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Opportunities and applications of dendrochronology in Africa

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Partly due to severe lack of instrumental climate data, the drivers of the African climate, their interactions and impacts are poorly understood. The paper demonstrates the prospects and applications of dendroecological and stable isotope techniques, such as to reconstruct climate variability, trends and atmospheric circulation patterns, to fill the knowledge gap in ecosystem productivity and hydrological cycle in different climatic zones of Africa. We summarize the contribution of tree-ring analyses to validation of climate and hydrological models for improved scenarios, and to identify agroforestry species with the ability to acclimate to exacerbated climate conditions. A high number of African tree species shows datable annual tree rings and may reach multi century age. To advance dendrochronology in Africa, collaborative efforts in capacity building of African universities and research organizations are needed.

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Introduction

Dendrochronology is the discipline of dating tree rings to the year of their formation and using exactly dated tree rings for detecting environmental signals that are common for a population of trees. Basics, principles and wider applications of dendrochronology are well described [1], and history and recent progress of tropical dendrochronology is documented in recent reviews [2,3]. In the last decades, the potential of stable-isotope signatures of carbon, oxygen, hydrogen, nitrogen in tree rings has been unravelled and applied to questions addressed in ecology, physiology and climate change studies [4].

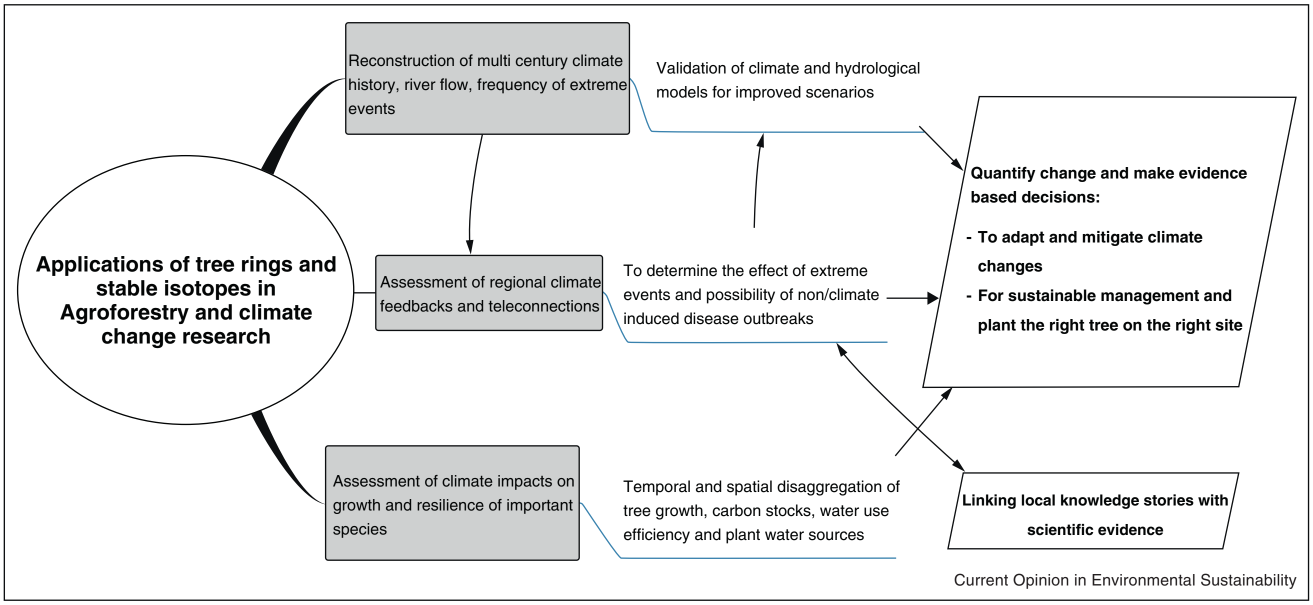
This paper focuses on dendrochronology in subsaharan Africa in general and its application in agroforestry/forestry and climate change research, in particular (Figure 1). Although dendrochronological work in Africa is still in its infancy, it has wide potential. We will first point to the challenges of tropical dendrochronology and will delve into how unravelling the past responses of trees to climate would contribute to address the following issues:

