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Dendrochronology Based Growth Pattern Analysis of *Toona ciliata* M. Roem in Northeast India

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ABSTRACT

Toona ciliata is a commercially and ecologically important timber species, which grows at faster rate and partake in socio-economic upliftment of forest dwelling communities. Understanding growth patterns is critical for developing effective silviculture and forest management strategies for any species. To accomplish this, a dendrochronological study was carried out in Manipur to determine the growth pattern analysis of *Toona ciliata*. The Haglof increment borer was used to extract 50 cores from 25 trees in order to analyze the tree rings using standard dendrochronological methods. A tree ring width chronology of 35 years was developed extending from 1984 to 2018. The growth pattern analysis of common period analysis (2004 to 2018) for trees showed an increasing basal area increment (BAI) trend over time, with a sharp decline in 2014, which reflect the disturbances from anthropogenic and climatic factors during that particular year.

Keywords *Toona ciliata*, Growth pattern, Basal area increment, Dendrochronology.

INTRODUCTION

Dendrochronology, also known as tree ring analysis, is a promising tool for obtaining data on tree age, growth rate, and tree age allied yield, which are essential for determining sustainable silvicultural practices (Verheyden *et al*. 2004, Locosselli *et al*. 2019). Trees typically form one growth ring per year, which reflects the growth of the same year, including early and latewoods that vary in thickness and density due to the influence of various internal and external factors (Sajab *et al*. 2021). Thus, tree ring analysis provides critical information on the stand age, diameter growth rates, and longevity, which is used to develop long-term sustainable forest management plans (Xu *et al*. 2019, Baral *et al*. 2022). For instance, knowledge of species lifespan is necessary to comprehend the growth patterns, mortality mechanisms, and natural succession, as reported by Castagneri *et al*. (2013)

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for spruce stands of boreal forests. As such, diameter increment and growth patterns for individual trees are primary tools for forest management operations, providing important information in selection of tree species for logging, identifying trees for preservation, estimating cutting cycles, and prescribing silvicultural practices (da Silva *et al*. 2002). Tree ring studies have been used to generate long-term growth data in order to identify the pattern of tree growth changes as they can potentially produce annual growth data dating back to when a tree was first planted, i.e., retrospective growth measurements (Bowman *et al*. 2013, Upadhyay and Tripathi 2019). Ecological factors such as precipitation, temperature, latitude, altitude, and even the species type have a significant impact on the establishment of annual rings in trees (Ols *et al*. 2018, Sajab *et al*. 2021). Tree growth is the proportional development of a tree over time (Bowman *et al*. 2013), which varies greatly between individuals' trees and is heavily influenced by forest stand and individual traits (Adame *et al*. 2008, Montoro Girona *et al*. 2017). Age structure, basal area, and tree mortality are related to the tree growth and mediate the development of a forest stand (Montoro Girona *et al*. 2017). The growth pattern of a tree changes over time and depends on tree species and site factors. The growth pattern of the basal area is generally modest at first and increases until the tree enters senescence; however, the effects of stem size and age on growth are difficult to distinguish because they both increase simultaneously under natural conditions (Bowman *et al*. 2013). Absolute stand growth values expressed as basal area increment (BAI) would help researchers better understand that how climate affects radial growth. BAI is crucial in ecological and physiological research because it explains the changes in biomass accumulation rates along bioclimatic gradients. It is also used to forecast forest yield and determine the best silvicultural practices for forest management (Bowman *et al*. 2013, Sanchez-Huerta and Pompa-García 2014). Annual variation in BAI, a common estimate of absolute growth and biomass, has been suggested as a reliable predictor of aboveground forest productivity(Lockwood *et al*. 2021). BAI is a desirable annual growth measure because it can easily be obtained from tree rings and allows for reconstruction of forest and stand biomass over time (Babst *et al*. 2018).

