Keynote Paper: Understanding Past, Present and Future Climate Changes from East to West Africa

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Abstract

Tree rings and stable isotopes in tree rings provide evidence of past climate variability. Given the short instrumental climate records that exist in Africa, dendrochronology adds an essential longer-term perspective on climate change and variability and on the adaptation of agroforestry landscapes and forest ecosystems. Tree-ring analyses were conducted as part of three independently established international research collaborations with different partner institutes in Germany and Africa. Stable carbon and oxygen isotopes in tree rings of *Sclerocarya birrea* from the Sahel region (Burkina Faso) showed strong climatic signals. Tree-ring chronologies spanning more than 100 years are under development for Burkina Faso and Tanzania. The ongoing project in Munessa Forest, Ethiopia may result in chronologies of more than 350 years. Finally, the tree-ring series developed in the three projects will be combined to establish large-scale correlation patterns between tree growth and sea-surface temperatures in order to explore continent-wide climate teleconnections. In order to have representative data sets and draw continent-wide recommendations, however, there is a need to extend the study to other parts of Africa.

INTRODUCTION

Climate change affects all sectors of society at local, regional and continental scales, but available evidence is not sufficient to guide policies. Unravelling past climatic events is essential if we are to understand the present and to derive reliable scenarios of future climate change. Thus interdisciplinary and international collaborations are needed to extend research frontiers and to develop regional and sub-regional climate models at a scale relevant for decision-makers (Gebrekirstos, 2009). The pattern in atmospheric circulation, plus the tendency of heavy isotopes to condense first and evaporate last, causes distinct isotope signals (relative to average 0.2% of O that is ^{18}O) in rainfall that reflect the degree of recycling of water vapour by re-evaporation of rainfall over land masses from its oceanic origin (Bowen, 2010). The role of evaporation from terrestrial vegetation in the causation of rainfall patterns is still hotly debated (Worden, 2007; Makarieva *et al.*, 2010) and the isotopic composition of rainfall is the major evidence available (Treble *et al.*, 2005; Noone, 2008). Analysis of isotopes in tree rings to obtain a dated historical indication of past rainfall

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patterns (Leavitt *et al.*, 2010) can thus contribute to determine an anthropogenic element of past climate change through tele-connections between forest cover and rainfall further inland.

In three current interdisciplinary research projects, analysis of tree rings (dendrochronology) is combined with analysis of current land use and options for adaptation. The project 'Adaptation of Land Use to Climate Change in Sub-Saharan Africa (ALUCCSA)' (www.aluccsa.de) is coordinated by the Centre for Tropical and Subtropical Agriculture and Forestry (Georg-August Universität, Göttingen, Germany) in collaboration with national partner institutes in Burkina Faso and the World Agroforestry Centre. The project aims to develop climate-change scenarios for the next 100 years on a regional/local scale for Sub-Saharan Africa and to achieve ready-to-use scenarios and recommendations for agroforestry and silvopastoral ecosystems. The project, 'Resilient Agro-landscapes to Climate Change in Tanzania' (ReACCT), is coordinated by the Leibniz-Centre of Agricultural Landscape Research, Germany. ReACCT aims to assess the regional impacts of climate change on agriculture and the environment in Tanzania (Morogoro) and to design adaptation strategies and practices for small-scale agriculture and land use (www.reacctanzania.com). Both projects are funded through the Adaptation of African Agriculture to Climate Change funding scheme initiated by BMZ (Ministry of technical cooperation of the federal government of Germany) and GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit, Germany). A separate project, funded by the German Research Foundation (DFG) and entitled 'Climate response of tree growth in Ethiopia along an altitudinal transect and implications on local climate and regional atmospheric circulation dynamics', has been running in Ethiopia since the beginning of 2008. Its goal is to reconstruct climate variability during historical times along an elevation gradient and to unravel large-scale variations of the East African–South Asian Summer Monsoon circulation during El Niños and La Niñas. Apart from other objectives, these projects have the common goal to put the existing short instrumental climate records in Eastern and West Africa (Fig. 1) into a longer perspective, and to investigate the impact of climate variability on the adaptation and water use of important forest and agroforestry tree species in the face of climate changes.

