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Tree-ring δ18O in African mahogany (*Entandrophragma utile*) records regional precipitation and can be used for climate reconstructions

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ABSTRACT

The availability of instrumental climate data in West and Central Africa is very restricted, both in space and time. This limits the understanding of the regional climate system and the monitoring of climate change and causes a need for proxies that allow the reconstruction of paleoclimatic variability. Here we show that oxygen isotope values ($\delta^{18}O$) in tree rings of *Entandrophragma utile* from North-western Cameroon correlate to precipitation on a regional to sub-continental scale (1930–2009). All found correlations were negative, following the proposed recording of the 'amount effect' by trees in the tropics. The capacity of *E. utile* to record the variability of regional precipitation is also confirmed by the significant correlation of tree-ring $\delta^{18}O$ with river discharge data (1944–1983), outgoing longwave radiation (a proxy for cloud cover; 1974–2011) and sea surface salinity in the Gulf of Guinea (1950–2011). Furthermore, the high values in the $\delta^{18}O$ chronology from 1970 onwards coincide with the Sahel drought period. Given that *E. utile* presents clear annual growth rings, has a wide-spread distribution in tropical Africa and is long lived (>250 years), we argue that the analysis of oxygen isotopes in growth rings of this species is a promising tool for the study of paleoclimatic variability during the last centuries in West and Central Africa.

1 . Introduction

The availability of instrumental climate data in West and Central Africa is very limited in both space and time, and constrains the understanding of climate variability in the regional and the ability to predict future changes (Washington et al., 2013; Gebrekirstos et al., 2014). The restricted availability of instrumental data causes a need for proxies that allow the reconstruction of climatic variability in the past. Such proxies records in Africa include stable isotope time series from lake sediment cores (Shanahan et al., 2009), ice cores (Thompson et al., 2002), speleothems (Talma and Vogel, 1992) and rock hyrax middens (Chase et al., 2010). These records are often long (spanning millennia), but generally coarse-scaled (with several years to decades between measurement points). A relatively new and promising tool for high-resolution (annually resolved) climate reconstructions on a centennial scale is the study of stable oxygen isotopes ($\delta^{18}O$) in growth rings of tropical trees (Zuidema et al., 2013). From these oxygen isotopes, information on large-scale atmospheric processes and precipitation over vast areas has been derived (Brienen et al., 2012; Schollaen et al., 2013b). The relation between tree-ring $\delta^{18}O$ and climate is based on the ability of trees to record the $\delta^{18}O$ variability of rainwater, which in the sub-tropics and tropics, is strongly determined by the amount of rainfall (Dansgaard, 1964). Often, this relation is more pronounced between rainwater $\delta^{18}O$ and the precipitation amount on a regional scale than at the individual cloud level (Kurita et al., 2009). Trees that record the $\delta^{18}O$ variability of precipitation in their growth rings can thus be archives of the amount of precipitation on large spatial scales (e.g. Brienen et al., 2012).

Previous studies have related tree-ring $\delta^{18}O$ to basin-wide precipitation in the Amazon (Ballantyne et al., 2011; Brienen et al., 2012), regional precipitation in Thailand (Poussart and Schrag, 2005) and Indonesia (Schollaen et al., 2013b) and to El Niño Southern Oscillation (ENSO) variability in Laos (Xu et al., 2011). So far, a few pilot studies on tree-ring $\delta^{18}O$ have been conducted in dry African regions (Verheyden et al., 2004; Gebrekirstos et al., 2011), but to our knowledge no study has been conducted in Africa's wet tropics (precipitation > 1500 mm). Here, we evaluated the climate signals in tree-ring $\delta^{18}O$ of an African mahogany species (*Entandrophragma utile*) from North-western Cameroon. To this end, we assessed (1) if growth rings in *E. utile* can be reliably dated, (2) if $\delta^{18}O$ values of multiple trees show a strong common signal and (3) whether a common $\delta^{18}O$ signal can be correlated to climatic variables that record regional precipitation. Because reliable meteorological data are scarce in the region we also used indirect proxies for regional climatic variability, including river discharge data, sea surface salinity, sea surface temperature and outgoing longwave radiation. We consider *E. utile* to be a species with a high potential for usage in climate reconstructions, because of its wide-spread distribution in tropical Africa, the presence of clear annual growth rings and a long lifespan (>250 years).

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2 . Material and methods

2.1. Regional setting

Trees were sampled inside the FSC-certified Forest Management Unit 11.001, of Transformation REEF Cameroon. This area is adjacent to the northwest border of Korup National park, in the Southwest Region of Cameroon, between 5°23′N, 9°09′E and 5°23′N, 9°12′E (Fig. 1a). The vegetation in the region consists of semi-deciduous lowland rainforest. The regional climate is equatorial, with a unimodal rainfall distribution and a dry season (with monthly rainfall < 100 mm) from December to February (Fig. 1b). Total annual precipitation varies strongly in the region. From 1968 to 2010, average annual precipitation amounted 2920 mm (range: 2070–3690 mm) at the Mamfé Airport weather station, ~40 km north of the study area, whereas at Mundemba meteorological station, ~40 km south of the study area, annual precipitation averaged 5220 mm (range: 3151–9345 mm). From these nearby records we estimate that at our site, annual precipitation is approximately 4000 mm and mean annual temperature approximately 26.5 °C (Fig. 1b).

