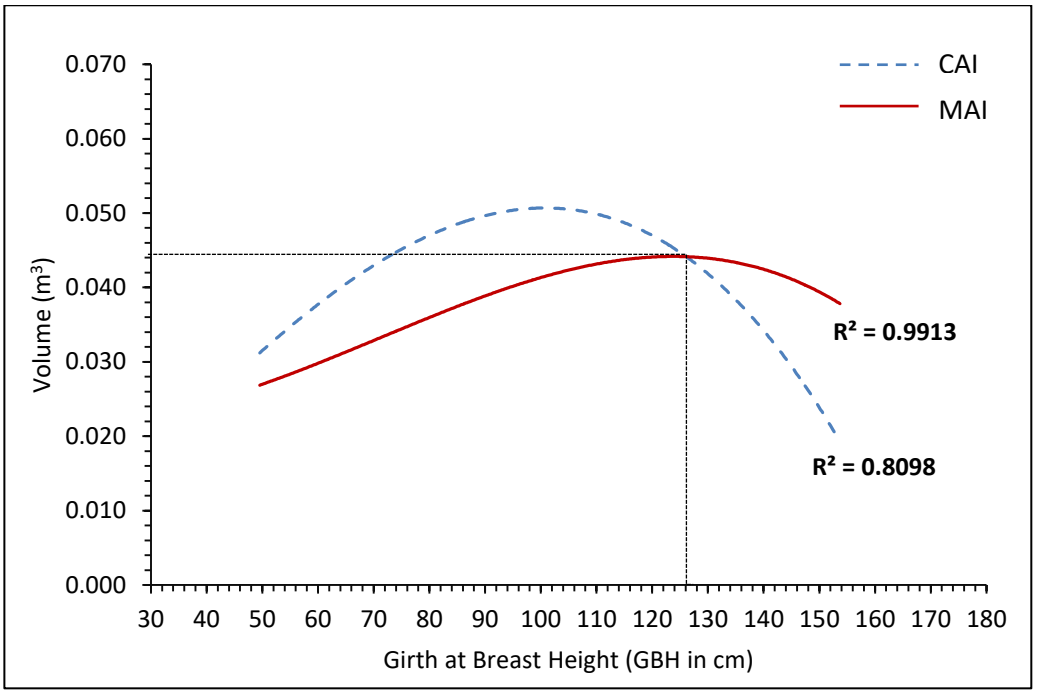


Fig 3.11 MAI and CAI volume intersection and rotation girth at breast height estimated for Site Quality-I

Chapter 4

DISCUSSION

Understanding the wood volume accumulation and biological rotation age of *Pinus kesiya* is essential for sustainable management and planning of Pine dominated natural forests in the state of Meghalaya. Therefore, present research study was undertaken to prepare the specific local and general volume equations along with calculation of current annual increment (CAI), mean annual increment (MAI) and rotation age of *Pinus kesiya* growing naturally in the state of Meghalaya. The study employs 11 different functional forms such as linear, quadratic, power, logarithmic and exponential models for the preparation of local volume equations to estimate volume (m^3) of standing *Pinus kesiya* trees based on the data of 38 sampled trees. Out of 11 models, 5 were single entry (DBH in centimeter) based and 6 were double entry (DBH in centimeter and total height in meter) based. Power models $V = aD^b$ and its linearized form $lnV = lna + blnD$ was adjudged to be the best fit local volume equation and for general volume equation, the power model $V = aD^bH^c$and its linearized form$lnV = lna + blnD + clnH$ was found to be best fit based on the lowest values of RMSE, MAPE and AIC.

The outcomes of the study align with previous studies on *Pinus* species in India and other countries, which have demonstrated the significance of DBH and height in estimating *Pinus kesiya* tree volume accurately (Fowler, 1997; Lumbers and Lee, 2013; Pant, 2001;ICFRE-RFRI, 2021) and Malata *et al.* (2017) for *Pinus patula* and *Pinus oocarpa*. Comparable research on *Pinus radiata* in different regions of the world, such as New Zealand (Kimberley and Beets, 2007) and Chile (Gonzalez-Benecke *et al.*, 2014; Gonzalez-Benecke *et al*., 2021), also emphasizes the importance of DBH in local volume estimation, albeit with variations in the specific functional forms of the models. Similar research on Pinus species growing in subtropical pine forests of Khyber Pakhtunkhwa, Pakistan (Ali *et al.*, 2020) particularly *Pinus roxburghii*, has shown variations in the effectiveness of different models. For instance, a study in Uttarakhand (Sharma, 1999) found that linearized form of power models provided better fits for predicting volume from DBH compared to linear models, corroborating the findings of the current study. Yousefpour *et al.* (2012) tested 28 different models to develop general volume equations and tables and they also found the linearized form of the power model with specific regression coefficients can predict volume most accurately in comparison to other models. Lee *et al.* (2017) estimated

and validated stem volume equations for *Pinus densiflora* and *Pinus koraiensis* in South Korea and the functional forms $V=a+bDH$ and $V=aD+bD^2$ were found to be the best fitted models upon validation. They tested 3 equations DBH based and 5 equations based on DBH and height by applying R^2, RMSE and MAD. Various other researchers (Lumbers *et al.* 2013; Tiwari and Singh, 2018 Thangjam *et al.,* 2019). Scattered plots of residuals against calculated volume show that small DBH trees have smaller deviations than larger ones. Similar observations were made for *Parkia timoriana* (Thamjang *et al.,* 2019), *Pinus pinaster* in Portugal (Alegria and Tome, 2011), *Tectona grandis* (Tiwari and Singh, 2018) and for *Pinus densiflora* and *Pinus koraiensis* by Lee *et al.* (2017).

The study also provides a prediction model for estimating DBH by using stump diameter of *Pinus kesiya* trees in Meghalaya. The results are aligned with the model developed by Eerikäinen(2002) for *Pinus kesiya* in Zambia and Zimbabwe. The study highlights significant differences in growth rates between *Pinus kesiya* trees in forests with poor site quality, exemplified by the Mookyndur forest, and those in forests with better site conditions. The observed slower growth of *Pinus kesiya* in the poor site quality, characterized by rocky hill slopes and shallow soil depth, is consistent with previous research on the influence of site quality on tree growth. Several published studies have demonstrated that soil depth, slope, and other site factors significantly impact tree growth rates and development. For instance, research by Sharma and Malik (2011) on influence of site factors on the growth of *Pinus roxburghii* forests found that aspect, soil organic carbon, soil depth and nutrient availability directly influenced the forest growing stocks. Their findings corroborate the notion that trees in poor site quality forests exhibit slower growth due to limited soil resources and harsher environmental conditions. Vanninen *et al.* (1995) recorded faster growth rates of *Pinus sylvestris* on the more fertile site. This aligns with the findings of Arunachalam *et al.* (1996), who reported similar trends in tree size variation across different site qualities in *Pinus kesiya* forests. Furthermore, studies by Moya *et al.* (2007), Xenakis *et al*. (2012) and Garcia-Aguilar *et al.* (2017) on *Pinus halepensis, Pinus patula* and *Pinus sylvestris* respectively, in different parts of world emphasized the importance of site quality assessments in predicting tree growth and forest productivity accurately.