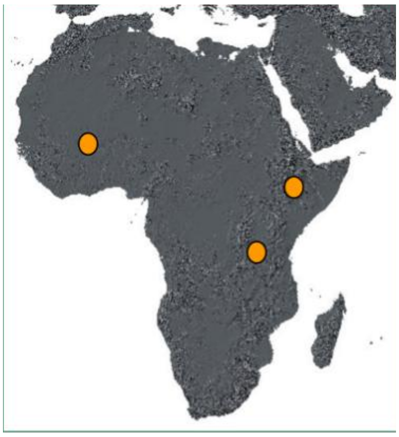

***Figure 1** Location of the study sites (Ethiopia, Tanzania and Burkina Faso)*

Tree Rings and Stable Isotopes as Climate Proxies

Tree rings are excellent archives, providing information about past climate changes and about the impact of ongoing climate variability on major constituents of forest ecosystems and agroforestry landscapes. Trees grow radially by adding new layers of wood cells on the inside of the cambium. The rings added each year can indicate the environmental conditions the tree experienced during the growing season. As a result, these rings are indicators of climate factors that played a significant role in the growth of that particular tree. In certain cases, trees can live for many hundreds and even thousands of years, like the famous bristlecone pine of the USA.

Dendrochronology is the discipline of dating tree rings to the year of their formation. By applying a wide spectrum of modern analysis techniques, the field has wide applications in environmental research (dendroecology) – in climatology, hydrology, glaciology, tectonics/volcanism, geomorphology and forestry sciences. In order to know more about climate over an even longer period, in some cases thousands of years, it is possible to date dead trees of unknown age and fossil wood that is well preserved. Their rings can be cross-correlated to construct longer records of former climate conditions. Trees forming annual growth rings are found in temperate climates. It has been widely assumed that trees growing in the tropics do not form annual rings. However, many authors have succeeded in using tree rings in tropical trees to determine tree age, understand growth dynamics, and carry out ecological and climate studies (Worbes, 2002). Although dendrochronological work in Africa is still in its infancy, there are successful results reported from different tropical regions. The potential of tree rings as climate proxy in semi-arid Africa has been reported (Fichtler *et al.*, 2004; Trouet *et al.*, 2006; Gebrekirstos *et al.*, 2008, 2010; Wils *et al.*, 2010). In more humid tropical environments with biannual rainfall distribution, annual ring formation is still uncertain. In such cases, high-resolution dendrometers have been successfully applied to document the dynamics of wood formation and to prove the formation of annual rings (Krepkowski *et al.*, 2010).

Since the early 1970s, stable carbon and oxygen isotope signatures in tree rings have been investigated as potential proxy indicators of past climatic conditions, and promising results have been reported (Leavitt and Long, 1991; Robertson *et al.*, 1997; Saurer *et al.*, 1997). Wood is formed on the basis of photosynthesis, which derives carbon from CO_2 and oxygen and hydrogen atoms from water. Once formed, the isotope composition of wood is stable, and still reflects the ease with which CO_2 could be derived from the atmosphere and the type of water available in the leaves. Gebrekirstos *et al.* (2009, 2010) demonstrated the potential of $\delta^{13}C$ in tree rings of *Acacia* species to reflect physiological responses to environmental and climate changes as a tool for palaeoclimatic reconstructions in Ethiopia. High correlations ($r > -0.82$) were found between the $\delta^{13}C$ chronologies and rainfall, demonstrating the potential to reconstruct precipitation in semi-arid tropics. Wils *et al.* (2010) applied $\delta^{13}C$ variations in *Juniperus procera* for reconstructing the flow of the Blue Nile River.

It is in this context that we extended the study to tropical moist forest in Ethiopia, parkland agroforestry systems in Burkina Faso and Miombo woodland in Tanzania. The overall purpose of the study was to establish large-scale correlation patterns between tree growth, precipitation and temperature that are affected by the Indian Summer Monsoon and the West African Monsoon in Eastern and West Africa, respectively. This knowledge will help us to explore local and regional climate processes.

In this paper, we present preliminary results that indicate the potential of stable oxygen and carbon isotopes in tree rings of *Sclerocarya birrea* from the Sahel region in Burkina Faso and Tanzania as a climate proxy. In addition, we briefly outline a research perspective for climate reconstructions from regions in tropical Africa influenced by different climatic regimes.