Toona ciliata, is a large timber species that grows 25 to 35 m tall and belongs to family Meliaceae. *T. ciliate* is native to South China (Feng *et al*. 2015, Li *et al*. 2018), and is also found sporadically in the highlands of Central and Southern India, Indus eastward in the tropical Himalayas, Laos, Myanmar, Pakistan, and east coast of Australia (Kumar *et al*. 2012, Li *et al*. 2017 and Li *et al*. 2018). In India, it grows widely in sub-Himalayan tracts, Assam, the Khasi Hills of Meghalaya, Manipur, Bihar, Madhya Pradesh, and the Western and Eastern Ghats (Shah and Mehrotra 2017). Toon thrives well in rich, well-drained soils and struggles in poor sandy and dense clayey soils (Tomazello *et al*. 2001). The species is of high ecological and economic value because every part of it benefits the society. For instance, its bark is used as medicine and leather tanning material, leaves as source of important aromatic compounds, flower as red or yellow dye for silk, wood as a source of aromatic oils as well as furniture, cabinets, cigar cases and tea boxes (Kumar *et al*. 2012). Furthermore, the toon is used in various reforestation program for its capability to reach high growth increment in short time and as ornamental tree in parks (Tomazello *et al*. 2001, Kumar *et al*. 2012). *T. ciliata* exhibits distinct annual tree ringsthat can be used to estimate the age and annual increment rate of the tree. These annual tree rings can be distinguished by their beginning parenchyma bands and semi-porous ring boundaries (Tomazello *et al*. 2001). Thereby owing to its potential for dendrochronological studies, *T. ciliata* has been used for various dendrochronological studies in different parts of the world. In Thailand, it is particularly used to investigate historical records of forest stand dynamics and disturbance history, to reconstruct long-term trends of repression, release, and growth, and to scrutinized wood density and its radial variation in relation to shade tolerance (Baker *et al*. 2005, Baker and Bunyavejchewin 2006, Shah and Mehrotra 2017). Similarly, tree ring studies of toon from Australia have deciphered the relationship between environmental conditions and its phenology, growth, and wood anatomy and provided useful insights on influence of climatic factors on its growth (Shah and Mehrotra 2017). In case of India, so far three different studies have been reported on dendrochronological potential of *T. ciliata* from Karnataka, South India, (Bhattacharyya *et al*. 1992), the subtropical wet hill forests of Kalimpong, eastern Himalayas (Shah and Mehrotra 2017) and North-western Himalayas (Panda *et al*. 2022), where toon was used for dendroclimatic and dendroecological analyses. The present study is an attempt to re-establish the dendrochronological potential of toon from a new provenance i.e., Manipur, northeast India. The main objective of this study is to determine growth pattern of the *T. ciliata* using the tree ring width as BAI from Chandel Forest, Manipur Northeast India.

MATERIALS AND METHODS

Study site

The study was carried out at the Japhou community forest of Chandel district, Manipur, India. Chandel district is a part of the hill districts of Manipur, a state situated in north-eastern part of India experiencing a warm, humid agro-ecological zone with a thermic ecology. The region faced an average yearly temperature higher than 22°C and average yearly precipitation between 2000 and 2400 mm (Singh and Athokpam 2018). In Manipur, forest covers an area of around 2689 km^2 out of the total geographical area of 3313 km^2 and the state receives the south west tropical monsoon between the months of June and August (Baite 2017, Monsang and Tripathi 2019). The study site is located at 24.33° N latitude and 94.01° E longitude and at an elevation ranging from 872 to 1029 m. a.s.l. The forest stand is dominated mainly by *Pinus kesiya* and *Lithorcarpus* spp., where others associated species include *Castanopsishystrix*, *Gmelinaarborea*, *Quercusserrata*, *T.ciliata*, *Machilus vilosa*, *Magnoliachampaca*, *Rhussemialata*.

Sample collection

The wood core sampling was carried out using the Haglof increment corer, taking a total of 50 cores from 25 healthy *T. ciliata* trees of three different diameter classes (10-30 cm, 11-50 cm and > 51 cm). The samples were collected randomly, by taking typically two cores per tree. The extracted cores were immediately placed in the plastic straw and properly labelled. Each tree was recorded for information such as DBH, height, and GPS coordinates. The sampled cores were processed and analyzed in the laboratory using a standard dendrochronological method (Speer 2010). To prevent shrinkage, the collected tree cores were allowed to air dry before being mounted on grooved wooden strips using water-based glue. To make the growth ring border readily apparent under a microscope, all core samples were sanded with sandpapers of different grades ranging from 120 to 1200. They were then further dated to the calendar year by marking a single dot for each decade.

