Diversity and Conservation of Plants and Traditional Knowledge 287 - 298. 2012.
Edited by: S. Panda & C. Ghosh
Published by: Bishen Singh Mahendra Pal Singh, Dehra Dun (India)

Role of Tree-ring study in forest management: Prospects in Indian context

Amalava Bhattacharyya, Mayank Shekhar and **Santosh K. Shah**
Birbal Sahni Institute of Palaeobotany, 53 University Road, Lucknow-226007, India
E-mails: amalava@yahoo.com, mayankshekhar01@gmail.com and santoshk.shah@gmail.com

Trees are living archives. In their tree-rings impact of climatic and non climatic events occurring at the surroundings of their life span are recorded. Analyses of tree-rings in respect to dating and their applications come under special sub branch of science called Dendrochronology. It offers a valuable tool in forest resource inventory by providing long term information about the cause and effect of factors controlling tree growth. In India, many trees especially conifers growing in the Himalaya and a few broad-leaved trees at the peninsular region are recorded to have dateable tree rings. These trees could be suitable for the analyses for application of different aspects of forestry viz., productivity trees in relation to several events like climatic change, recurrences of forest fire, insect outbreaks, air pollution etc. So far tree-ring data is mostly analyzed for climatic analysis other aspects are yet to be studied seriously.

Key words: Tree-ring, Forest inventory, Annual rings, Forest productivity, Management

INTRODUCTION

The forests of India are extremely diverse in relation to varied physiognomy and climate (Champion & Seth 1968). These forests are source of renewable raw material for energy, maintain biological diversity, mitigate climate change, protect land and water resources, provide recreation facilities, improve air quality, help to alleviate poverty and others. However such invaluable forest wealth is dwindling because of forest fire, grazing, pest and invasive species and is also the primary target for urban and agricultural expansion. As consequence of these many forest areas spread across the country have been depleted and degraded very rapidly and thus become a serious societal concern. As per current assessment, total forest cover of the country is 692,027 km^2 which works out as 21.05 % of the geographical area of the country (State of Forest Report 2011). With a view to monitor the changes taken place in the resource a carefully thought out strategy to be adopted to maintain a balanced equilibrium between production and utilization. In this context a forest inventory which defines the periodic assessment of the forest resource as well as the effect of various biotic and abiotic factors has a great contemporary relevance in India. This forest inventory provides a necessary data-base for long term strategic planning at various levels. In this context, trees are the "living archives" as impact of climatic and non climatic events occurring at their surroundings including the effect of various other forest practices are rerecorded in their tree-rings. The effect of these factors at the span of the tree life could be evaluated by studying these rings. The special branch of science Dendrochronology, deals with the study of chronological sequence of annual rings (tree-rings) and its applications on various aspects. It has become a valuable tool in forest resource inventory as it provides long term information about the cause and effect which would be very useful in evolving the judicious forest management practices. Tree-ring analysis since long has been used as a dating tool in archeology subsequently applied in climatic studies (Fritts 1976; Hughes *et al* 1982) and for last several years it has gained also importance in studying the impact of various environmental factors other than climate also on tree growth (Jacoby 1987; Schweingruber 1987). Since natural disturbances and various human activities modify or reduce the climatic effect on tree growth it has become of much relevance to understand their impact on tree growth as a part of forest management. The physiology of trees under their natural environment is little explored. Most of our knowledge in this regard is based on seedlings under controlled conditions of laboratory experiments where it is easy to operate a particular factor to understand its limiting effect over others. However, the measurements taken in the controlled conditions do not necessarily reflect the same conditions as in nature where interactions of several factors and their feedback actions are operating on trees under complex environmental conditions. Dendrochronology offers an immediate opportunity to understand the impact of various environmental factors such as climate, stand competition, insect attack, pollution and other silvicultural practices on tree growth under its natural environment. The applications of this science could be used as very economic tool in forest inventory with very high resolution for example; it could be analyzed to assess productivity trees in relation to several events like climatic change or occurrence of forest fire, insect outbreaks, air pollution etc. The Indian subcontinent offers a great promise for the successful application of dendrochronology for its diversified vegetation in relation to climate and physiognomy which such diversity provide a large number of dendrochronologcally suitable taxa (Bhattacharyya *et al* 1988; Bhattacharyya & Yadav 1989) for various applications. Several characteristics of tree-ring (ring width, wood density and isotopes like oxygen-18, deutrium, carbon-14 and carbon-13 in the cellulose of the rings) have been used to study the effect of different environmental factors on tree growth. However, in these parameters ring width is most commonly used parameter as it could be studied and measured easily from a finely sanded surface of wood samples by using dissecting microscope (Fritts 1976).