2.2. Study species

The study species, *E. utile* (also known as Sipo), is a shade-tolerant from the family Meliaceae. The species is deciduous and leafless from around January and February. The potential growing season at this location runs roughly from March to November. *E. utile* is an emergent tree species, which can reach a maximum age of around 260 years (Nzogang, 2009), a maximum dbh of 250 cm and a total canopy height of up to 60 m (Voorhoeve, 1965). It is found in tropical Africa from Guinea to Togo and from Benin to Uganda and Angola, preferring fertile and well-drained soils in both upland evergreen forests and semi-deciduous moist- and dry forests (Poorter et al., 2004). The annual nature of ring formation in this species has been demonstrated by Hummel (1946), Mariaux (1981) and more recently by Groenendijk et al. (2014). Ring boundaries are characterized by the formation of a band of terminal parenchyma (Fig. 1c).

2.3. Sample collection and preparation

Entire stem discs at ~1 m height were collected from five large trees that were felled during selective logging operations in March–April 2012. No logging had taken place in the area prior to 2012. The trees were collected from an area of 1600 ha. After drying, the surfaces of the stem discs were polished with sandpaper of grids up to of 600 grains/cm^2. Part of the disc was also cut with razor blades to enhance the visibility of the rings. Ring identification took place using a LINTAB 6 measuring table (Rinntech, Germany), but ring widths were measured using high-resolution scans (1600 dpi) and WinDendro software (Regent Instruments, Canada). We checked the dating of the rings in two ways, first by visually cross-dating the ring-width series from different directions on the same disc and secondly, by cross-dating the ring-width series of different trees. Because the latter proved difficult, we checked the quality of dating by radio-carbon (^{14}C) dating (Worbes et al., 2003). ^{14}C-values were determined for 9 rings from three different trees (Accelerator Mass Spectrometer, University of Groningen, the Netherlands).

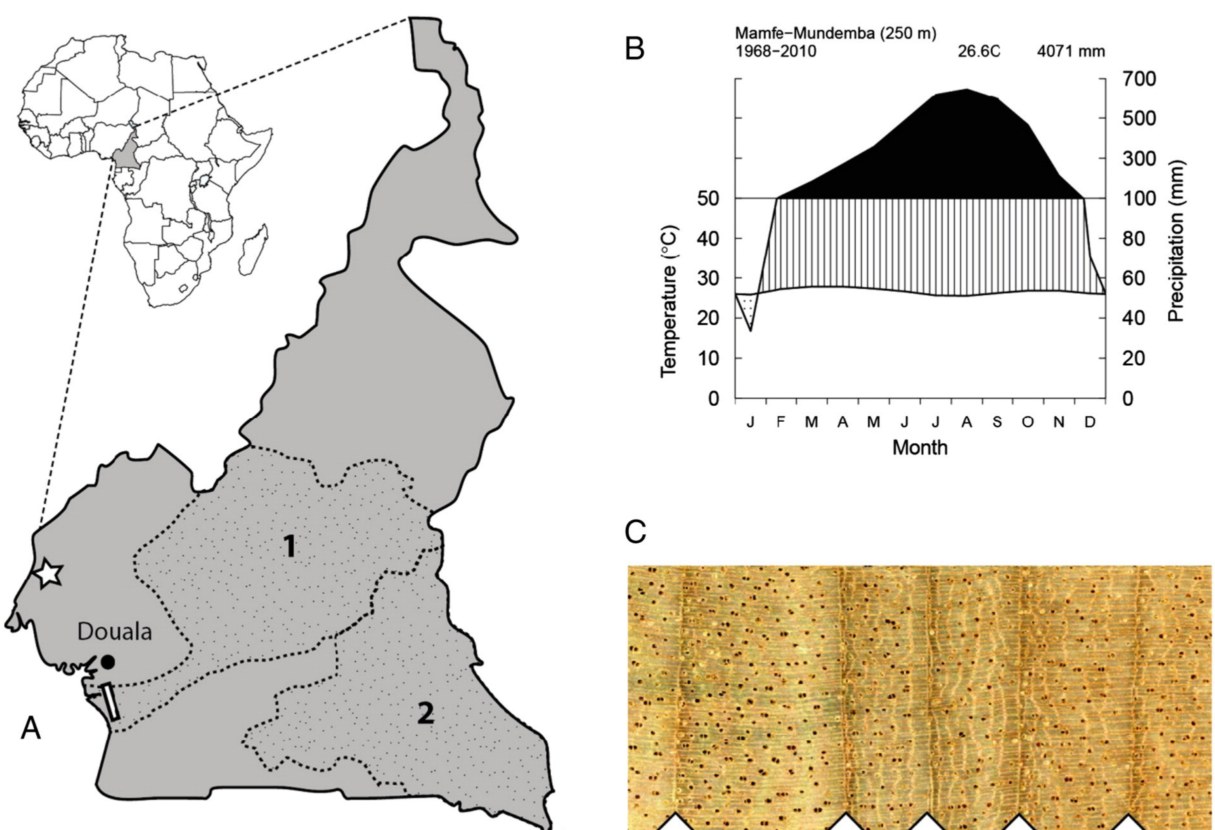

Fig. 1. (A) Map of Cameroon with the location of the sampled trees (indicated by the star), the Sanaga river basin (1) and the Cameroonian half of the Sangha river basin (2). White blocks indicate where river discharge was measured; black scale bar represents a distance of 200 km. (B) Climate diagram for the study site. Monthly precipitation and temperature (1968–2010) of two nearby stations were averaged: Mamfé Airport weather station (40 km north of study site) and Mundemba (40 km south of the study site). Dotted area indicates the dry season (precipitation < 100 mm/month), black area the rainy season (> 100 mm/month). (C) Growth rings in the wood of *Entandrophragma utile*. Triangles indicate ring boundaries (characterized by a band of terminal parenchyma).

