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Sustainable Forest Management under Climate Change : A Dendrochronological Approach

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Abstract Human induced persistent climate change has greatly affected the structure and functioning of natural as well as man made ecosystems. Forest ecosystem functioning, vegetation patterns and distribution of species is largely affected by the climate. Further, climate change can critically affect frequency and patterns of forest disturbance events e.g. forest fires, exotic species, insects and pests outbreak, drought, windstorms, landslides and can significantly affect the forest health. Dendrochronology provides the basis for studying these events at different time scales in relation to the changing climate. It helps in accumulating data about forest growth trends, species adaptation, physiological responses to stressed conditions and frequency and patterns of different disturbance events with respect to changes in climate. Analyzing this data can provide the basis for developing the better management plans for forests management under changing climate scenario and promote sustainable use of forest ecosystem.

Keywords Climate change, Dendrochronology, Forest inventory, Physiological responses, Sustainable forest management.

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Introduction

Forests are the source of innumerable goods and services to humanity. Humans have evolved alongside of the forest ecosystems. The people from almost all regions and especially from developing world are dependent forests for their livelihood and sustenance. The pressure on forest ecosystems has increased since This advent of the industrialized era (Brath et al. 2015). This industrialization and urbanization have become the necessity to sustain the ever-increasing human population. High rates of industrialization has put immense pressure on air, water and land resources and have polluted all of them (Brath et al 2015). The alarming amount of greenhouse gasses in the atmosphere is increasing the earth's temperature and destroying the protective layer of ozone.

These atmospheric changes are resulting in rising air temperature and altered rainfall and snowfall patterns with changes in their timing, amount and interannual variability (IPCC 2013). Climate has a profound effect on vegetation patterns and is believed to be the most significant factor to determine the forest ecosystem functioning and distribution of forest species (Solomon 1986, IPCC 1995, Kirschbaum et al. 1996). Forest are long-lived ecosystems and possibly sensitive to long-term climate vagaries due to a high-level of societal dependence on forests for sustenance and livelihood (Bernier and Schöne 2009). The global temperature has risen by 0.078 ^{0}C and is further projected to rise from 0.3 to 4.8 ^{0}C by 2090-2099 (Hansen et al. 2010, Priti et al. 2016). An increase in temperature (1-2 ^{0}C) less than the current projections may change the trend in forest productivity, species composition and biodiversity (Leemans and Eickhout 2004). The natural ecosystems have a significant effect of climate change on their structure and function as it can change frequency and pattern of biotic and abiotic events viz. forest fires, exotic species, insects and pests outbreak, drought, windstorms, landslides (Dale et al. 2001). Changes in temperature and rainfall could lead to species distribution range shifts and even loss of habitat in case of some species (Malcolm et al. 2006, Coetzee et al. 2009, Anderegg et al. 2015a). However, forest species and ecosystems have records for resilience to adaptation, the magnitude of future changes will be beyond the adaptive capacity to avoid the loss of vital ecosystem services and functions and extinction of species locally (Seppälä 2009).

Although, the climate could have a positive effect at some places and for some species due to increased temperature and growing season with CO_2 fertilization effect, but projections are mostly negative (Keenam 2015). Warming in cold-humid areas triggers the tree growth due to the prolonged season (Cuny et al. 2014, Rossi et al. 2016) but in drier areas triggers a physiological response against increased water demand to lower down hydraulic conductivity which results in decreased production, poor carbohydrate allocation for structural growth and tree mortality (Adams et al. 2017). Climate change effect has observed in vegetation distribution range shifts (Kelly and Goulden 2008, Lenoir et al. 2010) and plant mortalities due to drought and heat (Allen et al. 2010). The effects are further intensified due to anthropogenic activities viz. increasing O_3 concentration at low altitude, deposition of N pollutants, accidental introduction of exotic pests, habitat destruction and other disturbances (Bernier and Schöne 2009). Tidal freshwater forests being replaced by the tidal salt water forests (mangroves) due to sea level rise in coastal reaches of sub-tropics (Doyle et al. 2010, Di Nitto et al. 2014).

Sustainable management of forests involves baseline information related to growth pattern, age class distribution, reproduction rate and endurance of tree species under exploitation (Groenendijk et al. 2014). Permanent plots are the principal source of this information with close monitoring of all the individuals. These permanent plots are scarce, especially in India and available at only a few places. Above this, making accurate estimates of growth rate and tree age is rather difficult due to the availability of a few individuals and a short monitoring period (Groenendijk et al. 2014).Although, the large scale-forest inventories are available for some species and forest areas but they offer low temporal resolution (Rohner et al. 2016). Analyzing effects of age, spacing and choice of species composition on forest growth and better wood quality control are the keys to effective forest management (Spiecker 2002). Apart from this, information on species interaction with environmental changes on particular site is crucial for risk assessment (Spiecker 2002).