Moreover, the fluctuating CAIs of pine trees in both types of sites underscore the influence of climatic conditions on growth rates. This variability in growth response to climate is

consistent with the findings of numerous studies investigating tree growth-climate relationships (Singh *et al.,* 2016). Shah and Bhattacharyya (2012) conducted a dendrochronological study on *Pinus kesiya, Pinus merkusii* and *Pinus wallichiana in* the northeast. They revealed spatio-temporal variability has no significant impact on inter-species tree growth variations and suggested the possible impacts of anthropogenic impact or non-climatic factors on radial tree growth in this region. Upadhyay *et al.* (2019) observed a common event year with lower growth in *Tectona grandis* and *Pinus kesiya* in the state of Mizoram, which was due to the drought year. In our study climatic conditions were similar for all studied sites; therefore, variation in growth patterns in pine trees at different sites is mainly due to the edaphic factor as there is a significant variation in the edaphic factors of the site. Such studies in India emphasize the need to consider climatic factors when evaluating tree growth and predicting future forest productivity.

The estimation of rotation age plays a crucial role in forest management practice, determining the optimal time for timber harvesting and regeneration. The analysis conducted in the study to estimate the biological rotation age of *Pinus kesiya* trees provides valuable insights for forest planning and timber harvesting operations. The identified rotation ages of 27 years for the good site quality with better soil nutrient contents and 48 years for the poor site quality forests reflect the differing growth rates and productivity levels associated with site quality variations. These findings align with the principles of rotation age determination, which consider maximizing timber yield while ensuring sustainable forest management practices (Zhou et al.,2016; Delgado-Matas and Pukkala, 2012). Darado et al. (1997) calculated MAI and CAI by measuring growth rings and calculated rotation age of *Pinus elliottii*, *Pinus taeda* and *Pinus radiata* in two areas of the Calamuchita Valley, Argentina and found similar results, i.e. a rotation age of 20-30 years. Published research on rotation age estimation for Pine forests supports the notion that rotation ages vary depending on site quality and management objectives. Studies by Verzinoa et al. (1999) and Mugasha et al. (2021) on *Pinus patula* in Argentina and Tanzania respectively, have demonstrated similar approaches to rotation age estimation based on growth curves and increment analysis.

Chapter 5

Conclusion

The present research results provide valuable insights into the growth rates and rotation age of *Pinus kesiya* in varying forest environments along with development of volume equations and tables for the *Pinus kesiya*. The study focused on analyzing and comparing a number of volume models with the purpose of identifying the best fit volume model for *Pinus kesiya* growing in Meghalaya. Study reveals that the power model or its linearized form was the best fit for most of the species. The best fit models can be applied for use in determination of above ground biomass and carbon stock by applying specific gravity. The volume equations developed would be useful for the staff of the state forest department, FSI, farmers and wood-based industries of the state of Meghalaya to estimate the growing stock, biomass and timber of *Pinus kesiya* in the state. The farmers and wood-based industries would benefit from accurate volume estimation during the sale and purchase of standing trees for the purpose of timber. It is to be mentioned that the estimation of the volumes for the trees outside the height and DBH ranges used in preparation of the equation should only be done with caution.

The estimation of rotation age emerges as a critical aspect of forest management, determining the optimal time for timber harvesting and regeneration. The analysis conducted in this study provides valuable insights into the biological rotation age of *Pinus kesiya* trees offering guidance for forest planning and timber harvesting operations. Rotation ages were identified based on site quality variations, reflecting differences in growth rates and productivity levels. These findings underscore the importance of adaptive management strategies that account for site-specific conditions and long-term forest productivity goals.

By integrating the findings of present research work with published research, forest managers and policymakers can make informed decisions regarding forest management practices, including timber harvesting schedules and regeneration strategies in the state. However, further research incorporating long-term growth data and considering additional environmental variables is necessary to refine our understanding of *Pinus kesiya* growth dynamics and optimize forest management strategies for sustainable resource utilization.

References

Alegria, C., Tomé, M. 2011. A set of models for individual tree merchantable volume prediction for *Pinus pinaster* Aiton in central inland of Portugal. European Journal of Forest Research, 130:871–879.

Ali, A., Ashraf, M.I., Gulzar S. and Akmal, M. 2020. Development of an allometric model for biomass estimation of *Pinus roxburghii*, growing in subtropical pine forests of Khyber Pakhtunkhwa, Pakistan. Sarhad Journal of Agriculture, 36(1): 236-244.

Armitage FB, Burley J. 1980. *Pinus kesiya* Royle ex Gordon (syn. *P. khasya Royle, P. insularis*Endlicher). Oxford, Oxfordshire.

Arunachalam, A., Maithani, K., Pandey, H.N., Tripathi, R.S. 1996. The impact of disturbance on detrital dynamics and soil microbial biomass of a *Pinus kesiya* forest in north-east India. Forest Ecology and Management, 88:273–282.

Ashton, M. S. and Kelty, M. J. 2015. The Practice of Silviculture: Applied Forest Ecology. John Wiley & Sons.

Bettinger, P. and Li, R. 2009. Rotation age determination for even aged forest plantations. In Forest Management, Ed. Grossberg S.P, Nova Science Publishers, Inc.

Bray, R.H. and Kurtz, L.T. 1945. Determination of Total Organic and Available Forms of Phosphorus in Soils. Soil Science, 59:39-45. http://dx.doi.org/10.1097/00010694-194501000-00006

Chesnin, L., & Yien, C. H. 1950. Turbidimetric Determination of Available Sulphates. Soil Science Society of America Journal, 15:149-151.

Choudhary, V. K., Singh, S. L., Dixit, A., Arunachalam, A., &Bhagawati, R. 2014. Biomass and carbon sequestration potential of agroforestry trees in Arunachal Pradesh, North East India. Climate Change and Environmental Sustainability, 2(1): 48-54.

Delgado-Matas, C. and Pukkala, T. 2012. Growth and yield of nine pine species in Angola. Journal of Forestry Research, 23(2):197−204. DOI 10.1007/s11676-012-0239-3

Dorado, M., Astini, E., Verzino, G., Rienzo, J.D. Perpiñal, E. 1997. Growth curves for *Pinus elliottii*, *Pinus taeda*and *Pinus radiata* in two areas of the Calamuchita Valley (Córdoba, Argentina). Forest Ecology and Management, 95(2):173-181.