For the $\delta^{18}O$ measurements, wood samples were extracted from each ring of the five trees. Wood was extracted across the entire width of the ring. A total of 665 samples were taken. Cellulose extraction was performed on the wood samples using a modification of the Jayme-Wise method (Wieloch et al., 2011). Crude cellulose samples were subsequently homogenized in a demi-water solution by a mixer mill (Retsch MM301, Germany) and oven-dried at 60 °C. The $\delta^{18}O$ of the cellulose samples was analyzed at the Leicester Environmental Stable Isotope Laboratory (University of Leicester, United Kingdom), using a Sercon HT furnace coupled to a 20–20 isotope ratio mass spectrometer. The furnace was kept at 1400 °C and was equipped with a quartz reactor lined with a glassy carbon tube. The glassy carbon tube was filled to a height of 150 mm with glassy carbon chips with the addition of a small amount of Nickeled carbon powder catalyst. Carbon monoxide and nitrogen were separated on a GC column, packed with molecular sieve 5A at a temperature of 40 °C. The oxygen isotope composition ($\delta^{18}O$, in ‰) was calculated as:

$$\delta^{18}O_{\text{tree-ring}} = \left(R_{\text{sample}}/R_{\text{standard}} - 1\right)$$

where R_{sample} is the $^{18}O/^{16}O$ ratio of a sample and $R_{standard}$ the $^{18}O/^{16}O$ ratio of an internationally recognized standard material (Vienna-Standard Mean Oceanic Water; VSMOW).

2.4. Climatic data

Monthly measurements of $\delta^{18}O$ in precipitation from stations in West and Central Africa were obtained from the Water Isotope System for Data Analysis (IAEA/WMO, 2006). Monthly precipitation data from two local weather stations (at Mamfé and Mundemba) were obtained from these stations at site.

Regional climatic signals in tree-ring $\delta^{18}O$ values were assessed by relating $\delta^{18}O$ variability to gridded (regional) precipitation, river discharge data, sea surface salinity, sea surface temperatures and outgoing longwave radiation. Gridded regional precipitation at a 0.5° scale over the period 1930 to 2009 was obtained from the CRU TS 3.21 dataset (University of East Anglia Climate Research Unit 2012). Discharge data for the Sanaga and Sangha river basins, the two largest river basins in central and south Cameroon, was obtained from the Global River Discharge Database (Center for Sustainability and the Global Environment, Gaylord Nelson Institute for Environmental Studies, University of Wisconsin-Madison). The Sanaga River drains an area of around 130,000 km^2 in central Cameroon. The Sangha river basin drains a large part of southern Cameroon as well as part of the Central African Republic (around 150,000 km^2 in total). The discharges of these rivers are directly affected by the precipitation amount in their catchment areas and are thus proxies for regional precipitation.

Sea surface salinity (SSS) is strongly affected by freshwater input (e.g. from rivers; Dessier and Donguy, 1994), thus representing an indirect proxy for wet vs. dry years. We used sea surface salinity from 1950–2011 of the UKMO EN3 dataset (Ingleby and Huddleston, 2007). Rainfall variability in West and Central Africa is also profoundly influenced by the sea surface temperatures (SST) of the tropical Atlantic Ocean (Chang et al., 1997). We correlated tree-ring $\delta^{18}O$ to sea surface temperatures of the Gulf of Guinea from 1930–2011 using the HadISST1 1° reconstruction dataset (Rayner et al., 2003).

Finally, outgoing longwave radiation (OLR) is often used to distinguish areas of convection and indicates the amount of cloud cover (Liebmann and Smith, 1996). We correlated tree-ring $\delta^{18}O$ to gridded outgoing longwave radiation (OLR) data from the National Oceanic and Atmospheric Administration (NOAA, USA; Liebmann and Smith, 1996).

For the assessment of plant physiological controls on tree-ring $\delta^{18}O$, we used temperature data from the four closest stations (Mamfé, Douala and Nkongsamba in Cameroon and Calabar in Nigeria) obtained from the KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013). We also used gridded temperature and water-vapor pressure data from the CRU.TS 3.21 database (University of East Anglia Climate Research Unit 2012).

2.5. Data analyses

Annual ring-width series were de-trended and converted to ring-width indices (RWI) by expressing ring-width values as anomalies from a smoothing spline with a rigidity of 20 years. We took the average of the RWI and tree-ring $\delta^{18}O$ series of the five *E. utile* trees as a representation of the common signal in these trees, the 'chronology'. The Expressed Population Signal (EPS) and average inter-series correlation (r_{is}) were calculated to evaluate the strength of the RWI and $\delta^{18}O$ chronologies. The EPS quantifies how well a chronology represents the hypothetical perfect or true chronology (Wigley et al., 1984). For a chronology in which trees show a prefect synchronized signal, the EPS = 1. An EPS of 0.85 is usually used to separate between chronologies dominated by a strong common signal (EPS ≥ 0.85) and chronologies wherein tree-level instead of stand-level signals dominate (EPS < 0.85; Speer, 2010). The mean inter-series correlation gives the average correlation of all the series with each other.

We visualized decadal scale fluctuations in tree-ring $\delta^{18}O$ and climate data with a smoothing spline (wavelength of 5 years and a frequency response of 0.05). Pearson's correlations were used to relate tree-ring $\delta^{18}O$ values to local rainfall and temperature variability, river discharge data and the $\delta^{18}O$ of precipitation. All analyses were performed in R, version 2.12.2, (R foundation for Statistical Computing, Vienna, Austria), using the package dplR.