In the following account basic principles of dendrochronology and its application in forestry with relevance to Indian trees have been briefly discussed in the present article.

PRINCIPAL CRITERIA FOR DENDROCHRONOLOGY

Tress should have annual tree rings (Growth rings)

The most important part in tree-ring analysis obviously is the selection of trees producing annual tree-rings. A large number of trees grow according to an annual cycle which begins generally with the opening of leaf bud during March-April with the beginning of growing period and it continues just before leaf fall or commencement of winter. In response to this cycle, the trees thin walled cell (earlywood) during early part of the growing season and small thick walled cells (latewood) during later part of the growing season. These early and latewood zones together are known as an annual ring. The formation of annual rings is generally the characteristic of trees growing commonly in temperate and sub-alpine region. In the contrary even about 25 % of tropical tree growing in India has tree-rings or growth rings (Chowdhury 1964). In those tree-ring boundaries are demarcated by several wood anatomical features. Some dendrochronological promising tropical trees along with their anatomical features demarcated their ring boundaries are shown in Table 1.

Table 1. Some of the potential trees for tree-ring analysis along with anatomical features delineating boundary of their tree-rings (After Chowdhury 1964)

Anatomical Characters	Trees
Ring Porous	*Tectona grandis*, *Lagerstroemia speciosa, Melia azedarach*
Semi Ring Porous	*Juglans regia*, *Cedrela toona, Pterocarpus marsupium*, *Pterocarpus dalbergioides*
Differences in frequency of vessels in early and late wood	*Anogeissus spp*., *Ziziphus spp*., *Mansonia spp.*
Initial Parenchyma cells	*Terminalia tomentosa*, *Dalbergia spp., Albizia spp*. *Swietenia chloroxylon, Dysoxylum spp.*
Terminal Parenchyma cells	*Michelia champaca, Magnolia campbellii*

Trees should have datable growth Rings

For the study of temporal impact of climatic and non climatic factors on tree growth, tree-rings are needed to be dated in terms of calendar years of their formation. There is a great chance of error in dating of tree-rings of a living tree if it is made by just simple count from the outermost ring considering date is contemporaneous year of logging or sampling. Trees often show evidence of locally absent or multiple rings in response to the extremities or abnormal fluctuations of any growth controlling factors. For example, rings even may not be formed when severe/ extreme climatic conditions continue for some time in the beginning of the growing period. In contrast, double or multiple rings can be formed when cambial activity is disturbed during the growing period by unfavorable conditions before approaching to normal functioning when condition improved. Such anomalies in ring pattern can be detected by cross dating, a procedure through which patterns of narrow and wide ring in tree-ring series are matched on a year to year basis within and among trees (Stokes & smiley 1968).