Eerikäinen, K. 2002. Predicting the height–diameter pattern of planted *Pinus kesiya* stands in Zambia and Zimbabwe. Forest Ecology and Management, 175:355-366.

Food and Agriculture Organization (FAO). 2012. Sustainable Forest Management: From Concept to Practice. Retrieved from http://www.fao.org/docrep/015/i3010e/i3010e.pdf

Forest Inventory and Planning Institute. 1996. Vietna forest trees. Hanoi: Agricultural Publishing House. Pp 1-23.

Fowler, G. W. (1997). Individual Tree Volume Equations for Red Pine in Michigan. Northern Journal of Applied Forestry, 14(2):53–58.

FSI. 2019. State of forest report, 2019. Forest Survey of India, Ministry of Environment and Forests, Dehradun, India.

García-Aguilar, J. & Velasco-Velasco, V.A., Rodríguez-Ortiz, G., Valle, R.J.E. 2017. Influence of site index on the growth of *Pinus patula* Schltdl. et Cham. plantations. Revista Mexicana de Ciencias Forestales, 8:132-154.

Gonzalez-Benecke, C. A., Fernández, M.P., Albaugh, T.J., Ahumada, R. Bown, H.E., Gayoso, J., Gerding, V., Mardones, O.B., Rodríguez, A.R., Rubilar, R. 2021. General above-stump volume and biomass functions for *Pinus radiata, Eucalyptus globulus and Eucalyptus nitens.* Biomass and Bioenergy, 155:106280.

Gonzalez-Benecke, C. A., Gezan, S.A., Samuelson, L.J., Cropper, W.P., Leduc, D.J., Martin, T.A. 2014. Estimating *Pinus palustris* tree diameter and stem volume from tree height, crown area and stand-level parameters. Journal of Forestry Research, 25:43–52.

Govindarajan, M., Rajeswary, M., & Benelli, G. (2016). Chemical composition, toxicity and non-target effects of *Pinus kesiya* essential oil: an eco-friendly and novel larvicide against malaria, dengue and lymphatic filariasis mosquito vectors. Ecotoxicology and Environmental Safety, 129: 85-90.

Gupta, U. C. 1967. A Simplified Method for Determining Hot Water-soluble Boron in Podzol Soils. Soil Science, 103:424-428.

ICFRE-RFRI. 2021. Preparation of volume equations, volume, biomass and carbon tables for *Quercus serrata* and *Pinus kesiya* in Manipur. Project Report. ICFRE-Rain Forest Research Institute, Jorhat, Assam, India.

Islam S.M.Z and Chowdhury M.A.M. 2017. Equation for estimating stem volume for Agar tree (*Aquilaria malaccensis* Lamk) grown in the plantations in Bangladesh. Journal of Tropical Forestry and Environment, 7(2):85-96.

Kataki, R., &Konwer, D. (2002). Fuelwood characteristics of indigenous tree species of north-east India. Biomass and Bioenergy, 22(6): 433-437.

Kimberley, M.O. and Beets, P.N. 2007. National volume function for estimating total stem volume of *Pinus radiata* stands in New Zealand. New Zealand Journal of Forestry Science, 37(3):355-371.

Koskela, E., Ollikainen, M., &Pukkala, T. 2007. Biodiversity conservation in commercial boreal forestry: the optimal rotation age and retention tree volume. Forest Science, 53(3): 443-452.

Lee, D., Seo, Y. and Choi, J. 2017. Estimation and validation of stem volume equations for *Pinus densiflora, Pinus koraiensis*, and *Larix kaempferi* in South Korea. Forest Sci Technol. 13(2):77–82.

LeMay, V. M. 1996. Khasi pine (*Pinus kesiya* Royle ex Gordon). In: Laar, A. Van, & Akça, A. (Eds.), Forest management and planning (pp. 251–252). Kluwer Academic Publishers.

Lindsay W.L. and Norvel W.A. 1978. Development of DTPA soil tests for zinc, copper, iron and manganese. Soil Science Society of America Journal, 42:421–428.

López-Upton, J., Flores-López, H., Hernández-Díaz, J. C., & Quijano-Ruiz, L. M. 2014. Geographic distribution and environmental niche modeling of *Pinus kesiya* in the Philippines. Plant Ecology, 215(10), 1153–1169.

Lumbres, R.I.C. and Lee, Y.J. 2013. Development and validation of stem volume models for *Pinus kesiya* in Benguet province, Philippines. Southern Forests: a Journal of Forest Science, 75(3):123-128.

Lumbres, R.I.C., Pyo, J.K. and Lee, Y.J. 2013. Development of stem taper equations for Pinus kesiya in Benguet province, Philippines. Forest Science and Technology, 10(1):22-28.

Malata, H., Ngulube, E. S., Missanjo, E. 2017. Site Specific Stem Volume Models for *Pinus patula* and *Pinus oocarpa*. International Journal of Forestry Research, vol. 2017, Article ID 3981647, 6 pages.

Missanjo, E., & Matsumura, J. 2016. Wood density and mechanical properties of *Pinus kesiya* Royle ex Gordon in Malawi. Forests, 7(7), 135.

Moya, D., Espeltab, J.M., Verkaikb, I., Lopez-Serranoa, F., Heras, J. 2007. Tree density and site quality influence on *Pinus halepensis* Mill. reproductive characteristics after large fires. Annals of Forest Science, 64: 649–656

Mugasha, W.A., Laswai, F.F., Malimbwi, R.E., Chamshama, S.A.O., Abdallah, J.M., Mauya, E.W. 2021. Optimal Rotation Age of *Pinus patula* in Government Forest Plantations in Tanzania. Tanzania Journal of Forestry and Nature Conservation, 90(3):130-145

Nghiem, N. 2014. Optimal rotation age for carbon sequestration and biodiversity conservation in Vietnam. Forest Policy and Economics, 38, 56-64.

Pant, N. C. 2001. Volume Table Model and Inventory for *Pinus caribaea* in Madhya Pradesh. The Indian Forester. 127(3):180-188.

Patricio, J. H. P. and Tulod, A. M. 2010. Carbon sequestration potential of Benguet pine (*Pinus kesiya*) plantations in Bukidnon, Philippines. Journal of Nature Studies, 9(1), 99-104.

Prakash R. 1986. Forest Management, International Book Distributors, Dehradun.

Shah, S.K. and Bhattacharyya, A. 2012. Spatio-temporal growth variability of three Pinus species of Northeast Himalaya with relation to climate. Dendrochronologia, 30: 266–278

Sharma, D.P. and Malik, R.A. 2011. Influence of site factors on the growth of chir pine (*Pinus roxburghii* Sargent) forests along elevational gradient. Indian Forester, 137(1):71-82.

