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Journal of Tropical Ecology / Volume 32 / Issue 03 / May 2016, pp 213 - 225
DOI: 10.1017/S0266467416000134, Published online: 12 April 2016

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Stable carbon and oxygen isotopes in tree rings show physiological responses of *Pericopsis elata* to precipitation in the Congo Basin

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(Received 7 December 2015; revised 8 March 2016; accepted 9 March 2016; first published online 12 April 2016)

Abstract: In equatorial regions, where tree rings are less distinct or even absent, the response of forests to high-frequency climate variability is poorly understood. We measured stable carbon and oxygen isotopes in anatomically distinct, annual growth rings of four *Pericopsis elata* trees from a plantation in the Congo Basin, to assess their sensitivity to recorded changes in precipitation over the last 50 y. Our results suggest that oxygen isotopes have high common signal strength (EPS = 0.74), and respond to multi-annual precipitation variability at the regional scale, with low δ18O values (28–29‰) during wetter conditions (1960–1970). Conversely, δ13C are mostly related to growth variation, which in a light-demanding species are driven by competition for light. Differences in δ13C values between fast- and slow-growing trees (c. 2‰), result in low common signal strength (EPS = 0.37) and are driven by micro-site conditions rather than by climate. This study highlights the potential for understanding the causes of growth variation in *P. elata* as well as past hydroclimatic changes, in a climatically complex region characterized by a bimodal distribution in precipitation.

Key Words: Africa, Congo, stable isotopes, tree rings, tropical rain forest

INTRODUCTION

The Congo Basin is a key area for the global carbon cycle, hosting the second largest tropical forest after the Amazon (Detwiler & Hall 1988). Yet, the degree to which the Central African forest will cope with future global changes is under debate (Otto et al. 2013, Zelazowski et al. 2011). Understanding centennial scale growth dynamics of past tropical forests can provide baseline information for assessing future climate change impacts; unfortunately, such data are rare before the instrumental record (Gebrekirstos et al. 2014, Rozendaal & Zuidema 2011).

Tree rings can potentially fill this gap in our knowledge. In the tropics, the use of tree rings has been hindered by the lack of annual rings in most tree species, thus limiting their application for dendrochronological studies (Loader et al. 2013, Rozendaal & Zuidema 2011). However, tree-ring stable carbon and oxygen isotopes (δ13C, δ18O) in some cases have been shown to reflect tree growth response to climate forcing, even when annual rings are missing or unclear (Evans & Schrag 2004, Poussart et al. 2006).

Stable isotopes in tree rings are determined by distinct processes (McCarroll & Loader 2004). Generally, tree physiology controls δ13C, with fractionation occurring during uptake of CO2 through the stomata (diffusion, c. −4‰) and during CO2-fixation (carboxylation, c. −27‰). δ13C is therefore influenced by changes in the relative importance of diffusional versus biochemical limitations of photosynthesis (Francey & Farquhar 1982). Such changes occur as a result of environmental factors like water availability, light, but also nutrients and competition with neighbouring trees (McCarroll & Loader 2004). In contrast, tree-ring oxygen isotopes are more directly influenced by physical and climatic factors, rather than tree-internal physiological fractionations. Precipitation amount (amount effect, i.e. the depletion
of heavy isotopes with increasing rainfall), together with altitudinal and continental effects (i.e. Rayleigh fractionation) are the most relevant factors determining $\delta^{18}$O in precipitation (equilibrium processes, Dansgaard 1964). This precipitation isotope signal, taken up by the roots, is the major signal incorporated in plants, although further modification occurs in the plant leaves during transpiration, causing an enrichment controlled mainly by relative humidity and relatively constant biochemical enrichment (Roden et al. 2000). Stable isotope tree-ring series in the tropics are still rare and a relatively recent approach compared with temperate zones (Barbour 2007, Helle & Schleser 2004, McCarroll & Loader 2004, Schleser et al. 1999). Additionally, the attribution of isotopic changes to single environmental factors is often difficult to achieve (Gebrekirehos et al. 2014). This is particularly true for regions characterized by a bimodal distribution in precipitation (e.g. Eastern Congo), where the responses of species are controlled by multiple factors and still poorly documented.

In this study, we explore the nature of isotopic variability in tree-ring series from _Pericopsis elata_ (Harms) van Meeuwen, a light-demanding species common in moist semi-deciduous forest of Central and Western Africa (Vivien & Faure 2011), and with the advantage of annual growth rings (De Ridder et al. 2014). Specifically, we combine stable isotopes, ring-widths and precipitation data to test whether stable isotopes may record climate variability over the last 50 years, in an area characterized by a bimodal distribution in precipitation (two wet and two dry seasons). Alternatively, the isotopic composition in _Pericopsis elata_ may be mostly driven by local growth conditions (e.g. light availability), thus masking the climate signal. For this study, we focused on two slow- and two fast-growing trees, to account for the relative importance of tree growth for isotopic fractionation.