Dendrochronology

Dendrochronology is the branch of science which deals with annual rings of trees and infers the information about their age, growth rate, past events of forest fires and insect pests outbreaks, wood quality (density) and tree species interaction with the past environment with high temporal resolution. Tree rings record the environmental conditions through changes in their growth pattern and later used as an archive for the past environment (Spiecker 2002). Tree ring width measurements provide retrospective growth information across large environmental gradients and at different time scale from sub-annual to the multi-centennial. This information is crucial to realize global climate change impacts on forest vegetation (Babst et al. 2018). Tree rings has been used to study impact of climate change on forest growth, growth recovery from climate extremes, relationship between growth and canopy dynamics, signs of CO_2 fertilization (Babst et al. 2018). The other applications of dendrochronology include quantification of above aboveground biomass (Babst et al. 2014b) understanding physiology of wood development (Rathgeber et al. 2016) and standardization of climate reconstruction models (Guiot et al. 2014).

Climate change has become a definite feature of Anthropocene (Marotzke et al. 2017) and forecasting and quantifying the impact on natural ecosystems have become inevitable. Forests are the major sinks for anthropogenic CO_2 (Le Quéré et al. 2016) and store it in their woody biomass for a very long period of time (Körner 2017). The impact of biotic and abiotic changes on forest ecosystem can be understood at spatial and temporal scales through knowledge about the possible consequences of increased warming (Babst et al. 2018).

Applications of dendrochronology in climate resilient forest management

Tree rings and forest inventory data

Climate has strong influence on tree growth and tree rings give great insight into climate- growth relationship. Tree ring data is insufficiently available to understand the forest development at large spatial scales under climate change (Rohner et al. 2016). Combining tree ring measurements with forest inventory data can help in improving the models for forest dynamics (Evans et al. 2017). The robust forest dynamics models can improve our understanding on forest growth responses to anthropogenic climate change and develop better management plans to save the ecosystems and ecosystem services. Inventory data such as diameter at breast height (DBH) can be combined with tree ring data to reconstruct annual tree diameter (Bakker 2005) and further be transformed into absolute estimates of tree growth using allometric equations (Babst et al. 2018, Forrester et al. 2017). The absolute estimates of tree growth can be linked with carbon sequestration and forest productivity (Babst et al. 2018. Klesse et al. 2018). Demographic competition has critical influence on growth of individuals and important for carbon accounting work (Chen et al. 2016, Babst et al. 2018). Inventory data on forest stand basal area can be used to understand the forest vegetation competition in a given stand. Further, the two data sets can also be integrated through Bayesian hierarchical model to infer information about impact of multiple factors such as climate, biophysical conditions, tree size, stand level competition, canopy status and forest management practices on tree growth (Evan et al. 2017).

Integrating tree rings with genetic and physiological traits

IPCC (2013) has projected an increasing frequency of temperature dependent extreme events (drought or heat waves) which could result in niche shifts for many forest species (McKenney et al. 2014). This has raised the question about trees ability to stand with these rapid changes. Adaptation and niche shift of species is expected to be slow (Housset et al. 2018) and will be dependent on species sensitivity to climatic changes and its adaptation capacity (Aubin et al. 2016). The behavior of a species can be predicted under projected environmental changes using the information on genetic and physiological responses of species to climate (Aubin et al. 2016, Urban et al. 2016, Aitken and Whitlock 2013). Time series data based on tree rings is must to assess tree sensitivity to climate fluctuation and explaining its genetic makeup of adaptation (Alberto et al. 2013).

Genotype-environment association (GEA) and genotype-phenotype association (GAP) are the two genomic approaches applied to identify genes for local climate adaptation (Sork et al. 2013). GEA method establishes a correlation between genetic markers and environmental parameters of origin place of populations (Coop et al. 2010) whereas GPA shows a link between genotypes of shared environment and characters of interest and has an advantage over GEA (Eckert et al. 2015). Common garden experiments combined with genetic material from provenances and dendrometric characters viz. diameter or height are recommended to document local adaptation (Alberto et al. 2013) under rapid climate change scenario (Sork et al. 2013). Further, these experiments combined with genomic methods offer the advantage of decoding genomic makeup of local adaptation and identifying alleged genes or genomic regions of climate resilience (de Villemereuil et al. 2016).