Pearson's correlation maps of the $\delta^{18}O$ chronology with gridded CRU and GPCC precipitation, SST, SSS and OLR variability were created using the KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013), which uses the Grid Analysis and Display System (GrADS; Institute of Global Environment and Society, USA). All data were linearly de-trended before analyses to be certain that significant correlations are resulting from similarity in year-to-year variation, rather than concurrent long-term trends. In all cases, however, de-trending the data series had almost no effect on the outcome.

3 . Results

3.1. Dating accuracy and chronologies

Dating accuracy of the growth rings was checked by radio-carbon (^{14}C) dating of nine wood samples from three individuals. Age estimations based on radio-carbon analyses exactly matched those obtained from tree-ring analyses (within 1 year margin of error; Fig. 2). This indicated that no or very few dating errors were made over the tested period 1950–2010 for the trees analyzed. We tested three different samples: tree discs with very clear rings; with clear rings and samples with the presence of 'complex' rings: e.g. with periods of very small growth (suppressions) or strong wedging rings (see information in Groenendijk et al., 2014). We found no differences between these samples (Fig. 2), which shows that even the sample with 'complex' rings did not contain dating errors in the tested period.

Despite the highly accurate dating of the samples, the standardized ring-width (RWI) series of the five large *Entandrophragma* trees showed a very low common signal and poorly cross-dated with each other ($r_{is} = 0.038$, $p = 0.735$; EPS = 0.166; Supplementary Fig. A). The $\delta^{18}O$ chronology, on the other hand, strongly contrasted the RWI chronology and showed a significant inter-series correlation ($r_{is} = 0.367$; $p < 0.001$) and high EPS (0.737; Fig. 3) over the period 1930–2010. From 1900–2010, the inter-series correlation and EPS were slightly lower ($r_{is} = 0.319$, $p < 0.001$; EPS = 0.694), from 1860–2010 the EPS dropped to 0.642 and $r_{is} = 0.310$ (Fig. 3). We took 1930 as the starting point for

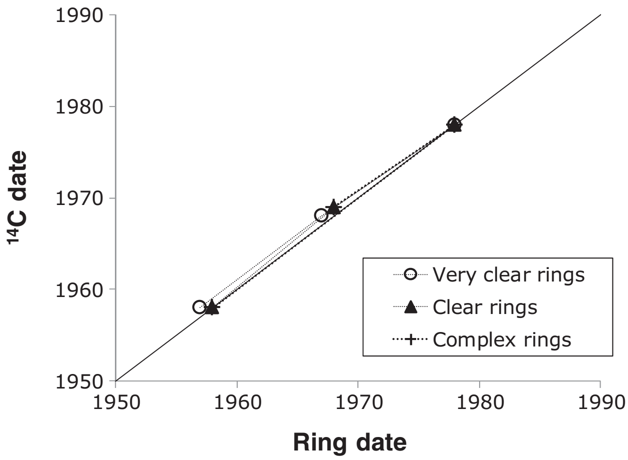

Fig. 2. Radio-carbon (^{14}C) bomb-peak dating of three *Entandrophragma utile* trees. We used three different types of samples: tree discs with very clear rings (open circles); with clear rings (closed triangles) and samples with the presence of 'complex' rings (crosses), e.g. with suppressions or strong wedging rings. Diagonal line indicates the 1:1 match between ring-based age estimations and ^{14}C-based age estimations.

the $\delta^{18}O$ chronology because the chronology becomes gradually weaker when including years before 1930.

3.2. Tree-ring, precipitation and proxy $\delta^{18}O$

Oxygen isotopes in precipitation have been measured in just a few locations in West and Central Africa (IAEA/WMO, 2006). At five locations, $\delta^{18}O$ of precipitation has been measured for more than 10 consecutive years and in five others, data were available for 5–9 years. None of these stations were located in close proximity of our study area (minimal distance was 650 km). We found no strong significant correlations between tree-ring $\delta^{18}O$ and precipitation $\delta^{18}O$. The highest correlations were found with precipitation $\delta^{18}O$ during the rainy season (March–November; Fig. 4), but none of these correlations were significant

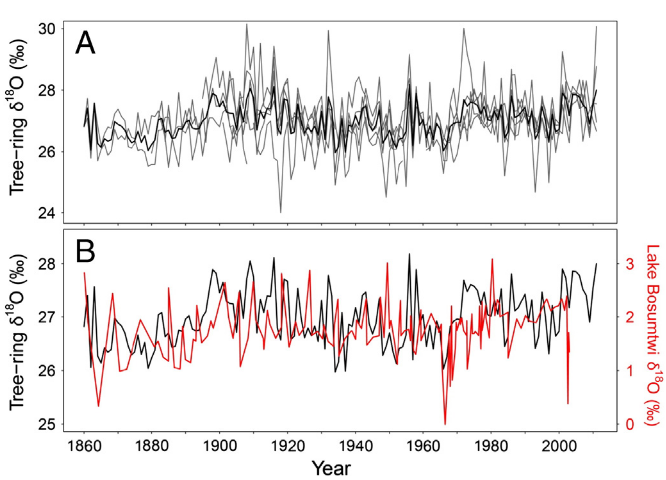

Fig. 3. (a) The $\delta^{18}O$ series of five large *Entandrophragma utile* trees from North-western Cameroon. Gray lines are the individual series; bold black line shows the average (referred to as the $\delta^{18}O$ chronology). Over the period 1860–2010 the average inter-series correlation is 0.310 ($p < 0.001$), the EPS = 0.642. From 1930 to 2010 the average inter-series correlation is 0.367 ($p < 0.001$), the EPS 0.737. (b) Averaged tree-ring $\delta^{18}O$ in *Entandrophragma utile* (black line; the $\delta^{18}O$ chronology) and $\delta^{18}O$ values measured on sediments of lake Bosumtwi, Ghana (red line; Shanahan et al., 2009). See location of lake Bosumtwi in Fig. 4. Pearson's correlation coefficient = 0.196, p = 0.053. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

except for Kano, Nigeria, were precipitation $\delta^{18}O$ was measured 1961–1966 and 1971–1973 (r = 0.695, p = 0.037, but n = 9 here).