**METHODS**

**Site**

The Yoko reserve (00°21′–00°06′N, 025°13′–025°17′E) is a protected area (Institut Congolais de la Conservation de la Nature, ICCN) located c. 20 km south of Kisangani (Tshopo district, Province Orientale, Democratic Republic of Congo, Figure 1). The area is relatively flat and with a total area of approximately 7000 ha, delimited by the Congo and the Biaro rivers (Figure 1b). It is presently covered by dense and semi-deciduous forest stands (Congolese mixed moist semi-evergreen forest), including light-demanding (_P. elata_, _Milicia excelsa_, _Musanga cecropioides_, _Piptadeniastum africacum_) and shade-tolerant tree species (_Cynometra sp._, _Gilbertiodendron dewevrei_, and mostly _Scorodophloeus zonkeri_, see Lomba-Bosombo 2002). Mean temperature in the region is around 25°C with maximum insolation between January–February and a minimum in August (Kisangani meteorological station, 1901–2009). Monthly precipitation (annual mean 1700 mm) shows a bimodal pattern (short and long rainy seasons: April–May and September–November, respectively), associated with the latitudinal migration of the Intertropical Convergence Zone (ITCZ). Relative humidity in the Congo Basin is mainly delivered by westerly winds from the Gulf of Guinea and recycled through the rain forests, before being delivered further east (Williams et al. 2012). Continental-scale climate patterns, such as the ENSO or the Indian Ocean Dipole (IOD) can also affect precipitation variability over decades (Farnsworth et al. 2011).

Trees of _Pericopsis elata_ have been planted in 1953 and 1954 in the reserve (00°19′35.2″N, 25°15′29.7″E), with a distance between trees of c. 5 m. A few _Terminiala superba_ Engl. & Diels trees were planted close to the _Pericopsis elata_, and some other species (such as _Elaeis guineensis_ Jacq, palms, _Piptadeniastum africacum_ (Hook.f.) Brenan and _Petersianthus macrocarpus_ (P. Beauv.) Liben) established spontaneously between the planted trees. In 2010, the distance between trees was c. 9 m. Although a more complete description of the forest stands and micro-site conditions were not available in this remote area at the time of sampling, edaphic conditions were relatively homogeneous in the plantation, and competition for light is the main determinant of tree growth in this light-demanding species. For our study, we randomly selected from the plantation trees with regular stems and without scars.

**Ecology of Pericopsis elata**

Among the long-living, light-demanding tree species, _P. elata_ is an ecologically versatile species, coping with both dry and waterlogged conditions (Bourland et al. 2012). It can be found in small (1 ha) aggregates, reproducing with anemochoric dispersal. Because of decades of exploitation for its highly valuable timber, it is included in the CITES list of protected species. To establish, _Pericopsis elata_ requires forest-gap disturbances (Hawthorne 1995); its distribution in Central Africa was favoured by moderate human impact before the colonial period (Brncic et al. 2007). Generally its growing season is determined by seasonal precipitation distributions (from March–April to November, Appendix 1), and wood formation is only interrupted for a few months during the driest season (December–March).

**Tree-ring widths and stable isotopes ($\delta^{13}$C, $\delta^{18}$O) analysis**

We collected stem discs from two slow- (discs 1 and 2) and two fast-growing trees (discs 3 and 4, Figure 2a),...
Stable isotopes in Pericopsis elata tree rings

Figure 1. Map of the study site, with MODIS derived distribution of central African rain forest (a) (modified after Mayaux et al. 2013); values in brackets indicate long-term average $\delta^{18}O$, weighted by amount of precipitation at selected GNIP stations (Rozanski et al. 1996). The location of the Yoko reserve (b) (modified after Lomba-Bosombo 2002). The microscopic view of a Pericopsis elata tree ring (c), showing the anatomically distinct ring border, separating early (dark fibres) and late seasons (light fibres with parenchyma) (c). Monthly rainfall changes, showing the bimodal distribution of precipitation (d). Changes in total precipitation near Kisangani over the last century (van Oldenborgh & Burgers 2005); the thick line represents the 5-y moving average (e).

in the Yoko reserve during 2009–2010. Discs were cut at approximately 30 cm above soil level and tree-ring widths were measured on four rays for each disc, following standard procedures (De Ridder et al. 2013a). We measured each ring considering the wood anatomical patterns specific to P. elata: a dark layer of fibres and no vessels, followed by a lighter layer with parenchyma produced later in the season (Figure 1c). An anatomically distinct growth-ring border is visible, and is also supported by information from cambial wounding experiments. For each disc, we used one measured ray (i.e. with no missing years, where possible), instead of the average tree-ring series. Cross-dating between trees (Douglas 1941) was not successful due to different growth history of trees (Figure 2a).