(1) Because of a severe lack of instrumental climate records, the drivers of the African climate, their interactions and local and global impacts are poorly understood.
(2) Potential changes in the hydrological cycle due to global warming may lead to negative impacts on food security and livelihoods in Africa.
(3) In Africa, knowledge on growth and population dynamics, the range of natural climate variability and the range of tree species tolerance to climatic extremes is scarce. This information is crucial for sustainable natural forest management and to support decisions in agroforestry and reforestation efforts.

Challenges and opportunities for dendrochronology in the tropics

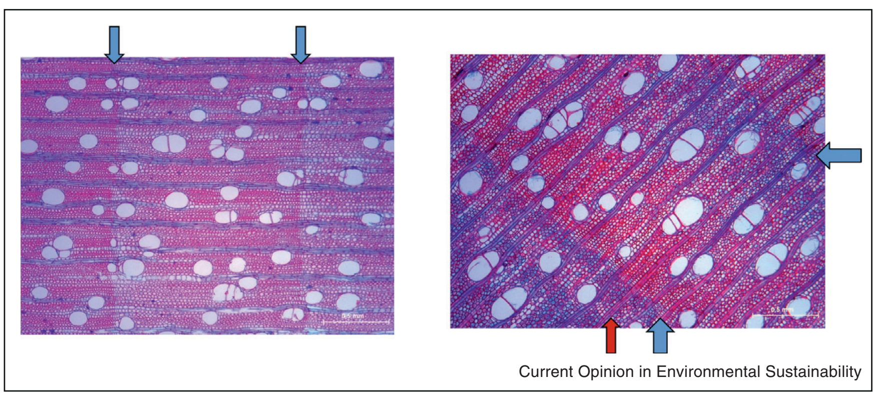
The presence of anatomically distinct, annual growth rings is the prerequisite for the development of correctly dated ring-width chronologies. Formation of distinct growth boundaries requires periods with growth limiting environmental conditions, which induce growth stops in trees (=cambial dormancy) [2,5]. In the tropics where seasonal changes in temperature are generally low and frost occurrence is limited to higher-elevation areas, growing seasons are mainly defined through precipitation changes (drought in dry areas and flooding in floodplains) [2]. Deciduous species are more likely to form growth rings than evergreen species. Under optimal conditions, radial growth can prevail all year long [6] but the probability for the formation of distinct growth rings increases with the climate seasonality. The major problems in applying dendrochronology in Africa are indistinct,

Figure 1



Possible applications of tree rings and stable isotopes in agroforestry and climate change research in Africa.

Figure 2



Site dependent double ring formation a major challenge of dendrochronology in tropics. Arrows indicate ring boundaries **(a)** Microsections of *Sclerocarya birrea* from Burkina-Faso Sahel region, showing very distinct annual rings because of clear climate seasonality **(b)** Microsections of *Sclerocarya birrea* from Tanzania, where formation of false rings is evident in some years in the form of intra annual density variations because of biannual rainfall and/or drought during the growing season (the red arrow shows a false ring boundary).

double (Figure 2), missing or wedging rings and are summarized by [6].

However, with the advancement of technology and emerging new methods during recent years the prospect for dendrochronology in Africa is considerable. For instance, regular microcoring of the cambium and microscopic analysis of the cells formed between sampling intervals (e.g. [7]), and dendrometer measurements [8,7] provide information on cambial dynamics, seasonal growth and sensitivity to climate variability. Intra-annual stable isotope ratio measurements have revealed seasonal cycles that can potentially be employed to date tree samples without distinct anatomical ring boundaries (e.g. [9,10••]). Linking tree ring analysis with remote sensing techniques (e.g. seasonal NDVI measures) may provide additional information on the start, end, and length of vegetation periods [11]. Thus, general judgements if tropical trees do form annual tree rings or not should be replaced by more differentiated views under which climate conditions growth rings are formed in an individual species (Figure 2) and what kind of measurements are necessary under specific site conditions.