METHODOLOGY

Tree Ring Measurement and Stable Isotopes

Study Sites and Climate

The study sites were in Burkina Faso, Miombo woodlands in Tanzania, and tropical moist forest (Munesa Forest) in Ethiopia (Fig. 1). In this paper, we focus on the results of the Sahel region in Burkina Faso. Burkina Faso has three major climate zones: the Sahel zone in the north, the Sudan–Guinea zone in the south, and the Sudano–Sahel in between. The Sahel zone is influenced by the Sahara Desert and the West African Monsoon. The rainfall distribution of the region is unimodal within a range of 500–600 mm in the north to 1,000 mm in the south. The rainy season starts in May and extends to September, with the wettest month in August. Mean annual temperature is about 37°C, with the hottest season lasting from March to May (about 40°C).

Study Species and Measurement of Stable Isotopes

Sclerocarya birrea (Anacardiaceae) is a common deciduous tree species in Eastern and West Africa, growing up to 20 m in height. For the $\delta^{13}C$ and $\delta^{18}O$ measurements, we selected stem discs of two *S. birrea* collected from the Sahel region in Tugure (13°22′17.5″N 00°28′16.7″W). The discs were dated using standard dendrochronological procedures (Gebrekirstos *et al*., 2008). The $\delta^{13}C$ and $\delta^{18}O$ analyses were performed at annual resolution from 1983 to 2007. Powdered samples of bulk wood were produced from two to three radii of each tree using a drill width of 0.5 mm (Fig. 2b). The powder was pooled into tin capsules and homogenised with a metal stick to represent the whole ring formed in each calendar year. After collecting each sample, the disc was cleaned with compressed air to avoid cross-contamination. From each sample, 1 and 0.2 mg of powdered wood was used for the $\delta^{13}C$ and $\delta^{18}O$ measurements, respectively. This analysis was carried out at the Center for Stable Isotope Research and Analysis, Forest Ecosystem Research, University of Göttingen, Germany.

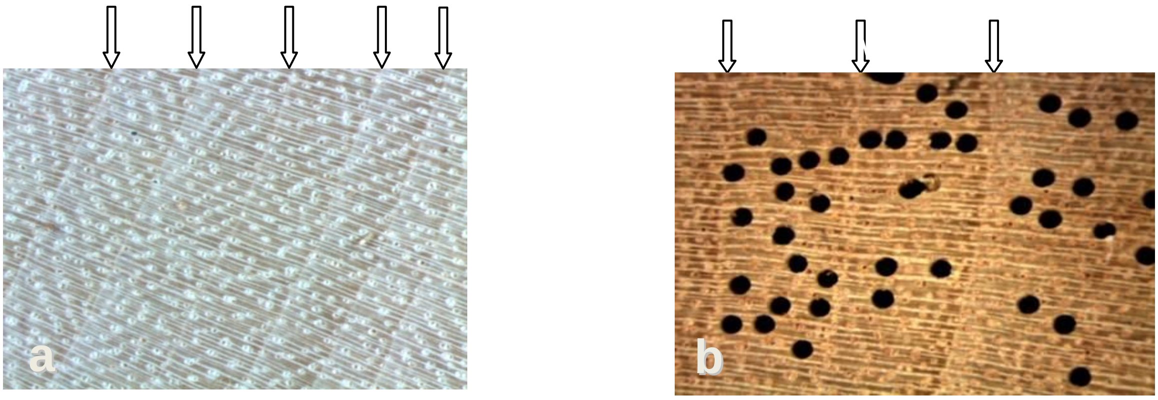

Figure 2 *Cross-sections of* S. birrea*: (a) arrows indicate annual growth boundaries; (b) method of sample preparation – black dots are holes drilled for obtaining wood material for stable isotope analyses.*

A long-term trend in $\delta^{13}C$ series, related to the decline in atmospheric $\delta^{13}C$ values, was determined following the method described by McCarroll and Loader (2004). To determine the relationship between the $\delta^{13}C$ and $\delta^{18}O$ values and climate variables, we used precipitation (monthly and annual means), Palmer drought severity index (PDSI), mean relative humidity, sunshine hours, maximum temperature and evapotranspiration. The climatic data were obtained from the Burkina Faso Meteorological Agency, except for PDSI data, which were obtained from Dai *et al.* (2004). We used data from Dori Meteorological Station, which is the closest available station to our study site. Unless stated otherwise, results are statistically significant at $P < 0.05$.