Dating of rings is done by cross matching of ring width variation or other characteristics of rings among several trees of same species or in different species within a locality. Cross matching in tree-ring sequences are seen because of common limiting factor usually controlling the tree growth of a particular site. In tropics where the climate suited to plant- growth throughout of the year do not show common growth pattern which precludes the dating of rings. Growth rings of most of the Indian conifers have been successfully dated through dating though missing and false ring are very in trees common depending upon the nature of the site and species (Bhattacharyya *et al* 1988, 1989). Various Indian tropical species are also known to produce growth rings (Gamble 1902; Chowdhury 1939, 1940). But the annual nature of these rings in many of these trees seems to be doubtful. This issue of dating problems associated with the tropical and sub-tropical trees from Indian subcontinent has been discussed earlier (Bhattacharyya & Yadav 1989). Many taxa of these forests have buttress in their trunk where rings are anastomosing making dating impossible. More often, anatomical features delineating ring boundary is also not conspicuous. For example, apparently appearing as distinct growth rings are in *Michelia champaca* and *M.nilagirica* growing in Koppa, Karnataka and Nilgiri respectively but after careful analyses these are reported not in annual in nature This is due to lack of synchronization in ring width variations among trees of the same species growing in those areas (Bhattacharyya *et al* 1992). In the contrary teak growing in the dry deciduous forest of Korzi, Andhra Pradesh (Yadav & Bhattacharyya 1996) and later from many sites has been found to have annual growth rings and suitable for the reconstruction of monsoon variability. Recently growth rings in three tropical tree species viz., *Acrocarpus fraxinifolius* (Caesalpiniaceae), *Dalbergia latifolia* (Fabaceae) and *Syzygium cumini* (Myrtaceae) growing in southern Western Ghats have been studied and recorded to be in annual in nature and climatic responsive (Nath *et al* 2012).

Fundamental idea of application of Tree Ring-Width

The growth of any tree either by diameter or height is considered to be the cumulative effect of genetic and various environmental factors. The genetic or inherent character of a tree regulates the adaptability and response of a tree to various environmental conditions. The supply of nutrients, moisture, temperature, light, carbon dioxide and others essential to growth is the product of environment. The width of a ring i.e., one year diameter growth increment is influenced by various factors which can be expressed by following simple quation $Rt = A_t + C_t + äD1_t + äD2t + E_t$ (after Cook *et al* 1990), where R is the observed ring-width and "t" denotes a particular year, A_t, the age size related growth trend in ring-width due to normal physiological aging processes. C_t, the climatically related environment signal that occurred during that year. $äD1_t$ and äD2t are the disturbances pulse caused by local endogenous disturbances and by stand-wide exogenous disturbances respectively, and the last one E_t the largely unexplained year to year variability not related to the other signals (ä in front of D1 and D2 indicates either a "0" for absence or "1" for presence of the disturbance signal). Therefore, to maximize the desired signal i.e., response of the parameters to be studied, the other factors (noise) should be minimized or deleted.

This is accomplished though standardization of tree-ring sequences by various curve fitting options (Cook *et al* 1990).

Longevity of Trees

The longevity of trees is not an essential criterion for tree-ring studies. Generally old trees in the lots get preference for its long tree-ring sequence so that the longest information about the factors operating in a forest site could be determined. In India, few species viz, *Cedrus deodara, Pinus gerardiana* and *Juniperus macropoda* have been reported to be very old and many of these trees growing in dry inner valleys of the Western Himalaya may cross millennium years (Bhattacharyya *et al* 1997; Yadav *et al* 2006).

APPLICATION IN FOREST MANAGEMENT

The application of tree-ring analysis could be of immense scope in the forest resource inventory of India. This may be used to date the events which affect the tree growths or kill the trees, as a proxy data could be used to reconstruct climate of a site or region, to record and quantify the effect of non climatic growth limiting factors.

Growth productivity

Forest is long lived ecosystem and their productivity is determined by the combined effect of long term climate and non climate events. A long term assessment of the effect of various growth regulating factors on forest productivity is of great necessity for the scientific management of the forest. For that knowing of age of trees of a particular forest is vital for the understanding of the tree growth/ productivity and forest dynamics. It may be estimated by 'direct' methods i.e., by counting the tree-ring or by 'indirect' methods which is calculated through ûeld measurements of growth rates. In forestry "indirect method" is usually in practice since long time (Gamble 1902). In India these are used as evaluation of growth rates of timber producing trees, wood productivity and quality, rotation cycle etc. A "direct method" though is considered to be more accurate, but lack of knowledge of systematic dating of trees earlier and non availability of suitable trees for counting rings such estimations are not in practiced. This method seems to be appropriate for many trees growing mountainous region but may not be appropriate in most of the trees growing in tropical environment.