Applications of dendrochronology

Reconstructing local climate variability and shifts in atmospheric circulation

Palaeoclimate records for African climate were reconstructed by (e.g. [12]), yet continent wide precise palaeoclimate records in Africa are scarce [13,14]. Africa's climate science is currently the least developed on the globe. The lack of observational climate data in Africa is recognized as a constraint to understanding current and future climate variability [14] and G8 Gleneagles Plan of Action 2005 noted that 'Africa's data deficiencies are greatest and warrant immediate attention' Climate-change impact scenarios for the continent are generally based on approximations from global circulation models (GCMs) and thus share the constraint of the coarse resolution of GCMs. Appropriate use of a range of such scenarios combined with analysis of trends in historic data can contribute to the understanding of future trends and uncertainties that are crucial for long-term planning perspectives [15].

Using tree rings as precisely dated high-resolution climate proxies may help to put the short or scarce existing instrumental climate records in Africa into a longer perspective. On the basis of tree-ring widths in *Pterocarpus angolensis* in South Africa, Therrell *et al.* [16] developed a climate reconstruction spanning the period from AD 1796 to 1996. In northern Namibia, a 100-year long chronology from *Burkea africana* and *P. angolensis* was reconstructed [17]. In East Africa, a chronology spanning 68 years was developed from drought-deciduous *Acacia* species (*Acacia senegal*, *Acacia seyal*, *Acacia tortilis* and evergreen *Balanites aegyptiaca* from rift valley of Ethiopia) [5]. From the southern and northern highlands of Ethiopia, *Juniperus procera* chronologies of up to 91 years were developed [18–19]. Krepkowski *et al.* [20•] attempted to date *Podocarpus falcatus* from southeastern Ethiopia and tree-ring width measurements resulted in tentative tree ages of 500 years that were confirmed by radiocarbon dating. In West Africa, Schöngart *et al.* [21•] reconstructed annual precipitation in Benin back to the year 1840. The reconstruction witnesses increasingly arid conditions during the last 160 years. In all studied species and sites, growth response to rainfall was positive [5,16,17,22,23] and often coupled to negative correlations with temperature [17]. Besides, El Niño years have been found to significantly influence tree growth [5,17,24•]. Negative pointer years, that is, conspicuous narrow growth rings replicated in several series [25] correspond to years of drought and famine years [5,19] and El Niño years [5,17]. It is worth noting that the El Nino effect is different in different regions in Africa and is not fully understood. For instance, during the driest month of the year, the 1997/8 El Niño caused extensive floods in Somalia and Kenya [14].

Measuring stable isotopes in tree rings provides additional information. Williams *et al.* [26••] measured annual ^{18}O ratios of *J. procera* from northern Ethiopia and found a decline in the proportion of precipitation originating from the Congo Basin during the past half century and increasing precipitation variability and drought frequency over the Greater Horn of Africa. Carbon isotope ratios ($\delta^{13}C$) on tree rings of the *Acacia* species [27,28••] proved $\delta^{13}C$ variations to be a strong indicator for water availability during the growing season. $\delta^{13}C$ chronologies of *J. procera* from northern Ethiopia display correlations with the Blue Nile base-flow, opening the possibility to reconstruct river flow back to AD 1836 [19]. Those studies clearly demonstrated the applicability of tree rings and stable isotopes analyses for understanding variations in basin-wide hydrological conditions and atmospheric circulation patterns which are connected to terrestrial ecosystem processes.

Plant water relationships

Global climate change is expected to modify patterns of rainfall variability and the composition of vegetation, with many implications on the use and management of trees in agroforestry and forestry, especially in dry regions of Africa [29]. Assessment of vegetation vulnerability, climate change resilience and human adaptation options require understanding tree species diversity in the current vegetation, of genetic and phenotypic growth strategies as well as temporal and spatial response to fluctuating water availability [28••,30]. Science-based knowledge on tree selection and management on farms is barely available for most native tree species [30]. Establishing experiments to evaluate the suitability of agroforestry species would take decades before solutions can be drawn, and plants' responses on longer time scale cannot be studied in manipulative experiments, can be uncovered by studying responses of plants' to past variation in climate factors.