RESULTS AND DISCUSSION

Formation of Growth Boundaries

Sclerocarya birrea forms very distinct ring boundaries characterised by marginal parenchyma bands, which run around the entire stem disc (Fig. 2a). This corresponds to the phenology of *S. birrea*, which is a drought-deciduous species shedding its leaves during the dry season, which lasts about 8 months and triggers the formation of annual growth boundaries. Compared with drought-deciduous *Acacia* species in Ethiopia, ring formation in *S. birrea* is very distinct.

Inter-annual $\delta^{13}C$ and $\delta^{18}O$ Variations

First results showed that the inter-annual patterns of $\delta^{13}C$ and $\delta^{18}O$ ratios in tree rings of *S. birrea* were uniform between the two individual trees, indicating that marked fluctuations in stable isotope ratios were synchronous. This is further confirmed by cross-correlation analyses of the species mean $\delta^{13}C$ series ($r = 0.42$) and $\delta^{18}O$ ($r = 0.62$). The $\delta^{13}C$ and $\delta^{18}O$ values ranged from –24.6 to –26.7‰ and 21.24 to 25.45‰, respectively. However, the statistical correlations are still preliminary and might change as sample size increases in the future.

The $\delta^{13}C$ and $\delta^{18}O$ mean values showed similar co-variation patterns with significant positive correlations ($r = 0.53$) (Fig. 3). The similar pattern of within and between $\delta^{13}C$ and $\delta^{18}O$ ratios indicates that external factors affected isotope fractionations in a similar way. Further analysis of the $\delta^{13}C$ and $\delta^{18}O$ ratios suggests that they provide information on the tree growth conditions in early, mid- and latter part of the growing seasons in the respective years.

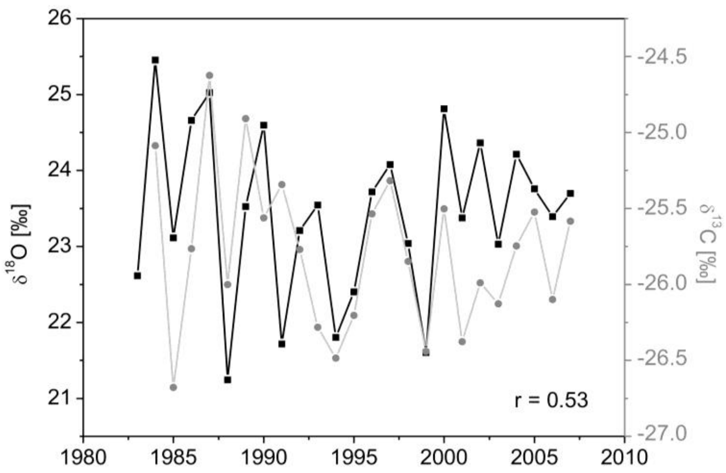

Figure 3 *Sclerocarya birrea* $\delta^{13}C$ *and* $\delta^{18}O$ *patterns and correlations*

$\delta^{13}C$, $\delta^{18}O$ and Climate

Sclerocarya birrea responded to the short rains that normally started in May, and showed significant correlations to the rainy season (July–September). In general, both $\delta^{13}C$ and $\delta^{18}O$ showed negative correlations with rainfall, humidity and PDSI. Conversely, they were positively correlated with sunshine hours, maximum temperature and evaporation (Fig. 4). Furthermore, precipitation in August (the wettest month) proved to have a stronger influence than annual precipitation on the $\delta^{13}C$ and $\delta^{18}O$ isotopic variations. Some of these relationships can be explained by the covariance of climatic factors, for example, high rainfall is accompanied by higher relative humidity and PDSI. Consequently, stomatal conductance is enhanced, resulting in the depletion of $\delta^{13}C$. In dry years, moisture stress will trigger stomatal closure and enrichment of the heavier isotopes (e.g. Gebrekirstos *et al.*, 2009; Wils *et al.*, 2010). Similarly, $\delta^{18}O$ in tree rings of *S. birrea* also records dry and moist years. During drier conditions, heavier water isotopes evaporate more slowly and hence higher concentrations of ^{18}O indicate drought years. In contrast, depletion of the heavier isotope ^{18}O indicates moist years. Treydte *et al.* (2010) report that $\delta^{18}O$ in tree rings primarily record source-water information. Hence the significant correlation of $\delta^{18}O$ with precipitation amount in the rainy season also documents that the main source of water for the growth of *S. birrea* is soil water.