Basal Area Increment (BAI)

The ring width measurement can also be converted to basal area increment; a common forestry unit used as an indicator for the pattern of the tree growth (Hornbeck *et al* 1987). To find the annual growth in terms of basal area increment for Year X, the following equation is used.

$$BAI= X-(X-1)/(X-1)$$

Where X is the basal area at year X and X-1 is the basal area of the tree measured the year previous to X. (units are cm and cm2). Basal area increment gives us one year's basal area growth.

Forest fire history

Forest fire is one the important factors which influence the process of natural forest ecosystems. Due to forest fire there is a huge loss in forest products every year in various parts of the country. Many trees in fire prone years exhibit fire-scar in their trunks. In a tree when the cambium gets damage by fire in some portion it produce a scar. These fire scars could be dated by dating that ring on which that scar is formed. This fire scar dating could be used to study the recurrence of fire incidence in past and its consequences (Stokes & Dieterich 1980). In India several commercially valuable timbers viz., chir pine (*Pinus roxburghii*), Kesiya pine (*Pinus kesiya*), Merkus pine (*Pinus merkusii*), teak (*Tectona grandis*) and others occasionally affected by forest fire .These trees survive after fire may exhibit fire scar in their trunks. So far, a preliminary investigation on the potential for developing long-term fire histories from India is made from chir pine forests in the Western Himalaya. (Brown *et al* 2011) This study records the oldest tree in the study site dated back to 1886, which helped date the fire scars in cross-sections collected from three trees. Fire frequency as determined from fire-scar dates was high, with mean and median fire intervals of 3 years from 1938 to 2006. Fire scars were generally recorded at false-ring boundaries and likely represent burning during the hot, dry period in May or early June before the onset of monsoon rainfall. This preliminary assessment shows there is a potential for additional samples from other stands to develop longer-term fire histories to better understand the role of fire in the ecology and management of chir pine throughout its range in the Himalaya region.

Insect epidemics

The diseases cause by insect are more acute in tropical forests where there is no marked dry season during which these could be controlled. Proper research to determine the cause, to determine actual and potential threat, to assess damage and to study factors leading to epidemics are necessary for adopting control measures and maintenance of forests in good health. Tree-ring study could be used to assess the losses in production of wood due to insect epidemics and its recurrence. Severe insect defoliation causes reduced tree growths which are reflected in the modified ring pattern. The recognition of modified ring pattern on long lived tree would provide data to reconstruct the insect outbreak history and consequent losses in biomass production. The working hypothesis for such studies is that the trees which are affected by insect are treated as host and which are not affected as non hosts. Both host and non host growing at same site and are behaving in a similar way to the climatic variables taken for tree-ring studies. If the graphical and statistical comparisons of the hosts and non host's series in conjunction with the historic records show reduced growth is considered as the effect of insect outbreak. Variation in the differences between host and non host chronologies could be used as an index of insect out breaks (Nash *et al* 1975; Swetnam *et al* 1985; Swetnam 1986). In India various trees suffer from defoliating insects. Trees of commercial value producing annual rings offer immediate potential to study the effect of insect infestation. Two valuable timber trees of India viz, Teak and deodar are good examples where wood productivity is deteriorated occasionally due to insect attack are potential to take up such analyses. It is known from long back from the report that that teak trees in Central provinces and Madras suffer from defoliation by the larvae of *Hyblaea puera* and *Pyrausta machaeralis* moths. Similarly, *Ectropis deodarae*, a defoliator causes an epidemic of deodar in the outer rings of the Himalayas in Uttar Pradesh, East Punjab (Stebbing 1914). In an exploratory study it has been observed that in the teak affected by insect defoliation had narrow growth rings while in normal trees such narrow rings were observed occasionally. Moreover, in comparison to normal trees, vessel lumen diameter remained more or less the same but its frequency was more in the affected trees. Other dimensional details like length, width, lumen diameter, frequency, etc., of individual xylem elements also showed considerable variation as compared to normal trees (Rajput *et al* 2005). We have recorded in deodar trees in the years affected by insect defoliation generally narrow growth rings associated with traumatic resin ducts. In normal trees such narrow rings were observed generally in draught years without traumatic resin duct.