Sharma, R. A. 1999. Tree Aerial Volume Models for *Pinus roxburghii*. The Indian Forester, 129(3):282-284

Singh, N.D., Yadav, R.R., Venugopal, N., Singh, V., Yadava, A.K., Misra, K.G., Singh, T.B., Sanjita, C. 2016. Climate control on ring width and intra-annual density fluctuations in *Pinus kesiya* growing in a sub-tropical forest of Manipur, Northeast India. Trees, 30:1711–1721

Subbiah, B.V. and Asija, G.L. 1956. A Rapid Procedure for the Estimation of Available Nitrogen in Soils. Current Science, 25:259-260.

Tewari, V. P. and Kumar, V. S. K. 2003. Volume equations and their validation for irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. Journal of Tropical Forest Science, 15(1): 136-146.

Thangjam, U, Sahoo, U.K., Thong, P. and Sileshi, G.W. 2019. Developing tree volume equation for *Parkia timoriana* grown in home gardens and shifting cultivation areas of North-East India, Forests. Trees and Livelihoods, 4:227-239.

Tiwari, V.P. and Singh, B. 2006. Total and merchantable wood volume equations for *Eucalyptus* hybrid trees in Gujarat State, India. Arid Land Research and Management, 20:147–159.

Tiwari, V.P. and Singh, B. 2018. Total wood volume equations for *Tectona grandis* Linn F. stands in Gujarat, India. Journal of Forest and Environmental Science. 34 (4): 313-320.

Upadhyay, K.K., Shah, S.K., Roy, A., Mehrotra, N., Tripathi, S.K. 2019. Dendrochronological Potential of *Tectona grandis*, *Pinus kesiya* and *Quercus serrata* from Mizoram, Northeast India. Indian Journal of Ecology, 46(4): 722-728.

Vanninen, P., Ylitalo, H., Sievanen, R., Makela, A. 1995. Effects of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). Trees, 10: 231–238.

Verzinoa, G., Ingaramoa, P., Joseaua, J., Astinia, E., Rienzob, J.D., Doradoa, M. 1999. Basal area growth curves for *Pinus patula* in two areas of the Calamuchita Valley, Coradoba, Argentina. Forest Ecology and Management, 124:185-192

Walkley A., and Black C.A 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science, 37:1367–1378.

Xenakis, G., Ray, D., Mencuccini, M. 2012. Effects of climate and site characteristics on Scots pine growth. European Journal of Forest Research, 131(2):427-439.

Yousefpour, M. Khoshkebijary, F.F., Fallah, A., Naghavi, F. 2012. Volume equation and volume table of *Pinus pinaster*Ait. International Research Journal of Applied and Basic Sciences, 3(5):1072-1076.

Zhou, H., Meng, S., Liu, Q. 2016. Diameter Growth, Biological Rotation Age and Biomass of Chinese Fir in Burning and Clearing Site Preparations in Subtropical China. Forests, 7(8):177. https://doi.org/10.3390/f7080177

Annexure-I

Table I. Local volume table for *Pinus kesiya* in Meghalaya

DBH (cm)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	19
Volume (m^3)	**0.0304**	**0.0384**	**0.0476**	**0.0580**	**0.0699**	**0.0831**	**0.0978**	**0.1140**	0.1318
DBH (cm)	20	21	22	23	24	25	26	27	28
Volume (m^3)	0.1513	0.1725	0.1954	0.2202	0.2469	0.2755	0.3061	0.3387	0.3735
DBH (cm)	29	30	31	32	33	34	35	36	37
Volume (m^3)	0.4104	0.4495	0.4909	0.5346	0.5806	0.6291	0.6800	0.7335	0.7895
DBH (cm)	38	39	40	41	42	43	44	45	46
Volume (m^3)	0.8481	0.9094	0.9734	1.0401	1.1096	1.1820	1.2573	1.3355	1.4167
DBH (cm)	47	48	49	50	51	52	53	54	55
Volume (m^3)	1.5010	1.5883	1.6787	1.7723	1.8691	1.9692	2.0726	2.1793	2.2893
DBH (cm)	56	57	**58**	**59**	**60**	**61**	**62**	**63**	**64**
Volume (m^3)	2.4028	2.5198	**2.6403**	**2.7643**	**2.8920**	**3.0233**	**3.1582**	**3.2969**	**3.4393**

*Figures given in bold are beyond the range of observed data

Annexure-II

Table IIa. General/standard volume table for *Pinus kesiya* in Meghalaya (Part-I)