Tree ring analysis

The Windendro™ Software was used to measure the tree-ring widths with an accuracy nearest to the 0.001 mm. The measurement accuracy was cross-checked with computer application COFECHA, which examines the errors in cross-dating and provides a statistical match between segments of each core and the master chronology (Holmes 1983, Grissino-Mayer 2001). Each raw ring width series was standardized using the computer program ARSTAN (Cook 1985), which preserved the signals for climate and environmental variables while removing the stand dynamics and age-growth related trend seen as noise in dendrochronological analysis (Fritts 1976). During standardization, the raw measurements for each series were first power transformed and then detrended using first Friedman super smoother and alpha curve with a sensitivity set to the moderate flexibility alpha value of 5 (Friedman 1984). To get the detrended ring width indices, the ring width values for each year were divided by the matching fitted curve values. The detrended indices of all the series were averaged using a bi-weight robust mean to generate a standard form of tree ring chronology that lessens the impact of outliers (Cook *et al*. 1990). A decline in sample size has been observed in initial part of the tree-ring chronology. Therefore, a subsample signal strength (SSS) criterion (Wigley *et al*. 1984) with threshold value of 0.85 was applied to ascertain the most reliable period of the chronology. Statistics for the tree-ring chronology of *T. ciliata* were calculated (Table 1).

Analysis of basal area increment (BAI)

Basal area increment (BAI) is typically favored over ring width for assessing growth trends because it is a two-dimensional measure that provides a better proxy

Table 1. Descriptive statistics of the tree ring chronology of *T. ciliata.*

Parameters	Statistics
Time span (Years)	35 (1984-2018)
Series inter-correlation	0.397
Mean segment length (Years)	22.1
Number of trees/Number of cores	25/50
Mean sensitivity	0.265
Standard deviation	0.197
1st auto correlation (AC-1)	-0.102
Common period analysis	
Time span (Years)	2004-2018 (15)
Number of trees/Number of cores	25/50
Common variance (PC-1)	19.4%
Signal to noise ratio	7.126
Year with sub- sample signal >0.85	0.888 (1997)
Expressed population signal	0.877

for the three-dimensional mass increment (Visser 1995, Castagneri *et al*. 2012). Bai helps to determine variations in tree and stand growth, which aids in accurately quantifying the tree productivity (Tiwari *et al*. 2020, Baral *et al*. 2022). The ring-width measurement data was transformed into tree BAI using the following equation:

$$BAI_t = \pi R_t^3 - \pi R^2_{t-1} \quad \text{(Biondi 1999)}$$

where R is the value of tree radius and t is the year of ring formation. R software was used to calculate BAI values from tree-ring width measurements. Finally, we generated unstandardized mean BAI series for each year using the individual tree BAI.

RESULTS AND DISCUSSION

Tree ring chronology

Tree-ring width chronology of *T. ciliata* extending from 1984 to 2018 (35 years) was developed using 50 cores from 25 trees (Fig. 1). The developed chronology exhibited high mean sensitivity (MS, 0.265), high standard deviation (SD, 0.197) and low values of first order autocorrelation (-0.102), indicating good potential for dendrochronological studies (Upadhyay *et al*. 2019). A high signal to noise ratio (SNR, 7.126) showed a more useful common signal, and an expressed population signal (EPS, 0.877) above the threshold (≥ 0.85, Wigley *et al*. 1984) showed agreement between the sample chronology and the population chronology (Upadhyay *et al.* 2021).The value of series intercorrelation (SIC, 0.321) revealed the accuracy of the cross dating of the tree ring to the calendar year, MS value indicated the potential of chronology for dendrochronological studies and the EPS exhibited the ability of chronology to capture the population signal for examining climate- growth relationship (Cook and Kairiukstis 1990, Baral *et al*. 2022). Further, the SSS value exceeded the recommended limit of ≥0.85 from the year 1997 onward (Wigley *et al*. 1984). The tree-ring width (TRW) chronology statistics also exhibited agreement with the TRW chronology of *T. ciliata* developed from subtropical wet hill forests of Kalimpong, eastern Himalaya (Shah and Mehrotra 2017). The low values of first order autocorrelation in current chronology indicated its potential for dendroclimatological studies as it signifies an effective elimination of the low-frequency persistence observed in raw tree-ring series (Carer and Urbinati 2004). The oldest tree of the present chronology was recorded as 35 years old revealing the young age of forest stands in the region. Similar results had also been reported by Thomte *et al*. (2020) for their 39 years (1980-2018 CE) TRW chronology of *Pinus kesiya* developed from Sielmat, Manipur.