Tree-Ring/Pollution

Pollution has now become a continuous problem with the increased demand due to rapid development in urbanization and industrialization leading to release and accumulation of pollutants in air water and soil. Tree-ring series could be used to assess the effect of pollutants on tree growth. Trees exposed to pollutants are affected by nutrient stress or disbalance in normal physiological activities and get susceptible to diseases and produce modified ring. Commencement year of pollution and loss of productivity could be assessed by comparing tree-ring series prepared from polluted site with that of control sites (Schweingruber *et al* 1983; Yokobori & Otha 1983; Eckstein *et al* 1984; Fox *et al* 1986). Moreover a systematic screening of the forest tree in order to select pollution tolerant/insensitive species would help in forestry programmer in polluted areas. Though there are good amount of work in this aspect carried out elsewhere but till date no work was pursued in this aspect from India.

Tree-Ring/climate

It is of great concern to know the climate change in advance and its effect on growth and yield tables which forest mangers could be used to estimate the forest productivity. For the understanding the climate trend and for its modeling, climatologist needs a long record of climate data. However, measured climatic data is not long enough in most of the meteorological stations of India to make the predictive climate model. Tree-rings could be used as proxy source to supplement the instrumental data (Fritts 1976; Hughes *et al* 1982 and others) long back. For climatic reconstruction, it is essential to have a period of overlap between existing meteorological data and tree-ring chronology. A portion of the over-lapping period is used to derive a mathematical relationship between the desired climate parameter and ring width indices. This step is known as the calibration. Remaining portion of overlapping data series is used to verify the calibration and that step is known as verification. In India tree-ring based climatic reconstructions are mostly restricted from the Western

Himalayan region. A large number of trees, especially conifers viz., *Cedrus deodara*, *Pinus gerardiana* and *Pinus roxburghii* of this region have been found suitable for climatic reconstruction. Among these, tree-ring data of *C. deodara* are extensively analyzed from several sites and found most promising for the reconstruction of pre-monsoon temperature (Borgaonkar *et al* 1996; Yadav *et al* 1999; Yadav & Singh 2002; Yadav 2007; Yadav *et al* 2011). Most salient features of these climate studies are the absence of any prominent large magnitude century scale excursions in negative anomalies from the long term average of the spring temperature of this region which might indicate regional feature of "Little Ice Age" (LIA) which had time span from around 1450 AD to 1850 AD. Even during this time span in these records there are comparatively warmer springs during 17th century. Moreover, evidence of recent global warming, which could be associated with the anthropogenic activities, has not been depicted in this region. In the contrary, data related to reconstruction of precipitation based on tree ring records are less in number. Reconstruction of precipitation for the non-monsoon months (previous October to current May) back to AD 1171 reveals that the wettest and the driest non-monsoon months are in the fourteenth and the thirteenth century, respectively. Both wet and dry spring years have been noted during the Little Ice Age (Yadav & Park 2000; Singh & Yadav 2005; Singh *et al* 2006). So far, Longest annual (August July) precipitation series back to AD 1330 was made based on a tree-ring data network of *C. deodara* from the Lahaul Spiti region. The rainfall reconstruction reveals high magnitude multidecadal droughts during the 14th and 15th centuries and thenceforth a gradual increase in precipitation (Yadav *et al* 2011). Data on tree-ring based climate reconstruction from the eastern part of the Himalaya are limited in number. Several conifers, viz., *Abies densa, Juniperus indica, Larix griffithiana, Pinus roxburghii, Pinus wallichiana, Taxus baccata* and *Tsuga dumosa* growing in diversified ecological sites are found to have datable tree-ring sequences and suitable for tree growth climate analysis. *Larix griffithiana*, a sub-alpine deciduous conifer growing in Sange, Arunachal Pradesh, has been recorded suitable for May temperature reconstruction (Chaudhary & Bhattacharyya 2000). *Pinus kesiya* growing several sites in and around Shillong plateau, does not show common response to climate records of Shillong (Chaudhary & Bhattacharyya 2002). The only report of climate reconstruction from this region is made from *Abies densa* growing at two sites, T-Gompa, Arunachal Pradesh and Yumthang, Sikkim. This reconstruction (July-September temperature) extends back up to AD 1757 and exhibits multiyear fluctuations punctuated with cool and warm periods. The warmest and coolest 10-yr periods of the entire span occurred in 1978 - 1987 (+0.25^{o}C) and 1801-1810 (-0.31^{o}C), respectively (Bhattacharyya & Chaudhary 2003).