In Ghana, $\delta^{18}O$ has been measured on carbonate in sediments of Lake Bosumtwi (Shanahan et al., 2009), about 1200 km from our study site. Carbonate $\delta^{18}O$ reflects that of Bosumtwi lake water, which is linked to the balance between precipitation and evaporation. We found a marginally significant correlation between tree-ring $\delta^{18}O$ and carbonate $\delta^{18}O$ in Lake Bosumtwi sediments from 1860 to 2003 (p = 0.053; Fig. 3B). Oxygen isotopes have also been measured on coral skeletons form the Island of Principe and Sao Tome in the Gulf of Guinea (Swart et al., 1998). The Pearson correlation coefficient of tree-ring $\delta^{18}O$ with coral $\delta^{18}O$ from Principe, measured from 1939–1992, was 0.229 (p = 0.09; Supplementary Fig. B), with coral $\delta^{18}O$ from the Sao Tome, measured from 1977–1993, r = 0.195 (p = 0.454; Supplementary Fig. B). Other proxy record data (e.g. ice cores and ocean sediments) are too coarse-scaled for proper comparison with annually resolved tree-ring data and were therefore not examined.

3.3. Tree-ring $\delta^{18}O$ and local precipitation and temperature

We found no significant correlation between the variation in tree-ring $\delta^{18}O$ and the variation in total annual precipitation over the period 1968 to 2010, measured at the two closest climate stations (Mamfé and Mundemba). Tree-ring $\delta^{18}O$ also did not correlate with wet season precipitation (March–November), nor when precipitation was averaged over the two climate stations. We subsequently used CRU gridded precipitation of a 2 × 2° square (5–7°N, 8–10°E) surrounding our study site, which is based on the interpolation of all climate stations in the area (but without climate data from Mundemba and Mamfé). Over the entire period for which CRU data are available (1901–2009), no significant correlation was found between tree-ring $\delta^{18}O$ and interpolated precipitation (r = −0.114, p = 0.237). However, a significant negative correlation was found between tree-ring $\delta^{18}O$ values and gridded total annual precipitation (r = −0.299, p = 0.007; Fig. 5) and precipitation during the wet season (r = −0.301, p = 0.007) when excluding the years before 1930. The gridded precipitation data correlated significantly with precipitation measured in Mamfé (1968–2009; Pearson's r = 0.456, p = 0.001), but not with precipitation in Mundemba.

For temperature, data were available from four stations in the area, only one of them located relatively close by (Mamfé at ~40 km distance). The other three: Douala and Nkongsamba in Cameroon and Calabar in Nigeria, are located >100 km away. We found no significant correlations between tree-ring $\delta^{18}O$ and average temperature in growth season (March–November), dry season (December–February) or with average annual temperature at any of these stations (results not shown). Interpolated temperature data during the growth season (CRU TS 3.21) of a 2 × 2° grid (5–7°N, 8–10°E) centering the study location also did not yield any significant correlations with tree-ring $\delta^{18}O$ (results not shown). We thus did not find any evidence for a temperature signal in the $\delta^{18}O$ chronology.

3.4. Regional climate signals in tree-ring $\delta^{18}O$

We explored the presence of regional climatic signals in the $\delta^{18}O$ chronology in two ways. First we correlated tree-ring $\delta^{18}O$ to gridded precipitation over West- and Central Africa. Second, we correlated tree-ring $\delta^{18}O$ to four proxies of regional climate variability: (1) river discharge data that are directly related to regional precipitation in the catchment area, (2) sea surface salinity, indicating freshwater input (e.g. by river runoff), (3) sea surface temperature in the gulf of Guinea, which exert a strong control on rainfall variability in West and Central Africa, and (4) interpolated longwave radiation, a proxy for cloud cover.

We found tree-ring $\delta^{18}O$ to show a significant negative correlation with gridded precipitation (CRU; 1930–2009) over large parts of West and Central Africa (Pearson's r between −0.2 and −0.5; Fig. 6). These