We measured stable isotopes ($\delta^{18}O$, $\delta^{13}C$) on each tree and ring separately, without pooling samples for maximizing sample size (as sometimes done for temperate species, Saurer et al. 1995). This implied a lower number of measured samples, but allowed accounting for differences in the isotopic signal due to varying growth patterns (Figure 2a). For isotope analysis, we manually split each selected ray with a scalpel obtaining c. 50 samples per disc, with each sample representing 1 y of tree growth. Alpha cellulose was extracted using standard methods from 1 mg of ground wood material prior to stable isotope analysis (Boettger et al. 2007). We excluded the innermost rings because photosynthesis rates may be different in the first years of growth and the influence of soil-respired CO2 higher (Fichtler et al. 2010). In total, we considered 47 rings for disc 1 (1962–2008), 51 for disc 2 (1960–2010), 53 for disc 3 (1958–2010) and 51 for disc 4 (1960–2010, Table 1). For data analyses, we considered the common period between discs (1962–2008).

To determine carbon isotopic ratios, samples were combusted to carbon dioxide at 1025°C using an elemental analyser (EA-1110; Carlo Erba Thermoquest, Milan, Italy), and the isotope ratios measured with a Delta S isotope ratio mass spectrometer (Thermo Finnigan, Bremen, Germany). Oxygen isotopic ratios were determined after pyrolysis to CO at 1420°C using a Pyro cube (Elementar, Hanau, Germany) connected in continuous flow mode to a Delta Plus XP (Thermo Finnigan, Bremen, Germany).
Table 1. *Pericopsis elata* tree-ring series used in this study. Trees were sampled in 2008 and 2010 in an even-aged plantation (1953–1954) located in the Yoko reserve (Eastern Congo). Age interval considered for stable isotope series did not include the first years of growth. Disks 2–4 were harvested at the beginning of the growing season, resulting in a not fully formed ring in year 2010.

<table>
<thead>
<tr>
<th>Disc</th>
<th>Museum code</th>
<th>Year of plantation</th>
<th>Gbh (cm)</th>
<th>Tree height (m)</th>
<th>Sampling date</th>
<th>Age interval considered for $\delta^{18}O$ and $\delta^{13}C$ analyses</th>
<th>No. of rings analysed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tw60900a</td>
<td>1954</td>
<td>97</td>
<td>20-22</td>
<td>11 August 2008</td>
<td>1962-2008</td>
<td>47</td>
</tr>
<tr>
<td>2</td>
<td>Tw622010a</td>
<td>1954</td>
<td>125.9</td>
<td>NA</td>
<td>24 May 2010</td>
<td>1960-2010</td>
<td>51</td>
</tr>
<tr>
<td>3</td>
<td>Tw62209a</td>
<td>1953</td>
<td>150.6</td>
<td>25-28</td>
<td>25 May 2010</td>
<td>1958-2010</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>Tw62212a</td>
<td>1953</td>
<td>178.8</td>
<td>NA</td>
<td>24 May 2010</td>
<td>1960-2010</td>
<td>51</td>
</tr>
</tbody>
</table>

Figure 2. *Pericopsis elata* tree-ring widths showing slow- (discs 1 and 2) and fast-growing trees (discs 3 and 4); values are on a log scale to highlight variation in low $\delta^{13}C$ (a). $\delta^{13}C$ series on alpha-cellulose expressed relative to the Vienna Pee Dee belemnite VPDB; $\delta^{13}C$ values were corrected by adding the difference between preindustrial and present $\delta^{13}C$, to account for the increase in carbon dioxide from fossil fuels since 1950 (b).
Carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopic ratios are expressed relative to the Vienna Pee Dee belemnite VPDB ($\delta^{13}C$, Coplen 1995), and Vienna Standard Mean Ocean Water VSMOW ($\delta^{18}O$), respectively (details in Saurer & Siegwolf 2004). The overall precision was 0.1‰ for carbon and 0.2‰ for oxygen. For $\delta^{13}C$, we accounted for the global increase in carbon dioxide from fossil fuels since 1950 (Epstein et al. 1990), which reduced the $^{13}C$ content in the atmosphere (McCarroll et al. 2010). We therefore corrected all $\delta^{13}C$ values by adding the difference between pre-industrial and present $\delta^{13}C$, for each year.