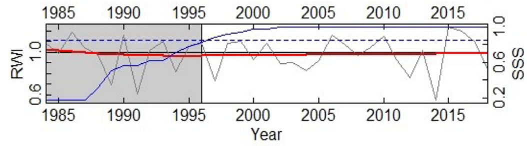

Fig. 1. Tree ring width chronology of *T. ciliata* with a red color curve representing 10 years spline-smoothing curve and blue colour curve representing sub-sample signal (SSS). RWI denotes ring-width index.

Basal area increment (BAI)

The BAI chronology of *T. ciliata* exhibited highest growth in the initial years, followed by a sharp decline and then, with a few exceptions, a stabilized increasing trend. However, the BAI for the common period (2004-2018) observed an increasing growth trend with slight fluctuations (Fig. 2) indicating the juvenile stage of forest stand, as young age trees typically show increasing growth rate followed by a plateau at maturity and then a fall in growth rate due

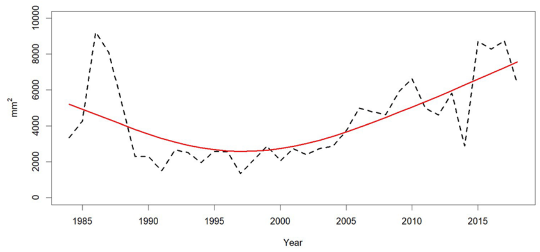

Fig. 2. Basal area increment (BAI) of *Toona ciliata*.

to ageing effects (Castagneri *et al*. 2013). Generally, growth trend of the BAI follows a sigmoidal curve (Tiwari *et al*. 2020, Baral *et al*. 2022). In healthy forest stands, BAI growth trend remains to increase or stabilize (LeBlanc *et al*. 1992, Duchesne *et al*. 2003), but trees experiencing senesce or substantial growth stress show a decreasing trend (Duchesne *et al*. 2003, Jump *et al*. 2006). The increased growth in the initial years could be attributed to fewer tree core samples representing earlier part of the BAI series, the position of core extraction could also contribute to the decline in BAI. Because extracting cores from breast height might result in loss of information for few early years' wood formation, which is causing decline in the BAI trend (Tiwari *et al*. 2020). Further, fluctuations in the growth trend may be influenced by environmental factors such as temperature, precipitation as well as site conditions and human activities. The basal area increment of forest trees varies widely, depending on the environment, inter-tree relationships, tree-specific factors (Vospernik 2021). Tiwari *et al*. (2020) found unhealthy BAI trend in *P. roxburghii* of Nepal indicating unhealthy forest resulting from untimely resin extraction and extreme human disturbances as well as longer pre-monsoon drought frequent in the central Himalayan region and young forest stand. Previous dendroclimatological studies (Bhattacharyya *et al*. 1992, Shah and Mehrotra 2017) have indicated a climate influenced growth in *T. ciliata*. Shah and Mehrotra (2017) observed positive link between TRW of *T. ciliata*, precipitation, and scPDSI (self–calibrated Palmer Drought Severity Index), where increased precipitation replenishes soil moisture and promotes tree growth during the developing period. The authors further concluded that ideal temperature, amount of precipitation and soil moisture all work together to control the radial growth of *T. ciliata* in the subtropical wet hill forests of Kalimpong region, eastern Himalaya. Similarly, a poor radial growth was observed during both years of excessive and insufficient rainfall for tree ring chronology (1800-1987) of *T. ciliata* developed from Southern India (Bhattacharyya *et al*. 1992, Shah and Mehrotra 2017). In Manipur, Thomte *et al*. (2020) and Singh *et al*. (2016) studied the tree rings of *P. kesiya* growing in Sielmat and Reserve Forest of Imphal, Manipur. Thomte *et al*. (2020) found availability of soil moisture throughout the pre-monsoon season as a crucial factor in controlling the annual growth of *P. kesiya*. High temperatures and low precipitation during pre–monsoon might trigger high evapotranspiration rates and lower the soil moisture content, which could hinder the growth of trees by producing moisture-stressed circumstances. Similarly, Singh *et al*. (2016) revealed an optimal temperature during April, May and June favoring the growth of *P. kesiya* in the region of Manipur. Various dendrochronology studies of different tree species had revealed the climate factors responsible for the tree radial growth (Carrer and Urbinati 2004, Singh and Yadav 2005, Singh and Venugopal 2011, Shah *et al*. 2014 and Upadhyay 2019). The fact that our common period BAI chronology revealed a consistent increase over time suggests that trees were growing healthily. Furthermore, observing fluctuations in BAI trend suggested that the growth may be sensitive to response of the climatic factors since our tree ring chronology revealed the young age stand which are highly sensitive to changes in climatic conditions. *P. kesiya*, which thrives in comparable climatic conditions in Manipur, demonstrated how climatic influences can limit growth (Singh *et al*. 2016, Thomte *et al*. 2020).