Functional characters related to climate adaptation are little known and their evaluation is rather difficult (Aitken and Bemmels 2016), especially the valuation of dendrometric characters which are the collective result of diverse climatic events. Measurement of these traits would require advanced tools and approaches to expand the knowledge about species sensitivity and adaptability (Urban et al. 2016)

Dendroecologist have developed several methods of linking wood anatomical traits changes with climate and allows quantification of climatic limits employed on trees (Girardin et al. 2016, Hartmann and Trumbore 2016, Housset et al. 2018). Cambial activity is the function of the physiological mechanism of trees related to water stress, resistance for freezing injuries and phenological dormancy. Measuring these characteristics of wood can help in developing reflective time-series data for growth characters. Quantification of yearly growth responses for prompt climatic extremes evaluates the influence of abiotic stresses (Montwé et al.2016).

Secondary xylem acts as archive for external signals which modifies its functional traits at periods of time (Baas and Wheeler 2011). In living trees, wood performs crucial functions of plant hydraulics, mechanical support, metabolism and defence against microorganisms and insects (Baas and Wheeler 2011).

Hydraulic conductivity of tree is determined by diameter and density of wood vessels, type of perforation plate (simple or scalariform) and porosity of pit membrane (Sperry 2003). These traits have control over cavitation of water columns, extension of embolism under high negative pressure and spread of air bubbles due to freeze-thaw cycles (Choat et al. 2008). Wood anatomical features interact with root-rhizosphere interface and stomatal water-air interface in hydraulic continuum (Barnard et al. 2011). The trajectories of wood structural feature and other hydraulic, biophysical and physiological traits are interrelated and results in different trade-off series and part of species tactics to-gain other resources along with water (Reich 2014, Anderegg and Meinzer 2015b), Xylem safety versus efficiency is the best example of hydraulic trade-off wherein highly conductive xylem is more prone to drought induced embolism (Anderegg and Meinzer 2015b). Wood density serves as strong proxy of an array of hydraulic traits and found to be related with trunk to branch vessel tapering and leaf-specific conductivity of branch as well as whole plant (Chave et al. 2009, Anderegg and Meinzer 2015b).

Higher CO_2 concentrations increases the intrinsic water efficiency (iWUE) of forests (Keenan et al. 2013) and allows them to sequester more carbon per unit of water (Ponce- Campos et al. 2013). It also affects xylem anatomy and results in larger canals in ring porous angiosperms and in some gymnosperms (Way 2013, Anderegg and Meinzer 2015b). Large sized canals result in increased hydraulic conductivity and susceptibility to water stress and often counter-balanced by CO_2 accelerated temperature and drought (Kilpeläinen et al. 2007, Anderegg and Meinzer 2015b). The close coupling among xylem anatomy, its functions and environment projects hydraulic traits act as an indicator of drought vulnerability of location, species and biomes (Nardini et al. 2013). Studies have shown the mortality risk in species due to hydraulic system failure and have reported that a loss of 50% in hydraulic conductivity in gymnosperms and 80% in angiosperms can result in plant death (Brodribb and Cochard 2009, Urli et al. 2013).

Dendrochronology and dendroanatomy offer opportunity to study above characters on different time scales and help in understanding the genetic and physiological traits of tree species related to climatic adaptation.

Linking forest disturbances and tree rings

Climate change has also affected the occurrence and frequencies of forest disturbance events such as forest, insect outbreak, floods, wind, avalanches, pathogen outbreak and drought (Speer 2010). Dendrochronology can also be linked with the disturbances in a forest stand. The history of forest disturbance events such as insect outbreak, disease outbreak, forest fires can bes studied using dendrochronology (Speer 2010).

The history of fires events is studied under dendropyrochronology. It helps dendrochronologists in determining the natural range of variability which describes the past incidences of fire, their frequency and extant (Speer 2010). Forest fire, a vital ecosystem process critically affects the trees in fire prone areas, affects mortality rate and stresses out the surviving individuals (Varner et al. 2009, Seifert et al. 2017). Its impact can be seen in the affected part of tree and also reflects in the ring-width due to systemic reaction of tree (Grissino-Mayer 2010, Fulé 2010). This has become important under current weather conditions of increasing temperatures and irregular rainfall due to climate change (Aldersley et al. 2011).