Data analysis

Instrumental climate data in the tropics are generally sparse and discontinuous; we therefore compared different precipitation datasets from instrumental records, including areas close to the sampling site (Kisangani, 20 km distant), or in the region (Yangambi, 100 km distant). Since most of these data are too fragmentary, or do not entirely cover our series (1958–2009), we only considered the interpolated (between 0 and 1°N and 24°and 25°E) precipitation time-series from 1908 to 2009, at local-to-regional scale (Royal Netherlands Meteorological Institute KNMI, van Oldenborgh & Burgers 2005, and NCAS British Atmospheric Data Centre). Temperature has generally little influence on growth conditions of tropical species, at least in this area (De Ridder et al. 2013b), and indeed our stable isotope series are only weakly correlated with temperature (Appendix 1). The KNMI data show a period of higher annual precipitation in the 1960s, followed by a drying trend (Figure 1e). When decomposing the time series, the distribution of seasonal precipitation during the two halves of the rainy season (short and long wet seasons) is also variable over the decadal time-scale (Appendix 1). We therefore compared our isotopic data, with changes in monthly and seasonal precipitation over the last 50 y (Appendices 2 and 3). All time-series are presented with raw data (with exception for the $\delta^{13}C$ corrected for fossil-fuel emissions). No standardization was applied to avoid losing any low-frequency signal (Robertson et al. 1997).

For carbon and oxygen isotopes, we calculated the expressed population signal EPS (Brieffa & Jones 1990) to assess the common signal strength of different trees. We used the averaged oxygen isotopes values (but not $\delta^{13}C$ series, because of lower inter-series correlations), to check whether oxygen isotopes in our series are related to precipitation data. The averaged $\delta^{18}O$ values are reported with confidence intervals calculated with a Student’s-t distribution. Additionally, we calculated the coefficient of variation CV (a normalized measure of dispersion), RBAR (a measure of common variance) and standard deviation statistics (Frank et al. 2007, Kress et al. 2010).

We also considered GNIP stations (Global Network of Isotopes in Precipitation) located in the west and the east of the Congo Basin (Figure 1a), to assess the isotopic signature of different source of air masses on precipitation (Araguas-Araguas et al. 2000). We only used the weighted mean as reported in Rozanski et al. (1996), because GNIP series are often discontinuous and do not allow a full comparison with our $\delta^{18}O$ series. Also, the closest station with continuous data (Entebbe, Uganda, Figure 1a), shows an isotopic signature which is mostly biased by moisture derived from evaporated water from Lake Victoria (Rozanski et al. 1996), and therefore not considered in this study.

RESULTS

Ring-width series and stable isotopes

The analysed stem discs showed large differences in ring-width patterns (Figure 2a), reflecting the different growth dynamic of trees growing in monospecific plantations. Disc 1 showed relatively constant narrow rings, suggesting less favourable conditions for tree growth, likely caused by the presence of a nearby growing Terminalia superba tree. Disc 1 also showed series of narrower rings, with minimum values in 1965, 1990 and 1998 (Figure 2a). Discs 2 and 3 exhibited highly variable ring-widths, with narrower rings after 1971 (disc 2) and 1980 (disc 3, Figure 2a). Disc 4 was still dominant at the time of sampling, and under more open conditions and light availability: ring widths showed a constant growth pattern, with favourable conditions for tree growth after 1977 (Figure 2a).

The common signal strength was different between $\delta^{13}C$ and $\delta^{18}O$ series, with Expressed Population Signal (EPS) much lower for $\delta^{13}C$ ($= 0.37$) than for $\delta^{18}O$ ($= 0.74$). Fast-growing trees (discs 3 and 4) were less depleted (i.e. higher $\delta^{13}C$ values) than slow-growing trees (i.e. disc 1, Figure 2b). For instance, between 1975 and 2010, discs 3 and 4 showed 2% higher values on average than discs 1 and 2 ($c. −24%$ vs $−26%$, Figure 2b). Disc 2, with high variability in tree-ring widths, had lower $\delta^{13}C$ values when tree growth decreased (after 1971, Figure 2). We also observed more variability in $\delta^{13}C$ during the period with highest total precipitation (1958–1970, Figure 1e), with disc 1 (slow-growing tree) reaching values as low as $−29%$.