DBH (cm)	Height (meter)													
	12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
16	0.0939	0.0995	0.1050	0.1104	0.1157	0.1208	0.1259	0.1310	0.1359	0.1408	0.1456	0.1504	0.1551	0.1597
17	0.1067	0.1130	0.1192	0.1253	0.1313	0.1372	0.1430	0.1487	0.1543	0.1599	0.1654	0.1708	0.1761	0.1814
18	0.1202	0.1274	0.1344	0.1413	0.1481	0.1547	0.1612	0.1677	0.1740	0.1802	0.1864	0.1925	0.1985	0.2045
19	0.1347	0.1427	0.1506	0.1583	0.1658	0.1733	0.1806	0.1878	0.1949	0.2019	0.2088	0.2156	0.2224	0.2290
20	0.1500	0.1589	0.1677	0.1762	0.1847	0.1929	0.2011	0.2091	0.2170	0.2248	0.2325	0.2401	0.2476	0.2550
21	0.1661	0.1760	0.1857	0.1952	0.2046	0.2137	0.2227	0.2316	0.2404	0.2490	0.2575	0.2660	0.2743	0.2825
22	0.1831	0.1941	0.2047	0.2152	0.2255	0.2356	0.2456	0.2554	0.2650	0.2745	0.2839	0.2932	0.3024	0.3114
23	0.2010	0.2130	0.2247	0.2362	0.2475	0.2586	0.2696	0.2803	0.2909	0.3014	0.3117	0.3219	0.3319	0.3419
24	0.2198	0.2329	0.2457	0.2583	0.2706	0.2828	0.2947	0.3065	0.3181	0.3295	0.3408	0.3519	0.3629	0.3738
25	0.2394	0.2537	0.2677	0.2814	0.2948	0.3080	0.3211	0.3339	0.3465	0.3589	0.3712	0.3833	0.3953	0.4072
26	0.2600	0.2755	0.2906	0.3055	0.3201	0.3345	0.3486	0.3625	0.3762	0.3897	0.4030	0.4162	0.4292	0.4421
27	0.2814	0.2981	0.3146	0.3307	0.3465	0.3620	0.3773	0.3923	0.4072	0.4218	0.4362	0.4505	0.4646	0.4785
28	0.3037	0.3218	0.3395	0.3569	0.3739	0.3907	0.4072	0.4234	0.4394	0.4552	0.4708	0.4862	0.5014	0.5164
29	0.3268	0.3463	0.3654	0.3841	0.4025	0.4205	0.4383	0.4557	0.4730	0.4900	0.5067	0.5233	0.5397	0.5558
30	0.3509	0.3718	0.3923	0.4124	0.4321	0.4515	0.4705	0.4893	0.5078	0.5261	0.5441	0.5618	0.5794	0.5968
31	0.3759	0.3983	0.4202	0.4418	0.4629	0.4836	0.5040	0.5241	0.5440	0.5635	0.5828	0.6018	0.6206	0.6392
32	0.4018	0.4257	0.4492	0.4722	0.4947	0.5169	0.5387	0.5602	0.5814	0.6023	0.6229	0.6433	0.6634	0.6833
33	0.4286	0.4541	0.4791	0.5036	0.5277	0.5514	0.5746	0.5976	0.6201	0.6424	0.6644	0.6861	0.7076	0.7288
34	0.4562	0.4834	0.5101	0.5362	0.5618	0.5870	0.6118	0.6362	0.6602	0.6839	0.7073	0.7304	0.7533	0.7759
35	0.4848	0.5137	0.5420	0.5698	0.5970	0.6238	0.6501	0.6760	0.7016	0.7268	0.7517	0.7762	0.8005	0.8245
36	0.5143	0.5450	0.5750	0.6044	0.6333	0.6617	0.6896	0.7172	0.7443	0.7710	0.7974	0.8235	0.8492	0.8747
37	0.5447	0.5772	0.6090	0.6402	0.6708	0.7008	0.7304	0.7596	0.7883	0.8166	0.8445	0.8721	0.8994	0.9264
38	0.5761	0.6104	0.6440	0.6770	0.7093	0.7411	0.7724	0.8032	0.8336	0.8636	0.8931	0.9223	0.9511	0.9796
39	0.6083	0.6446	0.6801	0.7149	0.7491	0.7826	0.8157	0.8482	0.8803	0.9119	0.9431	0.9739	1.0044	1.0345

*Figures given in shaded cells are within the range of observed data.

Table IIb. General/standard volume table for *Pinus kesiya* in Meghalaya (Part-II)

DBH (cm)	Height (meter)													
	18	19	20	21	22	23	24	25	26	27	28	29	30	31
40	0.8601	0.8945	0.9283	0.9616	0.9945	1.0270	1.0591	1.0909	1.1223	1.1533	1.1841	1.2145	1.2447	1.2746
41	0.9058	0.9420	0.9776	1.0127	1.0474	1.0816	1.1154	1.1489	1.1819	1.2146	1.2470	1.2791	1.3108	1.3423
42	0.9528	0.9908	1.0283	1.0652	1.1017	1.1377	1.1732	1.2084	1.2432	1.2776	1.3116	1.3454	1.3788	1.4119
43	1.0010	1.0409	1.0803	1.1191	1.1574	1.1952	1.2326	1.2695	1.3060	1.3422	1.3780	1.4134	1.4485	1.4833
44	1.0504	1.0923	1.1336	1.1743	1.2145	1.2542	1.2934	1.3322	1.3705	1.4085	1.4460	1.4832	1.5200	1.5565
45	1.1011	1.1450	1.1883	1.2310	1.2731	1.3147	1.3558	1.3965	1.4367	1.4764	1.5158	1.5548	1.5934	1.6316
46	1.1530	1.1990	1.2443	1.2891	1.3332	1.3767	1.4198	1.4623	1.5044	1.5461	1.5873	1.6281	1.6685	1.7086
47	1.2062	1.2543	1.3017	1.3485	1.3947	1.4402	1.4853	1.5298	1.5738	1.6174	1.6605	1.7032	1.7455	1.7874
48	1.2607	1.3109	1.3605	1.4094	1.4576	1.5052	1.5523	1.5988	1.6449	1.6904	1.7354	1.7801	1.8243	1.8680
49	1.3164	1.3689	1.4206	1.4716	1.5220	1.5718	1.6209	1.6695	1.7175	1.7651	1.8121	1.8587	1.9049	1.9506
50	1.3733	1.4281	1.4821	1.5353	1.5879	1.6398	1.6910	1.7417	1.7918	1.8414	1.8905	1.9391	1.9873	2.0350
51	1.4315	1.4886	1.5449	1.6004	1.6552	1.7093	1.7627	1.8156	1.8678	1.9195	1.9707	2.0213	2.0715	2.1213
52	1.4910	1.5505	1.6091	1.6669	1.7240	1.7803	1.8360	1.8910	1.9454	1.9993	2.0526	2.1053	2.1576	2.2094
53	1.5518	1.6137	1.6747	1.7348	1.7942	1.8529	1.9108	1.9681	2.0247	2.0807	2.1362	2.1911	2.2455	2.2994
54	1.6138	1.6782	1.7416	1.8042	1.8659	1.9269	1.9872	2.0467	2.1056	2.1639	2.2216	2.2787	2.3353	2.3913
55	1.6771	1.7440	1.8099	1.8750	1.9391	2.0025	2.0651	2.1270	2.1882	2.2488	2.3087	2.3681	2.4269	2.4851
56	1.7417	1.8112	1.8796	1.9471	2.0138	2.0796	2.1446	2.2089	2.2725	2.3354	2.3976	2.4593	2.5203	2.5808
57	1.8075	1.8796	1.9507	2.0208	2.0899	2.1582	2.2257	2.2924	2.3584	2.4237	2.4883	2.5523	2.6156	2.6784
58	1.8747	1.9494	2.0231	2.0958	2.1675	2.2384	2.3084	2.3776	2.4460	2.5137	2.5807	2.6470	2.7128	2.7779
59	1.9431	2.0206	2.0970	2.1723	2.2467	2.3201	2.3926	2.4643	2.5352	2.6054	2.6749	2.7436	2.8118	2.8793
60	2.0128	2.0931	2.1722	2.2502	2.3272	2.4033	2.4784	2.5527	2.6262	2.6989	2.7708	2.8421	2.9126	2.9825

*Figures given in shaded cells are within the range of observed data.

Glossary

Above Ground Biomass (AGB): Plant parts present above the ground, which includes stem, branches, leaves and twigs.

Absolute from factor: Basal area is measured at any convenient height but volume and height of the tree are above the point of the measurement.

Absolute form quotient: Ratio of diameter or girth of a stem at a height halfway above the breast height to the diameter or girth at breast height.

Age class: All trees in a stand within a given age interval, usually 10 or 20 years.