Tree rings are also used for reconstruction of insect outbreak events using both either direct host growth chronology or growth chronology of non-host to detect decreases in the growth of host species, the latter is preferred (Humbert and Kneeshaw 2011). These events are studied under dendroentomology and it documents information on outbreak occurrence, changes in insect population and outbreak duration, outbreaks frequency and their spread (Swetnam et al. 1985, Speer 2010). Dendroentomological tools are also used to study forest pathogen outbreaks and complex disturbance system of multiple agents (Thompson 2005, Welsh 2007, Speer 2010).

Another disturbance in forest ecosystems is occurrence of floods. As per the Intergovernmental Panel on Climate Change (IPCC), the intensity and frequency of floods is likely to increase due to increase in intensity and frequency of heavy precipitations IPCC 2012, Ballesteros-Cánovas et al. 2015). The tree ring studies of floods are based on process-event-response (Shroder 1978) and past evidences of flood can be traced through abrasion scars, stem abnormalities, bending of stems, dead trees and abnormalities in wood anatomy caused by prolonged submergence (Ballesteros-Cánovas et al. 2015).

Snow avalanches are common feature in mountainous regions and generally occur in high and steep mountain slopes (Köse et al. 2010). Tree rings record avalanche events and avalanches can be dated using dendrochronological methods (Schweingruber 1996, Köse et al. 2010). The avalanche frequencies, regions of occurrence and their boundaries can be determined using data related to tree rings and vegetation structure (Casteller et al. 2007, 2008, Köse et al. 2010).

Generally, wind damages the forest vegetation in a scale of low to intermediate severity but sometimes it severely affects forest ecosystem and coverts the landscape of thousands of hectares (Freiich 2002, Woodall and Nagel 2007, Zielonka et al. 2010). The information on past disturbances helps in identifying potential threats using current structural and compositional pattern and projecting future development (Zielonka et al. 2010). Dendrochronological techniques based on detection of tree ring reaction (e.g. growth release co-occcurred in time with enhanced production of reaction wood) to disturbance which occurs due to post-disturbance improbement of resource conditions. (Bergeron et al. 2002, Zielonka et al. 2010).

Combining tree rings with space-based indices

Application of high temporal frequency and long-time series remote sensing data taken from on different spectral channels has become common to monitor changes in vegetation. Several space-based vegetation indices (e.g. Normalized Difference Vegetation Index -NDVI, Enhanced Vegetation Index- EVI) have been developed to monitor and measure the status of vegetation. Among these, NDVI is most frequently used. The changes in the physiology and structure of the plant canopy can directly be viewed using NDVI (Wang et al. 2004b). The values of NDVI strongly correlate with leaf area index (LAI) and forest biomass, whereas, tree ring widths and maximum latewood density are closely related to forest productivity (Wang et al. 2004a, D' Arrigo et al. 2000). Tree rings provide high resolution data of age estimates and long-term growth which are crucial to understand tree population dynamics and development of sustainable management systems (Brienen and Zuidema 2005). Correlating tree rings width data with NDVI (canopy phenology) can help in refining forest productivity estimates (Babst et al. 2014a). Annually resolved long-term carbon budgets can be developed by distinguishing time of cambial activity and leaf phenology through tree rings and space-based indices (Babst et al. 2014a).

Conclusion

Dendrochronology has great scope in understanding the impact of climate change on forest ecosystem structure and functioning. It has wide range of applications in forestry researches and can be applied to study the impact of climate change on growth related trends of forest trees, species specific traits for local adaptation, physiological response of forest tree towards water stress condition and impact of forest disturbances (viz. forest fire, inset outbreak, floods, wind, avalanches, pathogen outbreak) on forest health. Tree ring data with high temporal and spatial resolution gives great insight into these events and helps in understanding the forest and individual tree response towards these events. Dendrochronological data from natural as well as permanent forest plots can play an important role in such studies. The findings from these studies could provide the basis for better forest management strategies under changing climate scenario and can help in managing the existing forests in sustainable manner.

References

Adams HD, Zeppel MJ, Anderegg WR, Hartmann H, Landhäusser SM, Tissue DT, Huxman TE, Hudson PJ, Franz TE, Allen CD (2017) A multi- species synthesis of physiological mechanisms in drought-induced tree mortality. Nature Ecol & Evolut 1 : 1285.

Aitken SN, Bemmels JB (2016) Time to get moving : Assisted gene flow of forest trees. Evolut Appl 9 (1) : 271—290.

Aitken SN, Whitlock MC (2013) Assisted gene flow to facilitate local adaptation to climate change. Ann Rev Ecol Evolut and Syst 44 : 367—388.