Correlations between oxygen and carbon, and between ring widths and stable isotopes, were significant only in a few discs and depended on their growth rates (Table 2). For instance, $\delta^{18}O$ and $\delta^{13}C$ were significantly correlated ($r = 0.53$, $P < 0.01$) only in disc 1, i.e. the tree with the slowest growth rates. Ring-widths and $\delta^{13}C$ were significantly correlated only in disc 4 ($r = 0.54$, $P < 0.01$),
Table 2. Pearson’s product-moment correlation between ring widths and stable isotopes in Pericopsis elata, measured on four discs from the Yoko reserve (Eastern Congo). Positive correlations exist between δ18O and δ13C in disc 1 and between δ13C and tree growth in disc 4; asterisk (*) indicates significance level at P < 0.01. Correlations are calculated over the common interval 1962–2008.

<table>
<thead>
<tr>
<th>Disc</th>
<th>Growth rate</th>
<th>δ18O vs δ13C avgGrowth</th>
<th>δ13C vs avgGrowth</th>
<th>δ18O vs avgGrowth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slow</td>
<td>0.53*</td>
<td>−0.10</td>
<td>−0.12</td>
</tr>
<tr>
<td>2</td>
<td>Slow</td>
<td>−0.25</td>
<td>0.30</td>
<td>−0.58</td>
</tr>
<tr>
<td>3</td>
<td>Fast</td>
<td>0.29</td>
<td>−0.30</td>
<td>−0.05</td>
</tr>
<tr>
<td>4</td>
<td>Fast</td>
<td>0.31</td>
<td>0.54*</td>
<td>0.28</td>
</tr>
</tbody>
</table>

a fast-growing tree (Figure 2a). δ18O and ring widths were instead weakly correlated for all discs (Table 2).

δ18O and precipitation data 1958–2009

Considering the high common signal strength for δ18O, we averaged δ18O series (Figure 3a) to allow comparison with the available 50 y of instrumentally recorded changes in precipitation (Appendix 1). At multi-annual scale, trends in δ18O followed changes in total precipitation (but not in temperature, Appendix 1). In general, low δ18O values occurred during 1960–1970, i.e. the period with higher precipitation (and to a lesser extent, during 1990–1995, Figure 3b–d). This period was followed by increasing δ18O values and a declining precipitation trend (i.e. after 1970, Figure 3d). We found, however, low correlations between δ18O series and annual or seasonal precipitation (Appendix 2 and 3). In particular, the weakened δ18O signal strength after 1980 (see increased C.I. in Figure 3b), was due to changing growth rates in disc 2, particularly after 1988 (Figure 2a), overall weakening the correlation between total precipitation and our δ18O series. Low signal strength in δ18O was also particularly marked for years 1965, 1984 and 1992–1994 (high STDEV and CVar in Figure 3c), and reflected by lower mean inter-series correlation (e.g. low RBAR between 1992–1995). By considering 5-y average values, the correlation between total precipitation and δ18O series (all discs) was significant (r = −0.7, P < 0.01).

DISCUSSION

Physiological and climatic controls over tree-ring δ13C

The δ13C signal in tree-rings is usually interpreted as the interplay between stomatal conductance (influenced by atmospheric humidity and soil moisture) and photosynthesis (influenced by light and nutrients availability), determining the total amount of intracellular CO2 in the leaf, and therefore the carbon isotope discrimination (McCarroll & Pawlek 2001). For instance, high δ13C values may result from increased photosynthesis or stomatal closure, depending on the relative importance of moisture for tree growth in the considered region. In Kenya, Gebrekirstos et al. (2009) found that moisture stress results in high δ13C in different Acacia species from semi-arid areas of East Africa. The (inverse) relationship between precipitation and δ13C in tree rings has also been used for regional-scale river flow reconstructions (Wils et al. 2010). In the Congo Basin instead, where moisture stress is a less limiting factor, we expect stomatal conductance to play a minor role for δ13C fractionation, compared with photosynthesis. We tested this by comparing our δ13C series with precipitation data and ring-width measurements, which can be used as indicators of photosynthetic rates (Worbes et al. 2003).