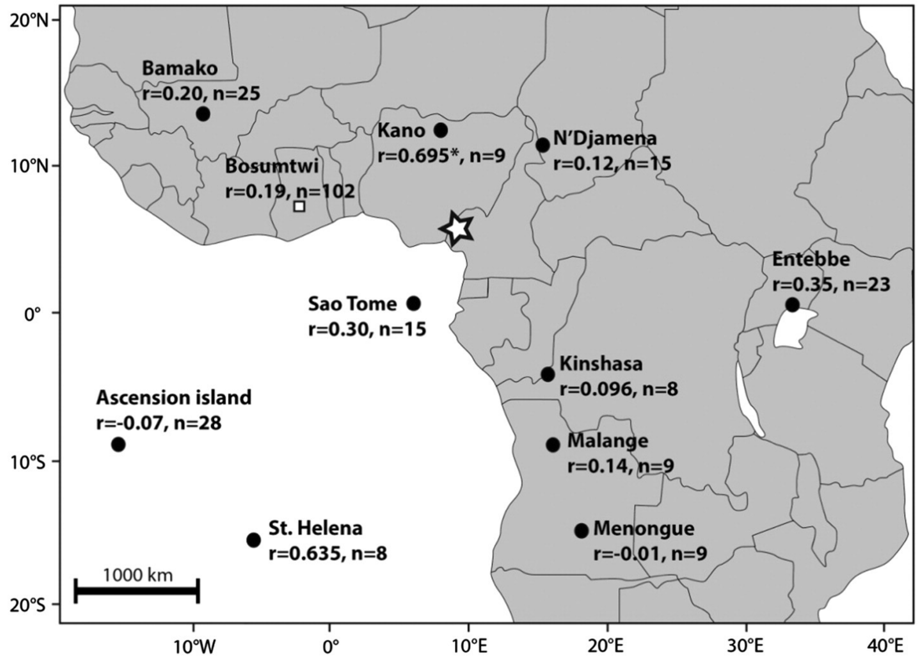

Fig. 4. Pearson's correlations between tree-ring δ¹⁸O values in *Entandrophragma utile* from Cameroon (white star) and δ¹⁸O in precipitation. All stations in the region where monthly δ¹⁸O in precipitation was measured for more than 5 consecutive years are shown (black dots). Best correlations were found with average δ¹⁸O of precipitation during the growing season (March–November); 'r' refers to the Pearson's correlation coefficients, 'n' is the number of years used in the correlation. No significant correlations were found, except for Kano, Nigeria ($p = 0.037$), but note that $n = 9$ here.

correlations were significant for precipitation over the entire country of Equatorial Guinea, Gabon and Congo, as well as large parts of Central and South Cameroon, western part of the Democratic Republic of Congo, North-western Angola and Southern Nigeria (Fig. 6).

For the indirect proxies of regional climate variability, the available discharge data of the Sanaga river (Fig. 1) from 1944 to 1979 correlated significantly, but weakly, to the δ¹⁸O chronology ($r = -0.329$, $p = 0.047$; Fig. 5). Discharge data of the Sangha river (Fig. 1), measured from 1948 to 1983 (at Ouésso, close to the border between Cameroon and the Republic of Congo) showed a significant and somewhat stronger correlation with tree-ring δ¹⁸O ($r = -0.524$, $p = 0.001$; Fig. 5). The discharges of the two river basins also correlated to each other ($r = 0.600$, $p < 0.001$). We also correlated river discharge data to CRU precipitation data averaged over an area spanning 5.5°–2.5°N and 12–15°E, roughly covering the combined drainages of these rivers (Fig. 1A). We found significant correlations between river discharge data and CRU precipitation for both the Sanaga River ($r = 0.589$; $p < 0.001$) and Sangha River ($r = 0.547$, $p < 0.001$).

Regional precipitation amount determines river discharges, which in turn affect sea surface salinity (Dessier and Donguy, 1994). We found a strong positive correlation between tree-ring δ¹⁸O and sea surface salinity of the coast of Cameroon from 1950–2011 (the period for which salinity data are available; Supplementary Fig. C). Regional precipitation is also affected by sea surface temperature in the gulf of Guinea (Chang et al., 1997). We found a significant negative correlation between tree-ring δ¹⁸O and gridded sea surface temperatures in the Gulf of Guinea from 1930–2010 (Supplementary Fig. C).

Finally, we related tree-ring δ¹⁸O variability to outgoing longwave radiation (OLR) data. OLR indicates differences cloud cover and can be used to distinguish areas of deep tropical convection (Liebmann and Smith, 1996). We found a strong correlation between tree-ring δ¹⁸O and OLR from 1974 to 2011 (the period for which OLR data are available; Fig. 6).

The correlations between tree-ring δ¹⁸O and regional precipitation, SSS, SST and OLR were found for all months of the wet season (March to November) and disappeared during the dry season (results not shown). This is likely because *E. utile* is a deciduous tree species and leafless during the dry season (January/February). As a consequence, growth is strongly limited or absent, and no ¹⁸O signals are recorded in tree-ring cellulose during these months. For sea surface salinity, highest correlations were found with months in the second half of the calendar year.

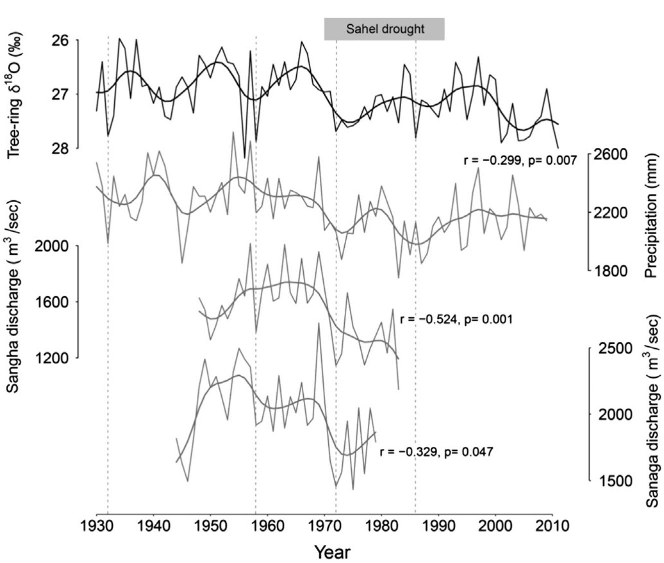

Fig. 5. The δ¹⁸O chronology based on five *Entandrophragma utile* trees (top; y-axis in reverse order) significantly correlated with interpolated total annual precipitation (2 × 2° square around the study site; 5–7°N, 8–10°E) over the period 1930–2009 (second line). Over entire period 1901–2009 for which CRU precipitation data is available Pearson's $r - 0.114$ ($p = 0.237$). The δ¹⁸O chronology also significantly correlated with discharge data of the Sangha river basin (third line) and Sanaga river basin (fourth line). Gray horizontal bar indicates a period of extended drought (the Sahel drought). The gray dashed vertical lines indicate some of the peaks in the δ¹⁸O chronology.