Alberto FJ, Aitken SN, Alia R, González –Martinez SC, Hänninen H, Kremer A, Savolainen O (2013) Potential for evolutionary responses to climate change-evidence from tree populations. Glob Change Biol 19 (6) : 1645—1661.

Aldersley A, Murray SJ, Cornell SE (2011) Global and regional analysis of climate and human drivers of wildfire. Sci Total Environ 409 : 3472—3481.

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim J-H, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259: 660—684. doi : 10.1016/j.foreco.2009.09.001.

Anderegg WRL, Hicke JA, Fisher RA, Allen CD, Aukema J, Bentz B, Hood S, Lichstein JW, Macalady AK, McDowell N, Pan Y, Raffa K, Sala A, Shaw JD, Stephenson NL, Tague C, Zeppel M (2015a). Tree mortality from drought, insects and their interactions in a changing climate. New Phytol 208 : 674—683.

Anderegg WR, Meinzer FC (2015b) Wood anatomy and plant hydraulics in a changing climate. In Functional and ecological xylem anatomy Springer, Cham. pp 235—253.

Aubin I, Munson AD, Cardou F, Burton PJ, Isabel N, Pedlar JH, Messier C (2016) Traits to stay, traits to move: A review of functional traits to assess sensitivity and adaptive capacity of temperate and boreal trees to climate clange. Environm Rev 24 (2) : 164—186.

Baas P, Wheeler EA (2011) Wood anatomy and climate change. Clim Change, Ecol and Syst 78 : 141—155.

Babst F, Alexander MR, Szejner P, Bouriaud O, Klesse S, Roden J, Ciais P, Poulter B, Frank D, Moore DJ, Trouet V (2014a) A tree-ring perspective on the terrestrial carbon cycle. Oecologia 176 (2) : 307—322.

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

Babst F, Bouriaud O, Alexander R, Trouet V, Erank D (2014b) Toward consistent measurements of carbon accumulation : A multi-site assessment of biomass and basal area increment across Europe. Dendrochronologia 32 : 153—161.

Bakker JD (2005) A new, proportional method for reconstructing historical tree diameters.Canadian J For Res Revue Canadienne De Recherche Forestiere 35 : 2515—2520.

Ballesteros-Cánovas JA, Stoffel M, St George S, Hirschboeck K (2015) A review of flood records from tree-rings. Prog in Physic Geogr 39 (6) : 794—816.

Barnard DM, Meinzer FC, Lachenbruch B, McCulloh KA, Johnson DM, Woodruff DR (2011) Climate -related trends in sapwood biophysical properties in two conifers: Avoidance of hydraulic dysfunction through coordinated adjustments in xylem efficiency, safety and capacitance. Pl, Cell & Environ 34 (4) : 643—654.

Bergeron Y, Denneler B, Charron D, Girardin MP (2002) Using dendrochronology to reconstruct disturbances and forest dynamics around Lake Duparquet, Northwestern Quebec. Dendrochronologia 20 : 175—189.

Bernier P, Schöne D (2009) Adapting forests and their management to climate change : An overview. Unasylva 60 : 5—11.

Brath B, Friesen T, Guerard Y, Jacques-Brissette C, Lindman C, Lockridge K, Mulgund S, Walke BJ (2015) Climate change and resource sustainability : An overview for actuaries. Canadian Institute of Actuaries, Canada.

Brienen RJ, Zuidema PA (2005) Relating tree growth to rainfall in Bolivian rain forests : A test for six species using tree-ring analysis. Oecologia 146 (1) : 1.

Brodribb TJ, Cochard H (2009) Hydraulic failure defines the recovery and point of death in water-stressed conifers. Pl Physiol 149 : 575—584.

Casteller A, Christen M, Villaba R, Martinez H, Stöckli V, Leiva JC, Bartelt P (2008) Validating numerical simulations of snow avalanches using dendrochronology : The Cerro Ventana event in Northern Patagonia, Argentina. Nat Hazard Earth Syst Sci 8 : 433—443.

Casteller A, Stöckli V, Villalba R, Mayer AC (2007) An evaluation of dendroecological indicators of snow avalanches in the swiss alps. Arct Antarct Alp Res 39 (2) : 218—228.

Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE (2009) Towards a worldwide wood economics spectrum. Ecol Lett 12 : 351—366.

Chen HY, Luo Y, R eich PB, Searle EB, Biswas SR (2016) Climate change associated trends in net biomass change are age dependent in Western boreal forests of Canada. Ecol Lett 19 : 1150—1158.