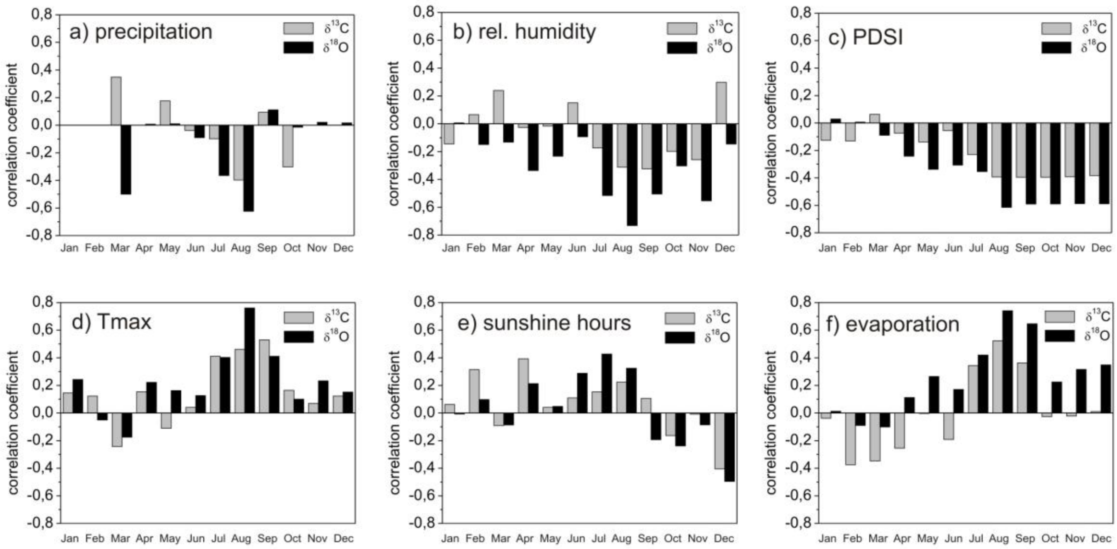

***Figure 4** Correlation between* Sclerocarya birrea *$\delta^{13}C$ and $\delta^{18}O$ and climate parameters* (T_{max} *= maximum temperature)*

Research Perspectives

Even though the three projects mentioned have been developed with specific objectives and different partner institutes, their results will enable us to draw important general conclusions. First, valuable information can be derived with regard to the adaptation potential of important agroforestry tree species in different climate regimes and agro-ecological zones. Using the stable-isotope technique, the water-use efficiency, growth strategy and adaptability to climate variability and climate change of key agroforestry species can be evaluated.

A second important field of application is the reconstruction of long-term climatic variability and climate trends from tree-ring width and stable-isotope series. Since instrumental climate data are scarce or of short duration for vast areas of Africa, the range of natural climate variability is poorly understood, and thus the range of tree species' tolerance to climatic extremes is not known. Previous results from Ethiopia show strong climatic signals in tree rings and stable carbon isotope series (Gebrekirstos, 2009; Gebrekirstos *et al.*, 2008, 2009, 2010). The ongoing project in Munessa Forest, Ethiopia may result in chronologies of more than 350 years from *Podocarpus procera*. The pilot measurement results from the Sahel region are encouraging. Tree-ring chronologies spanning more than 100 years are under development for Burkina Faso and Tanzania. These findings may help in the identification and interpretation of extreme environmental and climatological events, and may provide information about the ways in which societies and ecosystems respond to them during times when no historical meteorological records are available (Gebrekirstos, 2009). This may form important input to the future Intergovernmental Panel on Climate Change report from Africa as well.

Finally, the tree-ring series developed in the three projects will be combined to establish large-scale correlation patterns between tree growth and sea-surface temperatures in order to explore continent-wide climate teleconnections and variations of atmospheric circulation patterns. In order to do this, there is a need to extend this work to additional important species and other parts of Africa.

Furthermore, these regional chronologies will be combined with tree-ring series surrounding the tropical oceans, established by project partners in other regions – the Middle East: Iran (e.g. Pourtahmasi *et al.*, 2007); and southern Asia: Nepal (e.g. Bräuning, 2004) and the Tibetan plateau (Bräuning and Mantwill, 2004; Bräuning, 2006). Additional tree-ring series from tropical South America (Ecuador) have been established (Bräuning *et al.*, 2009). Altogether, this tree-ring network surrounds the Indian Ocean and the tropical eastern Pacific, and can therefore be used to establish large-scale correlation patterns between tree growth and sea-surface temperatures in order to explore global processes around the tropics.

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