CONCLUSION

The tree ring chronology clearly revealed that the trees are still young as the oldest tree was 35 years old. Consequently, BAI trend showed increasing trend over time in the common period (2004 to 2018) indicating that the forest is young, healthy and in growing age. Substantial increase in BAI in the initial age followed by considerable decline after 1986 could be related to the data represented by low tree ring series during those calendar years (i.e. initial stages) and/or due to other potential disturbances in the forest because of climatic factors. Since forests are dynamic ecosystems intricately balanced with the interaction of wide range of ecological components and processes and therefore, they are prone to any abiotic and biotic disturbances. This study suggests that the growth-limiting climatic factors as well as human influence on radial growth and BAI for this species needs to be further explored to impart our understanding on growth dynamics of the species. The information will be helpful to better understand the carbon sequestration potential of the species in a changing climate.

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REFERENCES

Adame P, del Rı´o M, Canellas I (2008) A mixed nonlinear height–diameter model for pyrenean oak (*Quercus pyrenaica* Willd.). *For Ecol Manag* 256(1): 88–98.

Babst F, Bodesheim P, Charney N, Friend AD, Girardin MP, Klesse S, Evans ME (2018) When tree rings go global: Challenges and opportunities for retro-and prospective insight. *Quat Sci Rev* 197: 1-20.

Baite S (2017) Status of education in Chandel District, Manipur. *Geograph* 12(1): 1-7.

Baral S, Gaire NP, Giri A, Maraseni T, Basnyat B, Paudel A, Vacik H (2022) Growth dynamics of *Shorea robusta* Gaertn in relation to climate change: A case study from tropical region of Nepal. *Trees*, pp 1-12.

Bhattacharyya A, Yadav RR, Borgaonkar HP, Pant GB (1992) Growth-ring analysis of Indian tropical trees: Dendroclimatic potential. *Curr Sci*, pp736-741.

Biondi F (1999) Comparing tree-ring chronologies and repeated timber inventories as forest monitoring tools. *Ecoll Appl* 9(1): 216–227.

Bowman DM, Brienen RJ, Gloor E, Phillips OL, Prior LD (2013) Detecting trends in tree growth: Not so simple. *Trend Pl Sci* 18(1): 11-17.

Bunn AG (2008) A dendrochronology program library in R (dplR). *Dendrochronologia* 26(2): 115–124.

Castagneri D, Storaunet KO, Rolstad J (2013) Age and growth patterns of old Norway spruce trees in Trillemarka forest, Norway. Scand. *J For Res* 28(3): 232-240.

Chaudhary V, Bhattacharyya A (2002) Suitability of *Pinus kesiya* in Shillong, Meghalaya for tree–ring analyses. *Curr Sci* 83(8): 1010–1015.

Cook ER (1985) A Time-series Analysis Approach to Tree-ring Standardization. PhD Dissertation, University of Arizona, Press Tucson, USA.