For the reconstruction of climate from the peninsular India, teak is analyzed from several sites. In general length of teak chronology is short does not extend beyond 150 years due to rapid depletion of old trees for its high demand for timber used in furniture and other household materials. Based on ring-width data of teak, mean monsoon precipitation of June-September back to AD 1835 has been reconstructed for Hoshangabad, Central India (Shah *et al* 2007). The reconstructed climate records show several alternating periods of high and low monsoon episodes. Many of these low monsoon years have been shown to coincide with most of the known principal drought years of India. Beside ring-width, other tree-ring parameter though not commonly has also been used. There is an attempt on isotopic analysis of tree-rings of teak. A positive correlation between the variations of stable isotope ratio of hydrogen (D) for the period AD 1820-1980 with the corresponding monsoon rainfall demonstrate its feasibility for reconstructing the monsoon rainfall (Ramesh *et al* 1989). In addition, size of vessel in dated tree-ring sequence of teak has also been found suitable for climatic analysis. Early wood vessel of teak (*Tectona grandis* Linnaeus) measured through image analysis from dated tree-rings from trees growing at Perambikulam, Kerala .It is recorded that rainfall during October and November (northeast monsoon) of the previous year and April of the current year is the most important climatic variable in limiting the early wood vessel area of an annual ring. Based on mean vessel area of early wood Northeast monsoon of this region has been reconstructed, which extends from AD 1743 to 1986 (Bhattacharyya *et al* 2007).

CONCLUSION

The application of tree-ring analysis could be of immense scope in the forest resource inventory of India. A good number of trees in the Himalaya and even some in the peninsular region are found suitable for pursuing different aspects of tree-ring analysis. These studies also reveal that tree-ring data of conifers in the Himalayan region are suitable proxy, mostly for the reconstruction of both pre-monsoon temperature and precipitation. We need suitable strategies to develop to date growth rings of tropical trees. Since in India these tropical forests constitute major part constituent (90 %) of total forest area and there were might be several taxa attaining great age and their tree growth seem to be limited by vagaries of monsoon and other environmental variables. Once the technique of dating of the tropical trees is developed, it would be useful in growth rate studies, analysis of population dynamics, aging, vagaries of monsoon and other environmental studies in the vast area of the Indian subcontinent. In future not only ring width which is widely used so far, other tree-ring parameters from diversified trees and from a large number of sites should also be taken in to consideration for better understanding of tree growth dynamics in relation to its controlling factor as a part of forest management strategy.

Acknowledgements

Authors would like to express their gratitude to Dr. N.C. Mehrotra, Director, Birbal Sahni Institute of Palaeobotany, Lucknow for encouragement and permission to publish this work. They also wish to thank the Indian forest officials of different region of Himalaya, Central and Peninsular India for giving permission and providing necessary facilities during collection of tree-ring samples for several publications cited in the text.

LITERATURE CITED

Bhattacharyya, A. & Chaudhary, V. 2003. Late-summer temperature reconstruction of the Eastern Himalayan Region based on tree-ring data of *Abies densa*. *Arctic, Antarctic, and Alpine Research.* 35(2): 196 – 202.

Bhattacharyya, A. & Yadav, R.R. 1989. Dendroclimatic research in India. *Proc. Indian Nat. Sci. Acad.*. 55A (4): 696 – 701.

Bhattacharyya, A.; La Marche, Jr.; V.C. & Telewski, F.W. 1988. Dendrochronological reconnaissance of the conifers of northwest India. *Tree-Ring Bull*. 48: 21 – l30.