Drought tolerance can be detected from growth responses to rainfall variability [17,5]. Variations in $\delta^{13}C$ in tree rings provide deeper insight into the occurrence of drought stress and related changes of intrinsic water-use efficiency (WUE_i). Because of its dependence on the closure of the leaf stomata, $\delta^{13}C$ has been found to be negatively correlated with moisture availability and proved a very valuable indicator to evaluate long-term tree responses to climate variations in dry tropical forests [27,31,28••] and trade-offs between growth, water-use efficiency and drought tolerance [28••]. The large and rapid ongoing changes in atmospheric CO_2 is also reflected in declining $\delta^{13}C$ trends in tropical tree rings [27,19,32,33••] and significantly affects plant–atmospheric interactions.

Furthermore, by its very nature, successful use of agroforestry requires a careful management of trees and crops to minimize competition for resources. Importantly, trees utilize water that would otherwise be lost from cropped fields by evaporation, runoff and drainage. Using stable oxygen isotopes in tree rings from Burkina Faso *Sclerocarya birrea* is found to be mainly dependent on soil water [34]. Depleted ^{18}O values of *Faidherbia albida* from Malawi, with clear seasonal variations, might indicate that the species is mostly dependent on ground water (Gebrekirstos in preparation) which also provides information on rooting depths and management needs.

Disturbance and resilience to environmental factors

Natural and human-caused disturbances are drivers of forest dynamics and succession in most tropical ecosystems. Disturbances affect population dynamics and tree growth across temporal and spatial scales [35]. Large disturbances such as mega droughts [36] but also human settlement activity connected with land conversion, grazing and exploitation of forest resources [37] leave traces in population structure by changing the stand-age structure [35,38]. Less catastrophic disturbances induce synchronous growth suppressions and growth releases recorded on surviving trees [39]. Short-term stress events, such as insect attacks and forest fires, can be recorded as pointer years [25] in the ring-width record.

Dendrochronology adds to classical approaches such as permanent sample plots [40,41] or chronosequence studies [42] to reconstruct long-term disturbance history and evaluate resilience of tropical tree species to natural and anthropogenic disturbances. Recently, analyses on long-term changes of nitrogen isotope ($\delta^{15}N$) composition in tropical forests have revealed human-induced long-term changes in the nitrogen cycles [43] that are a major future threat to biodiversity conservation [44]. Guerrier *et al.* [45] demonstrated the advantage of combining $\delta^{13}C$, $\delta^{18}O$, and $\delta^{15}N$ analyses to disentangle changes of assimilation and stomatal conductance as a result of N fertilization. Corresponding studies in Africa are urgently needed since N emissions have increased during the past decades [43] and will probably strongly alter N dynamics in African tropical soils.

Linkage to carbon accounting

Knowledge on growth rates and age–diameter relationships of tropical trees is poor [46,5]. Emerging need for scientific evidence of ecosystem productivity and its relation with mitigation of greenhouse gas require long-term growth data of individual trees [47]. The application of dendrochronology in assessing trends of biomass production could enhance growth trajectory models and also help to minimize high transaction costs of monitoring long-term research plots [48•,3]. The improvement of data acquisition through emerging technique could supplement permanent plot data scarcity and help acquired upgraded carbon accounting. Dendrochronology is a powerful methodology for a fast assessment of forest productivity at different stand ages and forest ecosystems [49•].

Assessing biomass accurately using cost effective methods is key to the success of carbon projects and is a high research priority for development of monitoring, reporting and verification in the African context [50]. This requires better knowledge of age–diameter relationships as background evidence on tree productivity [48•]. Such studies apply tree ring data (converted to diameter over bark) of individual trees and apply allometric models at various growth sizes to estimate biomass increment during the tree life time [3,49•].