Choat B, Cobb AR, Jansen S (2008) Structure and function of bordered pits: New discoveries and impacts on whole-plant hydraulic function. New Phytol 177 (3) : 608—626.

Coetzee BWT, Robertson MP, Erasmus BFN, Van Rensburg BJ, Thuiller W (2009) Ensemble models predict important bird areas in Southern Africa will become less effective for conserving endemic birds under climate change. Glob Ecol Biogeogr 18 : 701—710.

Coop G, Witonsky D, Di Rienzo A, Pritchard JK (2010) Using environmental correlations to identify loci underlying local adaptation. Genetics 185 (4) : 1411—1423.

Cuny HE, Rathgeber CB, Frank D, Fonti P, Fournier M (2014) Kinetics of trachei development explain conifer tree-ring structure. New Phytol 203 (4) : 1231—1241.

D'Arrigo RD, Malmstrom CM, Jacoby GC, Los SO, Bunker DE (2000) Correlation between maximum latewood density of annual tree rings and NDVI based estimates of forest productivity. Int J Rem Sens 21 : 2329—2336.

Dale VH, Joyce LA, McNulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D, Swanson FJ, Stocks BJ, Wotton BM (2001) Climate change and forest disturbances. Bioscience 51 (9) : 723—734.

de Villemereuil P, Gaggiotti OE, Mouterde M, Till-Bottraud I (2016) Common garden experiments in the genomic era : New perspectives and opportunities. Heredity 116 (3) : 249.

Di Nitto D, Neukermans G, Koedam N, Defever H, Pattyn F, Kairo JG, Dahdouh-Guebas F (2014) Mangroves facing climate change: Landward migration potential in response to projected scenarios of sea level rise. Biogeosciences 11 : 857—871. doi: 10.5194/bg-11-857-2014.

Doyle TW, Krauss KW, Conner WH, From AS (2010) Predicting the retreat and migration of tidal forests along the Northern Gulf of Mexico under sea-level rise. For Ecol Manag 259:770-777. doi : 10.1016/j.foreco.2009.10.023

Eckert AJ, Maloney PE, Vogler DR, Jensen CE, Mix AD, Neale DB (2015) Local adaptation at fine spatial scales : An example from sugar pine (Pinus lambertiana, Pinaceae). Tree Genet & Genom 11 (3) : 42.

Evans MEK, Falk DA, Arizpe A, Swetnam TL, Babst F, Holsinger KE (2017) Fusing tree-ring and forest inventory data to infer influences on tree growth. Ecosphere 8 (7) : e01889.

Forrester DI, Tachauer I, Annighoefer P, Barbeito I, Pretzsch H, Ruiz-Peinado R, Stark H, Vacchiano G, Zlatanov T, Chakraborty T (2017) Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. For Ecol Manag 396 : 160—175.

Freiich LE (2002) Forestdynamics and disturbance regimes: Studies from temperate evergreen-deciduous forests. Cambridge University Press, Cambridge, UK, pp 266.

Fulé PZ (2010) Wildfire ecology and management at Grand Canyon, USA: Tree-ring applications in forest fire history and modeling. In : Stoffel M, Bollschweiler M, Butler DR, Luckman BH (eds). Tree-rings and natural hazards. Advances in Global Change Res 41. Springer Verlag. Berlin .

Girardin MP, Bouriaud O, Hogg EH, Kurz W, Zimmermann NE, Metsaranta JM, Guo XJ (2016) No growth stimulation of Canada's boreal forest under half-century of combined warming and CO_2 fertilization. Proc Nat Acad Sci 113 (52) : E8406-E8414.

Grissino-Mayer HD (2010) Wildfire hazard and the role of tree-ring research. In : Stoffel M, Bollschweiler M, Butler DR, Luckman BH (eds). Tree-rings and natural hazards. Advances in Global Change Research 41. Springer Verlag. Berlin, pp 329—359.

Groenendijk P, Sass-Klaassen U, Bongers F, Zuidema PA (2014) Potential of tree-ring analysis in a wet tropical forest : A case study on 22 commercial tree species in Central Africa. For Ecol Manag 323 : 65—68.

Guiot J, Boucher E, Gea-Izquierdo G (2014) Process models and model-data fusion in dendroecology. Frontiers in Ecol and Evolut 2 : 52.

Hansen J, Ruedy R, Sato M, Lo K (2010) Global surface temperature change. Rev Geophysics 48 (4) : In press. https://doi.org/10.1029/2010RG000345

Hartmann H, Trumbore S (2016) Understanding the roles of non-structural carbohydrates in forest trees – from what we can measure to what we want to know. New Phytol 211: 86—403.