Annual growth: The yearly increase in wood volume, usually expressed in terms of board feet or cubic feet per acre.

Area: Forest and woodland area can be defined as net forest area – the land actually covered by trees (in the National Forest Inventory and Forecast System defined as to the drip line of the canopy); and gross forest area which includes both the area covered by trees and the open spaces (of less than 0.5 hectares) within the forest boundary (e.g. rides, glades, ponds).

Artificial form factor (Breast height form factor): Basal area is measured at B. H. and the volume refers to the whole tree both above and below the point of measurement of B.H.

Assortment tables: Volume tables which give volume in round down to various stated thin end diameter possible to find out volume of a tree of given linear dimensions when the conversion was done up to 25 cm, 20 cm, 15 cm diameter limit e.g. standard and commercial volume tables are special cases of assortment tables.

Basal area: The cross-sectional area of the stem of an individual tree at its breast height point. Alternatively, the sum of the basal areas of trees in an area of woodland.

Basal Area Factor (BAF): This is the multiplying factor associated with any instrument

$BAF = 2500\ K^2\ [K = 2 \sin \frac{\theta}{2}] = 10{,}000 \sin^2 (\theta$ = angle of instrument).

Basal area per hectare: The sum of the basal areas of trees in an area of woodland expressed on a per-hectare basis.

Below Ground Biomass (BGB): Plant parts present below the ground which includes roots, rootlets.

Biological potential: A term applied to forecast scenarios broadly consistent with the objective of maximising timber production. It typically involves felling stands in the year of maximum MAI and Management Table thinning. It may not take account of factors that

constrain thinning and felling, such as wind risk and pest infestation. The main biological potential forecast referred to in the published forecast reports involves constraints on thinning and times of felling to take account of wind risk.

Biomass of trees: It is the weight of the above ground vegetative matter produced per unit area. It includes wood, their branches, bark and leaves produced by trees, shrubs and herbs and other vegetation.

Bole height: Distance between ground level and crown- point. Crown Point is the position of the first crown forming of living or dead branch.

Branch: The woody material of trees excluding the stem, stump and roots.

Breast Height (BH): The point where measurement of diameter or girth is done. It is universally adopted as standard height for measuring diameter, girth and basal area of standing trees. Breast height is measured at 1.37 m (4 ft 6 inch) from ground level in India.

Calibration distance factor: It indicates the distance at which a given angle gauge will exactly cover or a prism will exactly deviate, a rectangular target which is one meter wide.

Canopy: The uppermost layer in a forest, formed collectively by tree crowns.

Canopy density: It is a measure of relative completeness of canopy and is expressed as a decimal coefficient taking closed canopy as unity.

Canopy layers: Forests with varying age classes may have several height classes. For example, an over story canopy layer of trees overtopping a lower canopy of other trees or shrubs.

Commercial bole height: It is the height of bole that is usually fit for utilization as timber.

Commercial volume tables: Gives the volume measured down to a thin end diameter to which conversion is done, the stump volume being omitted. This table is used for preparation of local volume table and usually temporary tables for individual coupes.

Commercial volume: Volume of stem measurement up to a thin end diameter to which conversion is usually done, (excludes volume of stump).

Component: This term has a number of uses within the production forecast (e.g. SCDB component, NFI component, surveyor component and growing stock component). In the majority of the Forecast Technical Documentation the term component is used to refer to the individual characteristics of the land within the sub-compartment.

Cord: A stack of wood that has a gross volume of 128 cubic feet. A standard cord measures 4 feet x 4 feet x 8 feet and should contain approximately 80 cubic feet of solid wood.

Crown: The branches and associated foliage of a tree.

Crown class: A category of similar trees based upon the position or elevation of their crowns compared to the crowns of other nearby trees.

Crown competition Factor (CCF): It is another measure of density and is claimed to be independent of site quality and stand age.

Crown cover: The horizontal projection on the ground of the tree crown.

Crown height: It is the height of the crown as measured vertically from the ground level to the point half way between the lowest green branch and the green branches forming green crown all round.

Crown length: Vertical length (measurement) of the crown of a tree from the tip to the point half way between the lowest green branches forming green crown all round and the lowest green branch on the bole.

Crown closure: The point when in a young stand, the crowns of the trees begin to touch each other.

Crown differentiation: The process whereby some trees grow faster and develop large, full crowns, while others fall behind in height and have smaller, sparser crowns.

Crown ratio: It is the ratio between the crown length to the total height of the tree.

Crown width: The maximum spread of the crown along its widest diameter.

Cruise: A survey of forest land to estimate timber quantity. Cull: The portion of the tree stem or log which is un- merchantable is called cull. It is mentioned as a percentage of the standard volume.

Cubic meter (m^3): Unit of volume, usually used as the unit for measurements of tree stem volumes.

Cumulative volume production: The total production of timber volume from a forest stand from the time of establishment up to a given age and is usually expressed in cubic meters per hectare.

Current Annual Increment (CAI): It is the increment which a tree or a crop puts on in single year.

DAMS (Detailed Aspect Methodology Score): A measure of exposure for a particular location. DAMS is sometimes used as a proxy indicator of the risk of catastrophic wind damage to a stand of trees. This may be used subsequently to make decisions about thinning and time of clear felling.

DBH (OB): Diameter at Breast Height Over Bark which is generally measured at height of 1.37 m from ground level.

DBH (UB): Diameter at Breast Height Under Bark which is generally measured at height of 1.37 m from ground level.

DBH: Diameter at Breast Height. Diameter is generally at height of 1.37 m from ground level.

Dead wood: A standing tree that has died before it is harvested, such as a tree that has been killed by fire or insects.

Debarking: The process of removing the bark from a log by applying pressure and frictions to its outer surfaces.

Diameter limit: The smallest (but occasionally the largest) size to which trees or logs are to be measured, cut, or used. Usually refers to the stump, breast height, or top diameter.

Diameter class: The measured diameter of trees are grouped into diameter class with an interval for easy recordkeeping and easy for calculation. In Indian 2 cm, 5 cm and 10 cm diameter class are generally used.

Diopter: This is a measure of the value of an angle expressed as its sine. 1 Diopter = 0.570 or 34.36.

Dry Biomass: Plant parts dried and having moisture content of about 12 %.

Economic rotation age: The point in time (stand age) during the growth of a stand when the rate of increase of the net value of the stand begins to decline; the economic rotation age generally occurs before the physical rotation.

Felling: The cutting down or harvesting of forest trees.

Final MAI: When MAI, calculated at the rotation age, then known as final MAI.

Forest cover: All lands, more than one hectare in area, with a tree canopy density of more than 10 percent irrespective of ownership and legal status. Such lands may not necessarily be a recorded forest area. It also includes orchards, bamboos and palms.