The need of improved understanding of drivers of deforestation — an important aspect of mitigation policies — requires better assessment of historical footprints of limiting factors of tree growth that can be tracked in the wood anatomy. Recent studies showed that wetter growing conditions may not imply more biomass accumulation at tree scale because of limiting factors such as fires or competition [48•]. In addition, the potential use of assessing wood quality through wood anatomy analysis gives additional advantage of assessing energy potentials of trees and hence optimizes the strategic underpinnings in managing forest resources to sustainably supply fuel wood and subsequently reduce deforestation.

At ecoregion scale, climate–growth relationships are important in biome net primary production assessment [3]. Using such methods for interpreting growth patterns in terms of releases, suppressions, and establishment dates of all trees in a certain area can be a basis for studying forest stand history and carbon sequestration potential. Integrated labelling experiments with enriched ^{13}C atmosphere in Ethiopian mountain forests have indicated that carbon turnover in broadleaved deciduous pioneer species (*Croton macrostachyus*) is fast and decays after one vegetation period, whereas late-successional evergreen conifer trees (*P. falcatus*) have a slow carbon turnover so that C carry-over effects were detected over three growing seasons [10••]. Similarly, 35% the $\delta^{13}C$ from the soil under the pioneer tree is lost in one year while only 15% under the successional tree species [51]. The study showed the potential impact of deforestation or change in species composition on above and below ground carbon sequestration.

Perspective

Compared to other parts of the world, scientific understanding of the African climate system as a whole is low. As climate change will affect all sectors of society, interdisciplinary and international collaborations are needed to extend research frontiers and to develop regional and subregional climate models at a scale for climatic teleconnections that would be meaningful to decision makers [52]. The former paragraphs have demonstrated the large potential of dendroecological techniques in different climatic zones of Africa. A high number of tree species shows datable annual tree rings and reach a considerable age. A still not utilized potential lies in the quantitative analysis of wood-anatomical properties which can be used as indicators of climatic variability and provide information about the water-conducting capacity of tropical trees. Linking dendrochronology with other methods (e.g. remote sensing, plant physiology, other palaeoclimatic reconstructions, modelling) is also a valuable approach to draw comprehensive scientific conclusions across temporal and spatial scales. Currently, there is strong interest to develop dendrochronology science in Africa, which will require collaborative efforts. Including dendrochronology in the curriculum of African universities might help to advance the wider use of dendrochronology.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Schweingruber FH: *Tree rings: basics and applications of dendrochronology*. Dordrecht: Kluwer Academic Publishers; 1988, .

2. Worbes M: **One hundred years of tree ring research in the tropics — a brief history and an outlook to future challenges**. *Dendrochronologia* 2002, **20**:217-231.

3. Rozendaal DMA, Zuidema PA: **Dendroecology in the tropics: a review**. *Trees Struct Funct* 2011, **25**:3-16.

4. McCarroll D, Loader NJ: **Stable isotopes in tree rings**. *Quaternary Sci Rev* 2004, **23**:771-801.

5. Gebrekirstos A, Mitlöhner R, Teketay D, Worbes M: **Climate–growth relationships of the dominant tree species from semi-arid savanna woodland in Ethiopia**. *Trees Struct Funct* 2008, **22**:631-641.

6. Wils TH, Sass-Klaassen UG, Eshetu Z, Bräuning A, Gebrekirstos A, Couralet C, Robertson I, Touchan R, Koprowski M, Conway D, Briffa KR, Beeckman H: **Dendrochronology in the dry tropics: the Ethiopian case**. *Trees Struct Funct* 2011, **25**:345-354.

7. Krepkowski J, Bräuning A, Gebrekirstos A, Strobl S: **Cambial growth dynamics and climatic control of different tree life forms in tropical mountain forest in Ethiopia**. *Trees Struct Funct* 2011, **25**:59-70.

8. Mäkinen H, Seo JW, Nöjd P, Schmitt U, Jalkanen R: **Seasonal dynamics of wood formation: a comparison between pinning, microcoring and dendrometer measurements**. *Eur J For Res* 2008, **127**:235-245.