Our data show a marked inter-tree variability in absolute δ13C values (Figure 2). Fast-growing trees tend to have around 2‰ higher values on average than slow-growing trees. Such differences in absolute δ13C have also been observed for subtropical forest species growing under different growth conditions, with lower δ13C values in shade conditions (West et al. 2001). Indeed, shading is a limiting factor for tree growth, especially for long-lived, light-demanding species such as P. elata (Bourland et al. 2013). Instead, water stress is not controlling growth variation between trees, as stomatal closure would result in higher δ13C, rather than low δ13C values as in our data (i.e. in the slow-growing discs 1 and 2, Figure 2). In agreement with the carbon fractionation theory (McCarroll & Pawlek 2001) our data therefore suggest that variation in δ13C is driven by individual growth histories of each tree, which at our site is mainly determined by variation in light availability. For instance, Disc 1 grew under reduced light conditions, due to a nearby Terminalia superba tree. The weak correlation between δ13C and ring widths on the yearly basis (Table 2) is possibly due to the relative importance of photosynthesis and stomatal conductance, which may be different during wet (e.g. 1950–1970) and dry periods (e.g. after 1970, Figure 3d), thus indicating an unstable climate-isotope relationship (Reynolds-Henne et al. 2007). In our data, photosynthetic rates are reflected in the δ13C variability in one tree only (disc 4, fast-growing), as suggested by the correlation with ring widths (r = 0.54, P < 0.01).

In the slow-growing disc 1, δ13C variability is instead more controlled by precipitation, as shown by δ13C values before 1970 (as low as −29‰, Figure 2b). Indeed, low δ13C values in slow-growing trees may result from the additive effect of low light availability (low photosynthetic rate), and wetter conditions (high stomatal conductance). A further mechanism explaining such low δ13C values could be related to CO2 from soil respiration (containing...
Figure 3. $\delta^{18}$O measured on four stem discs from *Pericopsis elata*, relative to the Vienna Standard Mean Ocean Water VSMOW. Raw $\delta^{18}$O series on alpha-cellulose (a); note the inverted Y axis to allow comparison with precipitation variability. Averaged $\delta^{18}$O series (b); solid line represents the 5-yr running mean and dashed lines the 90% CI of the four averaged series. Standard deviation (SD), 5-yr running mean correlation coefficient (RBAR) and coefficient of variation (CV) (c). Total precipitation variability over the last 50 y; the blue line represents the 5-yr running average (d).
less $^{13}$C), during early stages of growth in a more closed canopy (isotope juvenile effect, Fichtler et al. 2010). Early-stage effects are instead less marked (or absent) in the other trees.

Taken together, such variable responses of carbon fractionation to photosynthesis and stomatal conductance in trees of different growth histories may explain why overall $^{13}$C, tree-ring width and precipitation series are weakly related in our series (Appendix 2 and 3). Indeed, multiple controls over $^{13}$C fractionation such as nutrient availability (Kyereh et al. 1999, Veenendaal et al. 1996), root development (Ampofo 1972), solar irradiance and forest openness (e.g. grazing, fire, logging), are difficult to disentangle at this step. Notwithstanding these uncertainties, our data suggest that variation in $^{13}$C in *Pericopsis elata* is driven by light availability, rather than water stress.

**Relationship between tree-ring $^{18}$O and precipitation**

Factors controlling $^{18}$O in tree rings mostly depend on precipitation sources and physiological processes, including transpiration (McCarroll & Loader 2004). Rayleigh fractionation should result in $^{18}$O depletion (i.e. low $^{18}$O) in precipitation at our site, relative to values recorded closer to the ocean source (c. $-2\%o$ to $-3\%o$, Figure 1a; Araguas-Araguas et al. 2000). The isotopic ratio of precipitation is also influenced by transpiration processes resulting in recirculation of moisture, a mechanism less subject to $^{18}$O depletion than land-evaporated water (Gat & Matsui 1991). Transpiration processes are still relatively less well documented in the Congo Basin than for the Amazon (Gat & Matsui 1991).

This isotopic signature (i.e. high $^{18}$O values) is also visible in GNIP stations outside of the Congo basin (Levin et al. 2009), highlighting the relative importance of the Congo rain forest as a source of moisture for neighbouring regions.

Superimposed on these large-scale, spatial patterns are temporal changes in $^{18}$O of source precipitation (Levin et al. 2009). These changes should be reflected in the variation of tree-ring oxygen isotopes, assuming source water to be the dominant factor (Saurer et al. 1997), albeit modified by leaf water enrichment and biochemical fractionations (Rodén et al. 2000). In our data, the forcing by regional variation in moisture balance is reflected by the strong signal coherency in $^{18}$O of tree rings. This value (EPS = 0.74) is slightly lower than that conventionally accepted for reaching the theoretical population chronology (0.85, Wigley et al. 1984), but still suggests a common signal in $^{18}$O (in contrast to $^{13}$C). In general, the similarity between total precipitation and $^{18}$O trends (Figure 3b–d) shows that regional precipitation has influence over $^{18}$O, at least at the decadal scale. This anti-phase (i.e. low $^{18}$O values with high precipitation) is also more marked during periods of wetter conditions, such as 1950–1970 (Figure 1e). The Congo Basin and neighbouring areas (Sahel, Horn of Africa) experienced anomalously wetter conditions between 1950 and 1970, a trend out of phase with higher subtropical latitudes (Nicholson 2000), also visible in the westernmost part of the Congo Basin (Samba & Nganga 2012).