Forest growth model: A computer program that prepares estimates of forest yields by applying all of the factors known to affect forest growth.

Forest growth: The increase in the volume of wood in a forest that occurs over a specific period of time.

Forest type map: A map of the locations of different type of trees prepared from aerial photographs of the forest with the aid of instruments called a stereoscope.

Forest management: The application of scientific, economic, and social principles to managing a forest property for specific objectives.

Forest inventory: It is a procedure for obtaining information on the quantity, quality and condition of the forest resource, associated vegetation and components and many of the

characteristics of the land area on which the forest is located.

Forest mensuration: It is a branch of forestry which deals with the determination of dimensions (diameter, height, volume etc.), form, age and increment of single tree, stands or whole woods either standing or after felling.

Form class taper tables: Give for different form classes the diameters at fixed points on the stem expressed as percentages of DBH (UB).

Form class: One of the intervals in which the range of form quotients of trees is divided for classification and use. Also applies to the class of trees which fall into such an interval.

Form point: Point in the crown at which wind pressure is estimated to be cantered.

Form factor: The ratio of the volume of a tree or its part to the volume of a cylinder having the same length and cross section as the tree. (Or ratio between the volume of a tree to the product to the basal area and height).

Form height: The product of form factor and total height of tree or the ratio between the volume to basal area of a tree.

Form point or form height ratio: The relationship usually expressed as a percentage, of the height of the form point above ground level to the total height of the tree.

Form quotient: Form Quotient is the ratio between the diameter at some point above breast height to DBH.

Fractional quality: It is the site quality expressed as decimal subdivision of the height range of half a quality class, the figures running 0.0 to 2.0 within the whole quality class.

GBH: Girth at Breast Height. Diameter is generally at height of 1.37 m from ground level.

GBH (OB): Girth at Breast Height over Bark which is generally measured at height of 1.37 m from ground level.

GBH (UB): Girth at Breast Height Under Bark which is generally measured at height of 1.37 m from ground level.

General volume tables: Average volume of trees growing over a large geographical area are considered for preparation of this type of table by taking two variables as D.B.H. and total tree height.

General yield class (GYC): An index used in Britain of the potential productivity of even-aged stands of trees, based on assessment of stand age and top height.

Girth class: The measured girth of trees is grouped into girth class with an interval for easy record keeping and easy for calculation. The girth classes used in India are 30 cm, 15 cm and 5 cm for large, medium and small sized trees.

Global Positioning System (GPS): The use of satellite technology to accurately and consistently identify exact locations.

Green/ fresh Biomass: Freshly cut plant parts having moisture content more than 70 %.

Growing stock: A term broadly referring to the standing resource of living trees at a point in time. All the trees growing in a stand, generally expressed in terms of number, basal area, or volume.

Growth habit: The natural shape of a mature tree or other plant.

Growth impact: A calculation of the extent of insect damage, taking into account the timber losses due to reduced growth rates and deaths of trees.

Growth rings: The rings formed in the trunk of a tree as wood of different densities is produced at different times during the growing season.

Hectare (ha): Unit of area equivalent to 100 metres x 100 metres = 10,000 square metres. 1 ha = 2.47 acres.

Height class: Height class is one of the intervals into which the range of tree heights is divided for classification and use. In India 1, 3 or 5 meter height classes are used.

Increment: Increase in girth, diameter, basal area, height, volume, quality, price or value of trees or crops during a given period. Also, the increase in volume of a tree or a stand over a year or annualized over a specified period measured either in m^3 per year or in m^3 per hectare per year.

Increment boring: The boring of a tree stem with the borer to determine increment of trees with annual rings.

Increment percent: It is defined as the average annual growth in diameter, basal area or volume over a specified period expressed as a percentage of diameter, basal area or volume either at the beginning or more usually halfway between the beginning and end of the period.

Like-for-like (restocking): The restocking of areas of felled trees with trees of the same species and yield class.

Local volume Tables: Only DBH (OB) is measured. Compiled from the measurement of trees growing on restricted locality like a coupe or compartment.

M1: The stand-level growth and yield model developed by Forest Research which underpins the Forecast System.

Management Table thinning: The majority of Forestry Commission yield tables (which effectively represent a set of benchmarks for forest management) prescribe a sequence of thinnings over the life of a forest stand. Management table thinning refers to the pattern of thinning recommended in these yield tables. In standard yield tables the thinnings are set to an

intensity which aims to maximise diameter increment whilst also maintaining maximum cumulative volume production.

Maximum MAI: The maximum value of mean annual increment for a forest stand as observed directly or estimated from Forestry Commission yield tables. Under UK conditions, maximum MAI is usually achieved after a number of decades.

Mean annual increment (MAI): Mean annual increment is the average rate of volume production up to a given year, expressed in cubic meters per hectare per year. In even aged stands it is calculated by dividing cumulative volume production by age.

Mean DBH: The DBH corresponding to the mean basal area of the trees in an area of woodland.

Mensuration: The study of the measurement of lengths, areas, volumes and related quantities. Forest Mensuration is concerned primarily with the measurement of trees, woods and forests including standing and felled timber.

Normal form quotient: Ratio of mid- diameter or mid –girth of a tree to its diameter or girth at breast height.

Numbers of trees per hectare: The number of trees in an area of woodland expressed on a per-hectare basis.

Ordinary taper tables/diameter taper tables: Gives the taper directly for diameter at B. H. without reference to the tree form. Enable computation of volumes without reference to the tree form.

Oven Dry Tonne (ODT) Unit of mass. When applied to wood it, represents the mass of wood in tonnes, not including the mass due to the water content of green wood (which may vary considerably).

Overbark: Used as a qualification when the diameter or volume of wood includes the bark.

Overstocked: A subjective term used to describe a stand composed of: either trees whose continued growth is constrained by competition between their crowns or trees whose stocking density is greater than a specified target level, for example as obtained from a standard yield table or both of the above.

Periodic Annual Increment (PAI): It is the average annual increment for any short period.

Periodic MAI: When MAI is calculated for a portion of the total age, then it is known as periodic MAI.

Radial growth: Growth resulting in the increased diameter in a tree.

Regional volume tables: Compiled from measurement of trees growing in a region by taking diameter and height as variables, and having limited use.

Restocking plan: A plan describing details of how felled areas are to be replanted or regenerated (for example choice of species and target plant spacing).

Rotation age: The age or stage of maturity at which a stand of trees is harvested.

Rotation length: The number of years between planting and harvesting a forest.

SCDB/sub- compartment database: A live database used by the Forestry Commission to store detailed information about the composition of each sub- compartment within the public forest estate.

Sawn outturn assortment tables: Similar to assortment tables expect that they give sawn outturn in the number of standardized pieces instead of volume in round.