9. Verheyden A, Helle G, Schleser GH, Dehairs F, Beeckmann H, Koedam N: **Annual cyclicity in high-resolution stable carbon and oxygen isotope ratios in the wood of the mangrove tree *Rhizophora mucronata***. *Plant Cell Environ* 2004, **27**: 1525-1536.

10. •• Krepkowski J, Gebrekirstos A, Shribistova O, Bräuning A: **Stable carbon isotope labeling reveals different carry-over effects between functional types of tropical trees in an Ethiopian mountain forest**. *New Phytol* 2013 http://dx.doi.org/10.1111/nph.12266.

The study is the first of its kind in tropical regions and it showed the difference in carbon carry over effects between functional groups and the potential impact of deforestation on carbon turnover.

11. Wang J, Rich PM, Price KP, Kettle WD: **Relations between NDVI and tree productivity in the central Great Plains**. *Int J Remote Sens* 2004, **25**:3127-3138.

12. Nicholson S: **The nature of rainfall variability over Africa on time scales of decades to millenia**. *Global Planet Change* 2000, **26**:137-158.

13. Gebrekirstos A: **Climate change in Africa, based on tree rings and stable isotope results, and its potential for climatic tele-connections**. *Agric Innov Sustain Dev* 2009, **1**:66-72.

14. DFID *Climate change in Africa*. Key sheet 2004, 10.

15. Eastaugh C, Cheteu LB, Cobbinah J, Dwomoh F, Foahom B, Foli E,Idinoba M, Makungwas S, Nkem J, Oballa P, Utila H:Climate change impacts on African Forests and People. IUFRO Occasional Paper 2010. No. 24.

16. Therrell MD, Stahle DW, Ries LP, Shugart HH: **Tree-ring reconstructed rainfall variability in Zimbabwe**. *Climate Dyn* 2006, **26**:677-685.

17. Fichtler E, Trouet V, Beeckman H, Coppin P, Worbes M: **Climatic signals in tree rings of *Burkea africana* and *Pterocarpus angolensis* from semiarid forests in Namibia**. *Trees Struct Funct* 2004, **18**:442-451.

18. Sass-Klaassen U, Couralet C, Sahle Y, Sterck FJ: **Juniper from Ethiopia contains a large-scale precipitation signal**. *Int J Plant Sci* 2008, **169**:1057-1065.

19. Wils THG, Robertson I, Eshetu Z, Koprowski M, Sass-Klaassen UGW, Touchan R, Loader NJ: **Towards a reconstruction of Blue Nile baseflow from Ethiopian tree rings**. *Holocene* 2010, **20**:837-848.

20. • Krepkowski J, Bräuning A, Gebrekirstos A: **Growth dynamics and potential for cross-dating and multi-century climate reconstruction of *Podocarpus falcatus* in Ethiopia**. *Dendrochronologia* 2012, **30**:257-265.

This paper shows the potential to reconstruct multicentury climate proxy. The authors believe that further sampling in areas with different rainfall regimes, additional radiocarbon dating and measurements of stable isotopes might enable the establishment of a multi-century-long tree-ring series in the region.

21. • Schöngart J, Orthmann B, Hennenberg KJ, Porembski S, Worbes M: **Climate–growth relationships of tropical tree species in West Africa and their potential for climate reconstruction**. *Global Change Biol* 2006, **12**:1139-1150.

This is the longest climate reconstruction in West Africa, yet. The reconstruction witnesses increasingly arid conditions during the last 160 years which may have large impacts on the hydrological cycle and consequently on the ecosystem dynamics and socioeconomic sectors in the Guinea-Congolian/Sudanian region.

22. Couralet C, Sterck FJ, Sass-Klaassen U, Acker VJ, Beeckman H: **Species-specific growth responses to climate variations in understory trees of a central African rain forest**. *Biotropica* 2010, **42**:503-511.

23. Trouet V, Mukelabai M, Verheyden A, Beeckman H: **Cambial growth season of brevi-deciduous *Brachystegia spiciformis* trees from South Central Africa restricted to less than four months**. *PLoS ONE* 2012, **7**:e47364 http://dx.doi.org/10.1371/journal.pone.0047364.