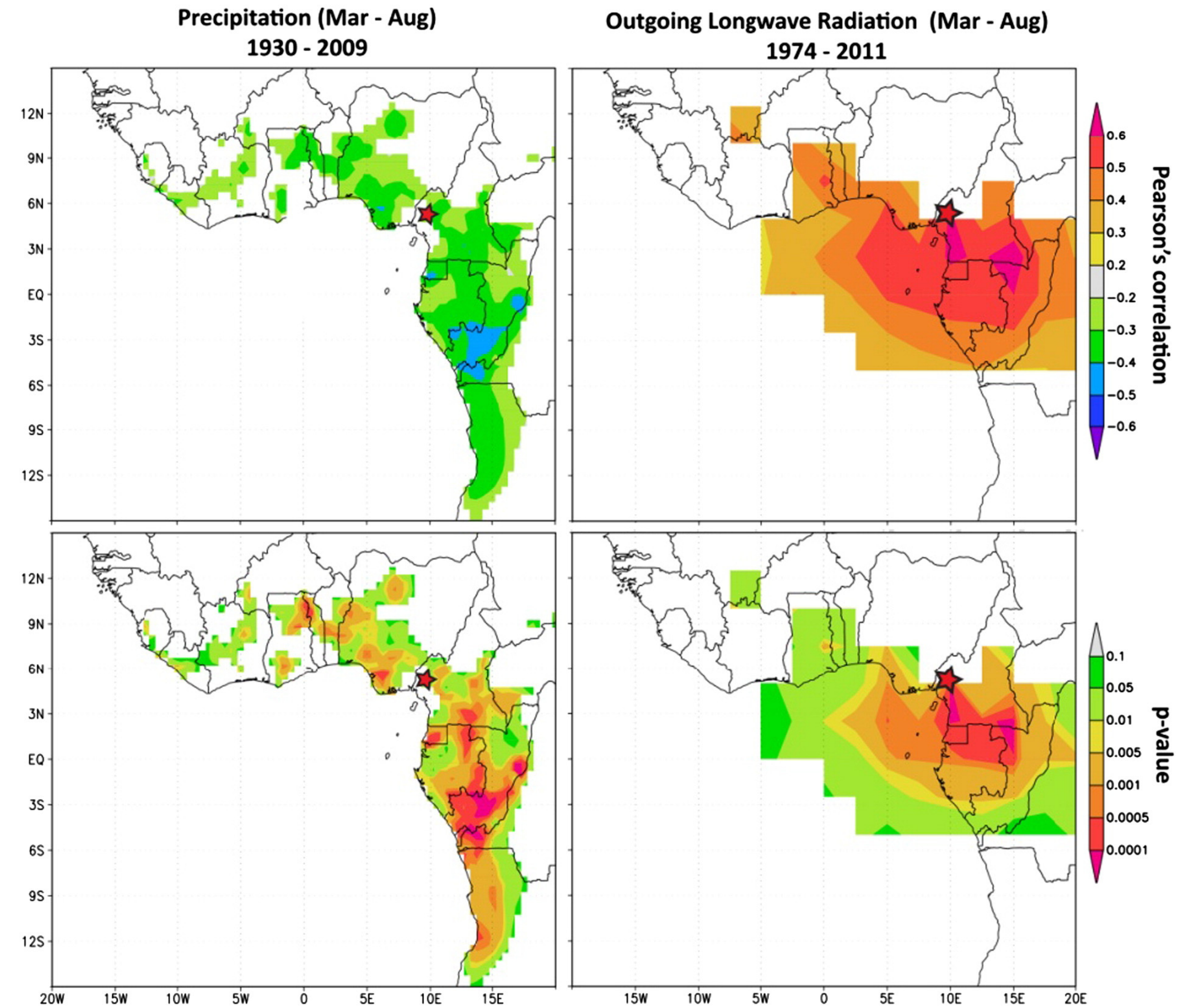

Fig. 6. Spatial correlation between the tree-ring $\delta^{18}O$ chronology of *Entandrophragma utile* and gridded precipitation (left panels; CRU TS 3.21 dataset) and interpolated outgoing longwave radiation (right panels; NOAA) during the peak of the growth season (March to August). Outgoing longwave radiation (OLR) is used as a rough proxy for cloud cover. Upper panels show the Pearson correlation coefficients; lower panels the associated p-values. The red star indicates the area where trees were sampled. For CRU precipitation, the highest correlations were found over the period 1930–2009, and become weaker when including the years before 1930. For outgoing longwave radiation, the entire period for which data were available was used.