Sawn outturn tables: Volume measured down to a thin end diameter to which conversion is done, stump volume being omitted (gives volume as sawn timber).

Single yield table: Data are given for one grade thinning, which is usually C – grade.

Stand: A distinct area of woodland, generally composed of a uniform group of trees in terms of species composition and spatial distribution, age class distribution and size class distribution of the trees.

Standard stem small wood volume: Volume of stem is calculated between 20cm diameter over bark and 5 cm diameter over bark. (Volume being taken inclusive of bark).

Standard stem timber volume: Volume of stem is calculated from ground level up to 20cm diameter over bark. (Volume being taken exclusive of bark).

Standard volume table: It gives separately the estimated outturn in the form of standard timber i.e. from ground level to the limit of the portion of tree stem or branch and small wood, i.e. the volume between the diameter limits of 20 cm and 5 cm and both measured over bark (volume is given in terms of round timber and includes volume of stump).

Standard timber bole height: Height of the bole from the ground level up to the point where average diameter over bark is 20 cm.

Stem/stem wood: The woody material forming the above ground main growing shoot(s) of a tree or stand of trees. The stem is defined as including all woody volume above ground with a diameter greater than 7 cm over bark. Stem wood includes wood in major branches where there is at least 3 m of ‘straight’ length to 7 cm top diameter.

Stem analysis: It is the analysis of a complete stem by measuring annual rings on a number of cross – sections at different heights in order to determine its past rates of growth.

Stocking/stocking density: Usually the number of trees in a given area. Usually expressed on a per hectare basis. Sometimes used to refer to basal area per hectare or volume per hectare.

Stump analysis: Analysis of a stump cross- section by measuring annual rings in order to estimate the age of the tree and its past rate of diameter and basal area growth.

Stump Height: Height of the top of the stump above ground.

Sub-compartment: A distinct parcel of land, distinguished from its neighbors through its overall land use, woodland composition etc. A sub-compartment may contain one or more sub-components.

Sub-component: Unique combination of stand description and intended management, which is passed to the Forecast System for processing.

Taper: The gradual diameter reduction of a tree or a log from the base to the top.

Tariff Tables: This is the volume table which gives the volume in terms of girth at breast height (GBH) alone, without differentiation of height class. This type of volume table was frequently used in France, Switzerland, and Germany.

Terminal height: The top height of a stand at which wind damage is expected to reach a level necessitating clear felling.

Timer calculators (Timer Measurement Tables): Give volume in metric system of round timber (calculated by quarter girth formula) for lengths from 1 to 25 m and girth up to 390cm and for sawn timber for length from 1 to 25m and cross section from 1×1 cm^2 to 25×25 cm^2.

Timber cruiser: A person who estimates the volume of marketable timber by taking sample measurements from sites throughout a stand of trees.

Timber yield: The timber volume in a forest on a particular date.

Thinning: The periodic harvesting of trees in woodland, involving the removal of some trees for commercial utilisation and the retention of others for future production or long-term retention.

Thinning intensity: A measure of the 'lightness' or 'heaviness' of a thinning, generally expressed in terms of the amount of timber volume per hectare removed relative to the growth rate of a forest stand.

Top diameter: The diameter of the smaller (top) end of a length of stemwood, branchwood or log, often used to define different categories of wood products (e.g. sawlogs, roundwood, pulp) and merchantable timber.

Top height: The mean total height of the 100 largest trees in a hectare of woodland. Usually assessed on a sample of the largest trees in a series of circular plots of 0.01 ha in area.

Total height: The vertical distance from ground level to the uppermost part of the tree.

Total increment (TI): It is the increment which a tree or a crop puts on from origin up to the

age at which the tree or crop is cut. It is the sum of the CAIs and represents the volume of the tree or the crop.

Total/ complete enumeration: The enumeration of the desired species above the specified diameter limit carried out over the entire area of the forest unit under consideration.

Tree factor: This is the number of trees per hectare/ acre represented by each tree tallied. This is obtained by dividing the associated plot area into the square meter area of one hectare.

Tree quality volume table: It contents the height of an individual tree with respect to its diameter. These tables are applicable to mixed forests where site quality cannot be determined.

Tree stem form: It is the rate of taper of a log or stem. Taper is the decrease in diameter of a stem of a tree or of a log from base upwards.



Ajay Kumar is a Scientist at the Green Credit Cell, Indian Council of Forestry Research and Education (ICFRE), Dehradun. He holds a postgraduate degree in Forestry (Economics and Management) from the Forest Research Institute, Dehradun, India. With over 13 years of experience in Forest Management, Forest Economics and Environmental Economics research, he has made significant contributions to the field. Ajay was stationed at the ICFRE-Rain Forest Research Institute in Jorhat, Assam for 10 years, where he completed several research projects related to forest mensuration and forest economics. Notably, he developed volume equations for the ten most abundant tree species found outside forests in Assam.



Dinesh Kumar Meena is a Scientist at Forest Ecology and Climate Change Division, ICFRE-Rain Forest Research Institute Jorhat. He obtained his Master degree in Forestry from the Forest Research Institute, Dehradun, India. He has more than 10 years of experience in Forest Soil, Forest Ecology, Climate Change and Forest Management. He has completed many research projects related to Soil quality, Soil seed bank, Forest mensuration and Ecosystem services funded by Department of Science and Technology, National Mission Himalayan Studies. Ministry of Environment, Forest and Climate Change Indian Council of Forestry Research and Education, Ministry of Earth Science etc.



Harish Chandra Chaudhary is an Indian Forest Service Officer. He has more than 31 years of experience of working under the Government of India, the Government of Meghalaya the Indian Council of Forestry Research and Education (ICFRE) and National Human Right Commission. While working under the ICFRE for five years he was associated in planning and execution of several forestry research projects. While working under the Government of India for more than six years, he dealt the matters relating to the Forest (Conservation) Act, 1980 and the Green India Mission. Under the Government of Meghalaya he has handled issues relating to forest management, protection, afforestation,wildlife and forestry research education and training. Currently, he is working as Principal Chief Conservator of Forest, Working Plan, Research & Training and District Council Affairs, Forest and Environment Department, Government of Meghalaya.



Dr.NitinKulkarni is a Forest Entomologist. He has more than 30 years' experience of working under Indian Council of Forestry Research and Education (ICFRE). He was director of ICFRE-Institute of Forest Productivity and Director-in charge of Tropical Forest Research Institute, Jabalpur. During his service, he worked on bioecology of major forest insect pest in nursery, plantation and natural forest along with their integrated pest management strategies. He has published 160 research articles in various national and international journals. Currently, he is working as director of ICFRE-Rain Forest Research Institute, Jorhat.

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