Cook ER, Kairiukstis LA (1990) Methods of Dendrochronology: Applications in the Environmental Sciences. Kluwer Academic Publishers, Dordrecht, USA, pp 394.

Cook ER, Kairiukstis LA (eds) (1990) Methods of dendrochronology: Applications in the environmental sciences. Kluwer Academic Publishers, Netherlands, pp 414.

Da Silva RP, Dos Santos J, Tribuzy ES, Chambers JQ, Nakamura S, Higuchi N (2002) Diameter increment and growth patterns for individual tree growing in Central Amazon, Brazil. *For Ecol Manag* 166(1-3): 295-301.

Duchesne L, Ouimet R, Morneau C (2003) Assessment of sugar maple health based on basal area growth pattern. *Can J For Res* 33: 2074–2080.

Feng LX, Chen R, Zhu CS, Yang SY, Liao YH, Mai KL, Su FB, Ceng JY, Yang SH, Luo SA (2015) Age structure and spatial distribution pattern of *Toona ciliata* population in northwestern Guangxi. *J Nor For Univ* 30: 46–50.

Friedman JH (1984) A variable span smoother. Laboratory for Computational Statistics, Department of Statistics, Stanford University: Technical Report (5).

Fritts HC (1976) Tree Rings and Climate. Academic Press: New York, USA, pp 564.

Grissino-Mayer HD (2001) Evaluating cross dating accuracy: A manual for the program COFECHA. *Tree-Ring Res* 57: 205-219.

Holmes RL (1983) Computer assisted quality control in tree ring dating and measuring. *Tree-Ring Bull* 43: 69-78.

Jump AS, Hunt JM, Penuelas J (2006) Rapid climate change-related growth decline at the southern range edge of *Fagus sylvatica*. *Glob Chang Biol* 12: 2163– 2174.

Kumar S, Rana M, Kumar D, Kashyap D, Rana M (2012) A mini review on the phytochemistry and pharmacological activities of the plant *Toona ciliata* (Meliaceae). *Int J Phyto Res* 2(1): 8-18.

LeBlanc DC (1992) Relationships between breast-height and whole-stem growth indices for red spruce on Whiteface Mountain, New York. *Can J For Res* 20 (9): 1399–1407.

Li P, Que QM, Wang F, Li JC, Zhu Q, Liao BY, Chen XY (2017) Optimization and primers selection of SRAP-PCR system in *Toona ciliata* Roem. *For Res* 30(1): 10–17.

Li P, Shang Y, Zhou W, Hu X, Mao W, Li J, Chen X (2018) Development of an efficient regeneration system for the precious and fast-growing timber tree *Toona ciliata*. *Pl Biotech*, pp 18-0130.

Lockwood BR, Maxwell JT, Robeson SM, Au TF (2021) Assessing bias in diameter at breast height estimated from tree rings and its effects on basal area increment and biomass. *Dendrochronologia* 67: 125844.

Locosselli GM, Camargo EP, de Moreira TCL, Todesco E, Andrade M, de F, André CDS, de André PA, de Singer JM, Ferreira LS, Saldiva PHN, Buckeridge MS (2019) The role of air pollution and climate on the growth of urban trees. *Sci T Environ* 666: 652–661.

Monsang NP, Tripathi SK (2019) Studies on Ethno-medicinal Plants used by Tribes of Chandel District, Manipur, pp 195-201. eds. Tripathi SK, Upadhyay Kalidas, Hegde Nagaraj. Medicinal Plants of India: Conservation and Sustain able Use. Today and Tomorrow's Printers and Publishers.

Montoro Girona M, Rossi S, Lussier JM, Walsh D, Morin H (2017) Understanding tree growth responses after partial cuttings: A new approach. *Plos One* 12(2): e0172653.

Ols C, Girardin MP, Hofgaard A, Bergeron Y, Drobyshev I (2018) Monitoring Climate Sensitivity Shifts in Tree-Rings of Eastern Boreal North America Using Model-Data Comparison: Shifts in Tree Growth Sensivity to Climate. *Ecosystems* 21(5): 1042–1057.

Panda S, Bhardwaj DR, Thakur CL, Sharma P, Kumar D (2022) Growth response of seven multipurpose tree species to climatic factors: A case study from northwestern Himalayas, India. *J For Sci* 68 (3): 83-95.