Housset JM, Nadeau S, Isabel N, Depardieu C, Duchesne I, Lenz P, Girardin MP (2018) Tree-rings provide a new class of phenotypes for genetic associations that foster insights into adaptation of conifers to climate change. New Phytol 218 : 630—645.

Humbert L, Kneeshaw D (2011) Identifying insect outbreaks : A comparison of a blind-source separation method with host vs non-host analyses. Forestry 84 (4) : 453—462.

IPCC (1995) Impacts, Adaptations and Mitigation of Climate Change, Scientific-Technical Analyses, 1996. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. In : Field CB, Barros V, Stocker TF et al. (eds). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York : Cambridge University Press, pp 1—582.

IPCC (2013) Summary for policymakers. Climate change 2013. The physical science basis. Cambridge University Press, Cambridge.

Keenam RJ (2015) Climate change impacts and adaptation in forest management : A review. Ann For Sci 72 (2) : 145—167.

Keenan TF, Hollinger DY, Bohrer G, Dragoni D, Munger JW, Schmid HP, Richardson AD (2013) Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. Nature 499 (7458) : 324.

Kelly AE, Goulden ML (2008) Rapid shifts in plant distribution with recent climate change. Proc Nat Acad Sci 105 : 11823—11826. doi:10.1073/pnas.0802891105

Kilpeläinen A, Gerendiain AZ, Luostarinen K, Peltola H, Kellomäki S (2007) Elevated temperature and CO_2 concentration effects on xylem anatomy of Scots pine. Tree Physiol 27 : 1329—1338.

Kirschbaum MUF, Cannell, MG R, Cruz RVO, Galinski W, Cramer WP (1996) Climate change impacts on forests. In :

Climate change 1995, Impacts, Adaptation and Mitigation of climate change : Scientific-Technical Analyses, 1996, Cambridge University Press.

Klesse S, Babst F, Lienert S, Spahni R, Joos F, Bouriaud O, Wilson R (2018) A combined tree-ring and vegetation model assessment of European forest growth sensitivity to inter annual climate variability. Glob Biogeochem Cycles 32 (8) : 1226—1240.

Körner C (2017) A matter of tree longevity. Science 355 : 130—131.

Köse N, Aydin A, Akkemik Ü, Yurtseven H, Güner T (2010) Using tree-ring signals and numerical model to identify the snow avalanche tracks in Kastamonu, Turkey, Natural Hazards 54 (2) : 435—449.

Le Quéré C, Andrew RM, Canadell JG, Sitch S, Korsbakken JI, Peters GP, Manning AC, Boden TA, Tans PP, Houghton RA (2016) Global carbon budget 2016. Earth Syst Sci Data 8 : 605—649.

Leemans R, Eickhout B (2004) Another reason for concern: Regional and global impacts on ecosystems for different levels of climate change. Glob Environm Change 14 : 219—228.

Lenoir J, Gegout JC, Dupouey JL, Bert D, Svenning JC (2010) Forest plant community changes during 1989-2007 in response to climate warming in the Jura Mountains (France and Switzerland). J Veg Sci 21 : 949-964. doi: 10.1111/j.1654-1103.2010.01201.x

Malcolm JR, Liu CR, Neilson RP, Hansen L, Hannah L (2006) Global warming and extinctions of endemic species from biodiversity hotspots. Conserv Biol 20 : 538—548.

Marotzke J, Jakob C, Bony S, Dirmeyer PA, O'Gorman PA, Hawkins E, Perkins- Kirkpatrick S, Le Quéré C, Nowicki S, Paulavets K (2017) Climate research must sharpen its view. Nat Clim Change 7 : 89.

Mckenney DW, Pedlar JH, Lawrence K, Papadopol P, Campbell K, Hutchinson MF (2014) Change and evolution in the plant hardiness zones of Canada. BioScience 64 (4) : 341—350.

Montwé D, Isaac-Renton M, Hamann A, Spiecker H (2016) Drought tolerance and growth in populations of a wide-ranging tree species indicate climate change risks for the boreal north. Glob Change Biol 22 : 806—815.

Nardini A, Barttstuzzo M, Savi T (2013) Shoot desiccation and hydraulic failure in temperate woody angiosperms during an extreme summer drought. New Phytol 200 (2) : 322—329.

Ponce-Campos GE, Moran MS, Huete A, Zhang Y, Bresloff C, Huxman TE, Scalley TH (2013) Ecosystem resilience despite large-scale altered hydroclimatic conditions. Nature 494 (7437) : 349.