It was followed by a reduction in precipitation during the 1970s and 1980s (mostly June–September precipitation, Williams et al. 2012). These decadal scale changes in precipitation are well reflected by our $^{18}$O series (Figure 3b–d). This decreasing trend in precipitation has been attributed to warming of the South Atlantic and Indian Oceans (Hagos & Cook 2008, Williams et al. 2012), although the relative sea surface temperature forcing (ENSO oscillations) on decadal scale precipitation variability is still relatively unclear (Camberlin et al. 2009, Nicholson 2000).

The observed relationship between $^{18}$O and total precipitation recorded in the instrumental record is in agreement with the theoretical fractionation mechanism related to precipitation intensity, or amount effect, and with the leaf isotope enrichment theory (Rodén et al. 2000), suggesting higher enrichment under dry conditions (or less enrichment under humid conditions). Such local effects of changes in relative humidity can also be related to atmospheric circulation changes, and are therefore not easy to separate.

In general, the decadal changes in precipitation are mirrored by trends in $^{18}$O, but the relationship between precipitation and $^{18}$O is much weaker on the annual basis (Appendix 2 and 3). Partly, this could be related to the quality of the meteorological data, or data not being fully representative for the study site. In their record from the Amazon, Brienen et al. (2012) explained low $^{18}$O-precipitation correlation scores with additional depletion resulting from air mass movement over the continent (Rayleigh distillation). If precipitation variability exerts a major control over $^{18}$O fractionations over decades, other factors, such as local conditions for tree growth (e.g. disc 2 in Figure 2a), soil water evaporation and leaf water enrichment (Rodén et al. 2000), can be dominant at the annual scale, weakening the correlation between precipitation and $^{18}$O.

**Potential and limitations of stable isotope analyses in *Pericopsis elata* tree rings**

Factors controlling variation in tree-ring isotope ratios at low altitudes in the tropics are still poorly understood, and few tree-ring stable isotope series exist for tropical Africa, due to site remoteness and challenges in tree-ring dating. In this respect, our study contributes

Our tree-ring δ13C and δ18O series generally agree with expected mechanisms for isotope fractionation (McCarroll & Loader 2004), but with some important differences. First, our results highlight the different sensitivity of stable carbon and oxygen isotopes to climatic factors in the light-demanding P. elata. δ13C absolute values seem to reflect local differences in growth factors, which in light-demanding species are controlled by competition for light (and to a lesser extent, by water stress). δ18O trends are instead controlled by precipitation over the multi-annual scale (Figure 3), with enriched δ18O values reflecting both large-scale atmospheric circulation changes, and humidity-driven enrichment by the leaves of the specific species. Secondly, the use of four trees for stable isotope studies in tree rings is often justified to represent a site isotope signal (Leavitt & Long 1984). However, this seems not to be sufficient for carbon isotopes series in P. elata, given the rather variable response of individual trees (Figure 2a). A larger sample size may be used to strengthen the link between δ13C and specific growth patterns (Figure 2), allowing estimation of local growth rates in P. elata and, indirectly, its productivity over time (Mbow et al. 2013), or for reconstructing patch-scale dynamics (Gebrekirstos et al. 2014). Also, once applied to a pool of species with different traits (e.g. pioneer vs shade-tolerant), δ13C series may allow differentiating the degree of shade tolerance, and thus classify functional types of species with poorly understood ecology (Werner & Magnus 2010). Oxygen isotopes instead show a stronger signal coherency than carbon in our trees (Figure 3). A higher EPS for δ18O series could be achieved by including more trees with only constant growth rates (e.g. for discs 1, 3 and 4 in Figure 2). The sensitivity of δ18O to precipitation changes indicates the potential in P. elata tree rings for precipitation reconstructions before the historical record. Stable isotopes from tree-rings are available from Western (van der Sleen et al. 2015) and Eastern Africa (Gebrekirstos et al. 2009), but are very scarce (if not absent) in this area, which is characterized by a complex bimodal precipitation distribution (Figure 1d).

Climate reconstructions from the Congo Basin, one of three major convective regions on the planet, are urgently needed to improve our understanding about synoptic climate systems delivering rainfall to the African rain forest, as also highlighted by disagreements in the existing model projections of future Congo rainfall (IPCC 2013).