Bhattacharyya, A.; Sharma, J.; Shah, S.K. & Chaudhary, V. 2007. Climatic changes during the last 1800 yrs BP from Paradise Lake, Sela Pass, Arunachal Pradesh, Northeast Himalaya. *Curr. Sci.* 93: 983 – 987.

Bhattacharyya, A.; Yadav, R.R & Chaudhary V.1997.The Himalyan conifers and their perspectives in dendroclimatic studies. *Himal. Geol.* 18: 169 – 176.

Borgaonkar, H.P.; Pant, G.P, & Rupa Kumar, K. 1996. Ring-width variations in *Cedrus deodara* and its climatic response over the western Himalaya. *Int. J. Climatol*. 16: 1409 – 1422.

Brown, Peter M.; Bhattacharyya, A. & Shah, S.K. 2011. Potential for developing fire histories in chir pine (*Pinus roxburghii*) forests in the Himalayan foothills, India. *Tree-ring Res.* 67(1): 57 – 62.

Champion, H.G. & Seth, S.K., 1968. *A revised survey of the forest types if India*. Government of India Press, Delhi.

Chaudhary, V. & Bhattacharyya, A. 2000. Tree ring analysis of *Larix griffithiana* from the Eastern Himalayas in the reconstruction of past temperature. *Curr. Sci*. 79(12): 1712– 1716.

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

Chowdhary, K.A. 1939. The formation of growth ring in Indian trees. Part II. *Ind. For. Rec*. 2 (2): 41 – 57.

Chowdhary, K.A.1964. Growth rings in tropical trees and taxonomy. *J. Indian Bot. Soc*. 43: 334 – 343.

Cook, E.R. 1990. A conceptual linear aggregate model for tree rings. In: E.R. Cook and L.A. Kairiukstis, eds., *Methods of Dendrochronology: Applications in the Environmental Sciences*. International Institute for Applied Systems Analysis, Kluwer Academic Publishers, Boston, MA: Pp. 98 – 104.

Eckstein, D.; Richter, K.; Aniol, R.N. & Quiehl, F. 1984. Dendrochronological investigations of the beech decline in the south western part of the vogelsberg (West Germany). [In German]. *Forstwiss. Cent.bl.* 103: 274 – 290.

Fox, C.A.; Kincaid, W.B.; Nash, III, T.H. & Fritts, H.C. 1986. Tree ring variation in western larch (*Larix occidentalis*) exposed to sulfur dioxide emissions. *Cand. J. For. Res*. 16 (2): 283 – 292.

Fritts, H.C. 1976. *Tree Ring and Climate*. Academic Press, London.

Gamble, J.S. 1902. *A Manual of Indian Timbers*. Sampsonlow, Marston and Co., London.

Hornbeck J.W.; Smith, R.B. & Federer, C.A. 1987. Extended growth decreases in New England are limited to red spruce and balsam fir. In *Proc. Intern. Symp. Ecol. Asp. Tree ring Anal*. New York, pp. 38 – 44.

Hughes, M.K.; Kelly P.M.; Pilcher, J.R. & LaMarche, V.C.1982. *Climate from tree rings*. Cambridge Univ. Press, London.

Jacoby, G.C. & Hornbeck. J.W 1987. *Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis*. U.S. Dept. of Energy Publ., Tarrytown, N.Y., U.S.A.; 18-21 August 1986. CONF- 8608144. 726p.

Nash, III T.H.; Fritts H.C. & Strokes M.A. 1975. A technique for examining non climatic variation in widths of annual tree rings with special reference to air pollution. *Tree Ring Bull.* 35: 15 – 24.

Nath, C.D.; Boura, A.; Franceschi, D.D. & Pelissier, R. 2012. Assessing the utility of direct and indirect methods for estimating tropical tree age in the Western Ghats, India. *Tree* 26: 1017 – 1029.

Rajput, K.S.; Rao, K.S. & Patil, U.G. 2005. Cambial Anatomy, Development and Structural Changes in the Wood of Teak (*Tectona grandis* L.f.) Associated with Insect Defoliation. *J. Sustainable For.*. 20(4): 51 – 63.