Sajad S, Jawad J, ul Haq I (2021) Dendrochronological study of Cedrus deodar Grown at Kumrat valley Dir Upper KPK, Pakistan: Evaluation of Tree Age and Increment Based on Increment Core. *J Ilmu Pertanian Indonesia* 26 (2): 201-208.

Sanchez-Huerta JS, Pompa-García M (2014) Climatic Influences on Basal Area Increment of Forests in a Mountainous Landscape. *Ann Res Rev Biol*, pp 1361-1371.

Shah SK, Mehrotra N (2017) Tree–ring studies of *Toona ciliata* from subtropical wet hill forests of Kalimpong, eastern Himalaya. *Dendrochronologia* 46: 46-55.

Shah SK, Bhattacharyya A, Chaudhary V (2014) Streamflow reconstruction of Eastern Himalaya River, Lachen 'Chhu', North Sikkim, based on tree-ring data of *Larix griffithiana* from Zemu Glacier basin. *Dendrochronologia* 32(2): 97-106.

Singh J, Yadav RR (2005) Spring precipitation variations over the western Himalaya, India since AD 1731 as deduced from tree rings. *J Geo Res* 110 (1): 1-8.

Singh KS, Athokpam H (2018) Physico-chemical characterization of farmland soil in some villages of Chandel Hill District, Manipur (India). *Int J Curr Micro Appl Sci* 7(2): 417-425.

Singh ND, Venugopal N (2011) Cambial activity and annual rhythm of xylem production of *Pinus kesiya* Royle ex. Gordon (Pinaceae) in relation to phenology and climatic factors growing in sub–tropical wet forest of North East India. *Flora–Morpho Distrib Func Ecol Pl* 206(3): 198–204.

Singh ND, Yadav RR, Venugopal N, Singh V, Yadava AK, Misra KG, Singh TB, 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(5): 1711–1721.

Speer JH (2010) Fundamentals of Tree Ring Research. The University of Arizona Press, Tucson, USA, pp 508.

Tiwari A, Thapa N, Aryal S, Rana P, Adhikari S (2020) Growth performance of planted population of *Pinus roxburghii* in central Nepal. *J Ecol Env* 44(1): 1-11.

Tomazello M, Botosso PC, Lisi CS (2001) The genus *Toona* (Meliaceae): Dendrology, ecology and wood anatomy with reference to its applicability for tropical dendrochronology. *Palaeobotanist* 50: 55-62.

Upadhyay KK (2019) Developing Growth Model using Dendrochronological and Remote Sensing Observations for Important Tree Species of Mizoram (Doctoral dissertation, Mizoram University).

Upadhyay KK, Shah SK, Roy A, Mehrotra N, Tripathi SK (2019) Dendrochronological potential of *Tectona grandis*, *Pinus kesiya* and *Quercus serrata* from Mizoram, Northeast India. *Ind J Ecol* 46(4): 722-728.

Upadhyay KK, Shah SK, Roy A, Tripathi SK (2021) Dendroclimatology of teak indicates prevailing climatic conditions of tropical moist forests in India. *Ecol Indic* 129: 107888.

Upadhyay KK, Tripathi SK (2019) Sustainable Forest Management under Climate Change: A Dendrochronological Approach. *Env Ecol* 37(3B): 998-1006.

Verheyden A, Kairo JG, Beeckman H, Koedam N (2004) Growth rings, growth ring formation and age determination in the mangrove *Rhizophora mucronata*. *Ann Bot* 94(1): 59-66.

Visser H (1995) Note on the relation between ring widths and basal area increments. *For Sci* 41: 297304.

Vospernik S (2021) Basal area increment models accounting for climate and mixture for Austrian tree species. *For Ecol Manag* 480: 118725.

Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series with applications in dendroclimatology and hydrometeorology. *J Clim Appl Meteo* 23: 201-213.

Xu K, Wang X, Liang P, Wu Y, An H, Sun H, Wu P, Wu X, Li Q, Guo X, Wen X, Han W, Liu C, Fan D (2019) A new tree-ring sampling method to estimate forest productivity and its temporal variation accurately in natural forests. *For Ecol Manag* 433: 217–227.