ACKNOWLEDGEMENTS

This study was financed by the Swiss National Science Foundation to DC (grant no. PZ00P2_145077) and supported by the Belgian Federal Science Policy Office (grant no.BR/132/A1/AFRIFORD). We thank L. di Gesualdo for laboratory help and D.G. Gavin, W. Tinner, D. Verschuren and the AFRIFORD group for fruitful discussions. We are also grateful to one anonymous reviewer for the evaluation of the manuscript and improvements to the text. Data will be available upon request from the author.

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Appendix 1. Temperature and precipitation time series (a–b, Kisangani area), showing the relative contribution of seasonal precipitation (c–f) to total annual rainfall (a). The bimodal pattern in precipitation (long and short rainy seasons) is mostly associated with the latitudinal migration of the ITCZ (see main text). Precipitation data are from the NCAS British Atmospheric Data Centre, accessed with the KNMI climate explorer (van Oldenborgh & Burgers 2005). Temperature data are from Kahindo Muhongya (2011).
Appendix 2. Pearson’s product-moment correlation values showing a weak linear relationship on the annual basis between stable isotopes ($\delta^{18}O$) and corrected $\delta^{13}C$ measured on *Pericopsis elata*, and monthly precipitation in Eastern Congo (Kisangani area).

<table>
<thead>
<tr>
<th>Disc</th>
<th>Stable isotope</th>
<th>January (mm)</th>
<th>February (mm)</th>
<th>March (mm)</th>
<th>April (mm)</th>
<th>May (mm)</th>
<th>June (mm)</th>
<th>July (mm)</th>
<th>August (mm)</th>
<th>September (mm)</th>
<th>October (mm)</th>
<th>November (mm)</th>
<th>December (mm)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Carbon</td>
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<td>0.08</td>
<td>0.00</td>
<td>0.11</td>
<td>−0.14</td>
<td>0.09</td>
<td>−0.20</td>
<td>0.07</td>
<td>−0.06</td>
<td>0.24</td>
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<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
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<td>−0.09</td>
<td>0.10</td>
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<td>−0.05</td>
<td>0.15</td>
<td>−0.23</td>
<td>0.05</td>
<td>−0.04</td>
<td>0.02</td>
<td>−0.02</td>
<td>0.12</td>
</tr>
<tr>
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<td>−0.15</td>
<td>−0.02</td>
<td>0.17</td>
<td>0.18</td>
<td>−0.10</td>
<td>0.16</td>
<td>0.05</td>
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</tr>
<tr>
<td>3</td>
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<td>0.03</td>
<td>0.02</td>
<td>−0.18</td>
<td>0.19</td>
<td>−0.20</td>
<td>−0.27</td>
<td>−0.02</td>
<td>0.11</td>
<td>0.24</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>−0.17</td>
<td>−0.08</td>
<td>0.05</td>
<td>−0.07</td>
<td>−0.07</td>
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<td>−0.09</td>
<td>−0.01</td>
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<td>−0.03</td>
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<tr>
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<td>−0.03</td>
<td>0.13</td>
<td>−0.07</td>
<td>−0.10</td>
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<td>0.04</td>
<td>0.19</td>
<td>0.19</td>
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</table>

Appendix 3. Pearson’s product-moment correlation considering the seasonal distribution of precipitation in Eastern Congo (Kisangani area), with the growing season for *Pericopsis elata* between April and November.

<table>
<thead>
<tr>
<th>Disc</th>
<th>Stable isotope</th>
<th>Long dry season (December–March)</th>
<th>Short dry season (April–May)</th>
<th>Short rainy season (June–July)</th>
<th>Long rainy season (August–November)</th>
<th>Growing season (April–November)</th>
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<tbody>
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<td>1</td>
<td>Carbon</td>
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<td>−0.03</td>
<td>−0.08</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>0.08</td>
<td>−0.10</td>
<td>−0.22</td>
<td>0.18</td>
<td>−0.02</td>
</tr>
<tr>
<td>2</td>
<td>Carbon</td>
<td>0.04</td>
<td>0.10</td>
<td>−0.20</td>
<td>0.17</td>
<td>0.09</td>
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<tr>
<td></td>
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<td>−0.01</td>
<td>0.12</td>
<td>−0.10</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
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<td>−0.21</td>
<td>0.24</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>0.02</td>
<td>0.07</td>
<td>−0.17</td>
<td>0.29</td>
<td>0.19</td>
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<tr>
<td>4</td>
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