Ramesh R, Bhattacharya S.K & Pant G.B 1989 Climatic signiûcance of äD variations in a tropical tree species from India; *Nature.* **337** 149–150.

Schweingruber, F.H. 1987. Tree Rings. Basics and Applications of Dendrochronology. D. Reidel Publishing, Dordrecht, Netherlands.

Schweingruber, F.H.; Kontic, R. & Winkler-Seifert, A. 1983. Application of Annual Ring Analysis in Investigation of *Conifers Dieback* in Switzerland. *Swiss Inst. For. Res. Rep.* 253: 1–29, Birensdorf, Switzerland [in German].

Shah, S.K.; Bhattacharyya, A. & Chaudhary, V. 2007. Reconstruction of June-September precipitation based on tree-ring data of teak (*Tectona grandis* L.) from Hoshangabad, Madhya Pradesh, India. *Dendrochronologia*. 25: 57 – 64.

Singh, J. & Yadav, R. R. 2005. Spring precipitation variations over the western Himalaya, India, since A.D. 1731 as deduced from tree rings. *J. Geophys. Res*. 110, D01110.

Singh, J.; Park, W.K. & Yadav, R.R. 2006. Tree-ring-based hydrological records for western Himalaya, India, since A.D. 1560. *Clim. Dyn.* 26: 295 – 303.

State of Forest Report 2011. Forest Survey of India (Ministry of Environment & Forests) Forest cover, Chapter 2. Kaulagarh Road, Dehradun, India.

Stebbing, E.P. 1914. *Indian forest insects of economic importance. Coleoptera*. Eyre and Spottiswodde Ltd. London.

Stokes, M.A. & Dieterich, J.H. 1980. Proceeding of the Fire History Workshop. USDA *For. Serv. Gen. Tech. Rep.* RM–81.

Stokes, M.A. & Smiley, T.L. 1968. *An Introduction to Tree-Ring Dating*. University of Chicago Press, Chicago, USA.

Swetan, T.W.1986. Radial growth losses in douglas fir and white fir caused by western spruce budworm in northern New Mexio:1700-1983 US. *Dept. Agric. SW. Reg. For. Rest. Manag. Rep*. 386 – 262 pp.

Swetnam, T.W.; Thompson, M.A. & Sutherland, E.K.1985.Using dendrochronology to measure radial growth of defoliated tree. *US Dept. Agric. For. Surv. Agric. Handbook* 639: 39 pp.

Yadav, R.R.; Singh, J.; Dubey, B. & Mishra, K.G .2006. A 1584-year ring-width chronology of *Juniper* from Lahul, Himachal Pradesh: Prospects of developing millennia long climate records; *Curr. Sci*. 90**:** 1122 – 1126.

Yadav, R.R. 2011. Tree ring evidence of a 20th century precipitation surge in the monsoon shadow zone of the western Himalaya, India. *J. Geophys. Res.* 116, D02112

Yadav, R.R. & Park, W.K. 2000. Precipitation reconstruction using ring-width chronology of Himalayan cedar from western Himalaya: preliminary results. *Proc. Indian Acad. Sci.*. A 109: 339 – 345.

Yadav, R.R. & Bhattacharyya, A. 1996. Biological inferences from the growth climate relationship in teak from India. *Proc. Indian Acad. Sci.* B 62(3): 233 – 238.

Yadav, R.R. & Singh, J. 2002. Tree-ring-based spring temperature patterns over the past four centuries in western Himalaya. *Quat. Res*. 57(3): 299 – 305.

Yadav, R.R. 2007. Basin specificity of climate change in western Himalaya, India: Tree-ring evidences. *Curr. Sci*. 92(10): 1424 – 1429.

Yadav, R.R.; Park, W.K. & Bhattacharyya, A. 1999. Spring-temperature variations in western Himalaya, India, as reconstructed from tree-rings: AD 1390-1987. *The Holocene* 9(1): 85 – 90.

Yokobori, M. & Otha, S. 1983. Combined air pollution and pine ring structure observed xylochronologically. *Europ. J. For. Pathol*. 13 (1): 30 – 45.