24. • De Ridder M, Trouet V, Van den Bulcke J, Hubau W, Van Acker J, Beeckman H: **A tree-ring based comparison of *Terminalia superba* in West and Central Africa**. *Trees Struct Funct* 2013 http://dx.doi.org/10.1007/s00468-013-0871-3.

This is interesting cross regional comparisons.

25. Schweingruber FH, Eckstein D, Serre-Bachet F, Bräker OU: **Identification, presentation and interpretation of event years and pointer years in dendrochronology**. *Dendrochronologia* 1990, **8**:9-39.

26. •• Williams AP, Funk C, Michaelsen J, Rauscher SA, Robertson I, Wils THG, Koprowski M, Eshetu Z, Loader NJ: **Recent summer precipitation trends in the Greater Horn of Africa and the emerging role of Indian Ocean sea surface temperature**. *Climate Dyn* 2011 http://dx.doi.org/10.1007/s00382-011-1222-y.

This study shows the importance of tree rings to understand atmospheric climate dynamics and basin wide hydrological cycle.

27. Gebrekirstos A, Worbes M, Teketay D, Fetene M, Mitlöhner R: **Stable carbon isotope ratios in tree rings of co-occurring species from semi-arid tropics in Africa: patterns and climatic signals**. *Global Planet Change* 2009, **66**:253-260.

28. •• Gebrekirstos A, Noordwijk M, Neufeldt H, Mitlöhner R: **Relationships of stable carbon isotopes, plant water potential and growth: an approach to assess water use efficiency and**

growth strategies of dry land agroforestry species. *Trees Struct Funct* 2011, **25**:95-102.
This study shows the tradeoffs between growth, drought tolerance and water use efficiency using stable isotope and ring width measurements to select resilient agroforestry species.

29. IPCC Climate Change: Synthesis Report. 2007 IPCC.

30. Gebrekirstos A, Teketay D, Fetene M, Mitlöhner R: **Adaptation of five co-occurring tree and shrub species to water stress and its implication in restoration of degraded lands**. *For Ecol Manage* 2006, **229**:259-267.

31. Fichtler E, Helle G, Worbes M: **Stable-carbon isotope time series from tropical tree rings indicate a precipitation signal**. *Tree-Ring Res* 2010, **66**:35-49.

32. Brienen RJW, Wanek W, Hietz P: **Stable carbon isotopes in tree rings indicate improved water use efficiency and drought response of a tropical dry forest tree species**. *Trees Struct Funct* 2011, **25**:103-113.

33. •• Brienen RJW, Gloor E, Zuidema PA: **Detecting evidence for CO_2 fertilization from tree ring studies: the potential role of sampling biases**. *Global Biogeochem Cycle* 2012, **26**:GB1025 http://dx.doi.org/10.1029/2011GB004143.
This shows how to avoid sampling bias and the caution needed in the interpretation of historical growth trends from tree rings.

34. Gebrekirstos A, Neufeldt H, Mitlöhner R: **Exploring climatic signals in stable carbon and oxygen isotopes of *Sclerocarya birrea* tree ring chronologies from the Sahel region in West Africa**. *TRACE* 2011, **9**:143-148.

35. Baker PJ, Bunyavejchewin S, Oliver CD, Ashton PS: **Disturbance history and historical stand dynamics of a seasonal tropical forest in western Thailand**. *Ecol Monogr* 2005, **75**:317-343.

36. Cook ER, Anchukaitis KJ, Buckley BM, D'Arrigo RD, Jacoby GC, Wright WE: **Asian monsoon failure and megadrought during the last millennium**. *Science* 2010, **328**:486-489.

37. Tolera Feyissa M, Sass-Klaassen UGW, Eshete A, Bongers F, Sterck FJ: **Frankincense tree recruitment failed over the past half century**. *For Ecol Manage* 2013, **304**:65-72.