Priti H, Aravind NA, Uma Shaanker R, Ravikanth G (2016) Modeling impacts of future climate on the distribution of Myristicaceae species in the Western Ghats, India. Ecol Engg 89 : 14—23.

Rathgeber CB, Cuny HE, Fonti P (2016) Biological basis of tree-ring formation: A crash course. Front Pl Sci 7 : In press.

Reich PB (2014) The world -wide fast-slow plant economics spectrum : A traits manifesto. J Ecol 102 (2) : 275—301.

Rohner B, Weber P, Thürig E (2016) Bridging tree-rings and forest inventories : How climate effects on spruce and beech growth aggregate over time. For Ecol and Manag 360 : 159—169.

Rossi S, Anfodillo T, Čufar K, Cuny HE, Deslauriers A, Fonti P, Frank D, GriČar J, Gruber A, Huang JG (2016) Pattern of xylem phenology in conifers of cold ecosystems at the Northern Hemisphere. Globa Change Biol 22 : 3804—3813.

Schweingruber FH (1996) Tree-rings and environment : Dendroecology. Paul Haupt AG Bern.

Seifert T, Meincken M, Odhiambo BO (2017) The effect of surface fire on tree-ring growth of Pinus radiata trees. Ann For Sci 74 (2) : 34.

Seppala R (2009) A global assessment on adaptation of forests to climate change. Scand J For Res 24 :469—472. doi : 10.1080/02827580903378626

Shroder JF (1978) Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. Quater Res 9 : 168—185.

Solomon AM (1986) Transient responses of forests to CO_2-induced climate change: Simulating modeling experiments in Eastern North America. Oecologia 68 : 567—579.

Sork VL, Aitken SN, Dyer RJ, Eckert AJ, Legendre P, Neale DB (2013) Putting the landscape into the genomics of trees : Approaches for understanding local adaptation and population responses to changing climate. Tree Genet & Genom 9 (4) : 901—911.

Speer JH (2010) Fundamentals of tree-ring research. University of Arizona Press.

Sperry JS (2003) Evolution of water transport and xylem structure. Int J Pl Sci 164 (S3) : S115—S127.

Spiecker H (2002) Tree-rings and forest management in Europe. Dendrochronologia 20 (1-2) : 191—202.

Swetnam TW, Thompson MA, Sutherland EK (1985) Using dendrochronology to measure radial growth of defoliated trees. US Department of Agriculture, Forest Service. Cooperative State Research Service.

Thompson DR (2005) Fine scale disturbance and stand dynamics in mature spruce-subalpine fir forests of central British Columbia. MS thesis. University of Northern British Columbia.

Urban MC, Bocedi G, Hendry AP, Mihoub JB, Pe'er G, Singer A, Gonzalez A (2016) Improving the forecast for biodiversity under climate change. Science 353 (6304): aad8466.

Urli M, Porté AJ, Cochard H, Guengant Y, Burlett R, Delzon S (2013) Xylem embolism threshold for catastrophic hydraulic failure in angiosperm trees. Tree Physiol 33 : 672—683.

Varner JM, Putz FE, O'Brien JJ, Hiers JK, Mitchell RJ, Gordon DR (2009) Post-fire tree stress and growth following smoldering duff fires. For Ecol and Manag 258 (11) : 2467—2474.

Wang J, Rich PM, Price KP, Kettle WD (2004a) Relation between NDVI and tree productivity in the Central Great Plains. Int J Rem Sens 25 : 3127—3138.

Wang Q, Tenhunen J, Dinh NQ, Reichstein M, Vesala T, Keronen P (2004b) Similarities in ground and Satellite- based NDVI time series and their relationship to physiological activity of a Scot pine forest in Finland. Rem Sens Environ 93 : 225—237.

Way DA (2013) Will rising CO_2 and temperatures exacerbate the vulnerability of trees to drought ? Tree Physiol 33 : 775—778.

Welsh C (2007) The relationship between climate and outbreak dynamics of *Dothistroma* needle blight in Northwest British Columbia, Canada. MS thesis. University of Northern British Columbia, pp 187.

Woodall CW, Nagel LM (2007) Downed woody fuel loading dynamics of a large-scale blowdown in Northern Minnesota, USA. For Ecol and Manag 247 : 194—199.

Zielonka T, Holeksa J, Fleischer P, Kapusta P (2010) A tree-ring reconstruction of wind disturbances in a forest of the Slovakian Tatra Mountains, Western Carpathians. J Vegetation Sci 21 (1) : 31—42.