38. Pederson N, Varner JM, Palik BJ: **Canopy disturbance and tree recruitment over two centuries in a managed longleaf pine landscape**. *For Ecol Manage* 2008, **254**:85-95.

39. Rozendaal DMA, Soliz-Gamboa CC, Zuidema PA: **Assessing long-term changes in tropical forest dynamics: a first test using tree-ring analysis**. *Trees* 2011, **25**:115-124.

40. Zuidema PA, Brienen RJW, Schöngart J: **Tropical forest warming: looking backwards for more insights**. *Trend Ecol Evol* 2012, **27**:193-194.

41. Chave J, Condit R, Lao S, Caspersen JP, Foster RB, Hubbell SP: **Spatial and temporal variation of biomass in a tropical forest: results from a large census plot in Panama**. *J Ecol* 2003, **91**:240-252.

42. Brienen RJW, Lebrija-Trejos E, van Breugel M, Perez-Garcia EA, Bongers F, Meave JA, Martinez-Ramos M: **The potential of tree rings for the study of forest succession in Southern Mexico**. *Biotropica* 2009, **41**:186-195.

43. Hietz P, Turner BL, Wanek W, Richter A, Nock CA, Wright SJ, Wright SJ: **Long-term change in the nitrogen cycle of tropical forests**. *Science* 2011, **334**:664-666.

44. Phoenix GK, Hicks WK, Cinderby S, Kuylensierna JCI, Stock WD, Dentener FJ *et al.*: **Atmospheric nitrogen deposition in world biodiversity hotspots: the need for a greater global perspective in assessing N deposition impacts**. *Global Change Biol* 2006, **12**:470-476.

45. Guerrier R, Mencuccini M, Shepard LJ, Saurer M, Levy PP, Sutton MA *et al.*: **The legacy on enhance N and S deposition as revealed by combined analysis of $\delta^{13}C$, $\delta^{18}O$, and $\delta^{15}N$ in tree rings**. *Global Change Biol* 2011, **17**:1946-1962.

46. Worbes M, Staschel R, Roloff A, Junk WJ: **Tree ring analysis reveals age structure, dynamics and wood production of a natural forest stand in Cameroon**. *For Ecol Manage* 2003, **173**:105-123.

47. Lewis SL, Lopez-Gonzalez G, Sonke B, Affum-Baffoe K, Baker TR, Ojo LO, Phillips OL, Reitsma JM, White L, Comiskey JA *et al.*: **Increasing carbon storage in intact African tropical forests**. *Nat Lett* 2009, **457**:1003-1006.

48. • Mbow C, Chhin S, Sambou B, Skole D: **Potential of dendrochronology to assess annual rates of biomass productivity in savanna trees of West Africa**. *Dendrochronologia* 2013, **31**:41-51.
This paper shows that better accounting of carbon sequestration in the tropics using cost effective methods based on tree ring analysis will increase compliance to technical specifications of the carbon market.

49. • Schöngart J, Arieira J, Felfili FC, Arruda E, Cunha C: **Age-related and stand-wise estimates of carbon stocks and sequestration in the aboveground coarse wood biomass of wetland forests in the northern Pantanal, Brazil**. *Biogeosciences* 2011, **8**:3407-3421.
This paper shows the importance combining tree ring analysis with allometric models for carbon stock estimates.

50. Mbow C, Skole D, Dieng M, Justice C, Kwesha D *et al.*: *Challenges and prospects for REDD+ in Africa: desk review of REDD+ implementation in Africa*. Copenhagen: GLP-IPO; 2012, .

51. Shibistova O, Yohannes Y, Boy J, Richter A, Wild B, Watzka M, Guggenberger G: **Rate of belowgrpound carbon allocation differs with successional habit of two afromontane trees**. *PLoS ONE* 2012, **7**:e45540 http://dx.doi.org/10.1371/journal.pone.0045540.

52. Gebrekirstos A, Bräuning A, Van Noordwijk M, Mitlöhner R: **Understanding past, present, and future climate changes from East to West Africa**. *Agric Innov Sustain Dev* 2011, **3**:77-86 [Edited by CTA and FARA].