4 . Discussion

4.1. Ring-width and $\delta^{18}O$ chronologies

Radio-carbon (^{14}C) dating revealed a highly accurate identification of growth rings, since tree-ring-based age estimations perfectly matched ^{14}C-based age estimations (Fig. 2). A good match was also found in the sample with so called 'complex' rings (e.g. suppressions and strong wedging rings), indicating that false rings or locally absent rings are rarely formed in this species. However, we found that a common growth signal in the five trees was absent (Supplementary Fig. A). This is probably the result of the very high precipitation in the study area (~4000 mm yr^{-1}) and low seasonality (Fig. 1b). In that case, tree growth rates can be controlled by local site conditions (e.g. the availability of light) which are often more heterogeneous on a spatial scale than precipitation (Speer, 2010). The absence of a common growth signal in tree species with clear and annual growth rings has been found in other wet tropical forests (Fichtler et al., 2003).

The $\delta^{18}O$ values of the *Entandrophragma* trees significantly correlated between the five trees and did show a clear common signal (the $\delta^{18}O$ chronology; Fig. 3). We found the highest EPS and inter-series correlation when excluding the years before 1930. A lower cross-dating of tree-ring series further back in time is usually the result of an accumulation of dating errors, causing an increasing mismatch of growth (and stable isotope) patterns between trees. This could be the case here, especially because we were unable to make a ring-width chronology (Supplementary Fig. A), which could have helped to detect dating errors. Although the radio-carbon data suggests few, if any, dating errors were made after ~1950, such errors could have been made in the years before 1950. We do note that the older rings (i.e. inner rings) were not more difficult to identify than the younger ones (i.e. outer rings).

The strength of the common $\delta^{18}O$ signal in *E. utile* from 1930 to 2010 ($r = 0.367$; $EPS = 0.737$) was lower than found in chronologies of similar duration (50–100 years) in trees from Laos (Xu et al., 2011), Bolivia (Brienen et al., 2012) and Indonesia (Schollaen et al., 2013b). In these studies, trees were sampled in areas with a distinct dry season and an average annual precipitation of less than 2000 mm (930–1900 mm/year). The relatively low EPS and the low amplitude in our $\delta^{18}O$ chronology (Fig. 3) are likely the result of the low variability of climate in our study site. In the 43 years for which data are available, total annual precipitation did not drop below 2000 mm in Mamfé or below 3000 mm in Mundemba. Thus, very dry years that might result in strong synchronized $\delta^{18}O$ peaks in trees are relatively rare at our study location compared to other studies (e.g. Poussart and Schrag, 2005; Brienen et al., 2012).

The significant inter-series correlation ($p < 0.001$) nonetheless suggests that even under these very wet conditions, trees sampled in a large area (~1600 ha) recorded a highly similar $\delta^{18}O$ signal. To test if this signal is the $\delta^{18}O$ variability of precipitation, we correlated tree-ring $\delta^{18}O$ to precipitation $\delta^{18}O$ (Fig. 4) and found a significant correlation with one of the closest stations (720 km away), Kabo in Nigeria ($r = 0.695$, $p = 0.037$). However, precipitation $\delta^{18}O$ was measured for only nine years at this station, making it difficult to validate this correlation. In very few locations in West and Central Africa has Precipitation $\delta^{18}O$ been measured and most datasets contain missing data and have large gaps between the years measured. This partially explains why no other significant correlations were found with stations where precipitation $\delta^{18}O$ was measured (Fig. 4).

4.2. Climatic signals in the tree-ring $\delta^{18}O$ chronology

No significant correlations were found between tree-ring $\delta^{18}O$ and precipitation measured at two climate stations in the vicinity (~40 km north and south) of the study site. However, these stations also did not correlate to each other ($r = 0.156$, $p = 0.318$), indicating that these datasets are either of low quality or that rainfall in the area is highly variable and that precipitation data from these stations does not accurately reflect the precipitation amount at the site where trees were sampled. Such a high spatial variability of rainfall patterns may be caused by variable rain shadows of Mount Cameroon (4000 m high) or of lower (500–700 m high) ridges close to the study site.

At a slightly larger spatial scale (a 2° × 2° grid centering the study location) we did find a significant negative correlation between interpolated precipitation and tree-ring $\delta^{18}O$ (from 1930–2009; Fig. 5). Furthermore, when we correlated tree-ring $\delta^{18}O$ of *E. utile* to gridded precipitation on a sub-continental scale we found significant correlations with (wet season) precipitation over vast areas in Cameroon, as well as other areas in Central and West Africa (Fig. 6). These results suggest that tree-ring $\delta^{18}O$ reflects primarily what happens during water-vapor transport to the site rather than local precipitation amount. This result has also been found in other studies (e.g. Poussart and Schrag, 2005; Ballantyne et al., 2011; Brienen et al., 2012). During air-parcel transport, heavy isotopes tend to condense more readily, and thus water vapor loses relatively more of the heavier isotopes (Rayleigh distillation; Dansgaard, 1964) and gets gradually more depleted during transport. The degree of "rainout" of heavy isotopes is generally larger during years with high amounts of precipitation along the air-parcel trajectory than during years with low precipitation (Lee and Fung, 2008; Risi et al., 2008; Kurita et al., 2009; Brienen et al., 2012). Therefore, more depleted water vapor (more negative $\delta^{18}O$) at the end of the trajectory is present during wet years compared to dry years. This signal can be enforced by the recycling of rainwater by vegetation during water-vapor transport (Salati et al., 1979; Risi et al., 2008). The negative correlations found between tree-ring $\delta^{18}O$ and precipitation amount on a regional, rather than local scale is consistent with this mechanism.

The strongest correlations between tree-ring $\delta^{18}O$ and precipitation amount were found mainly south of the study area. This pattern can be explained by the location of the intertropical convergence zone (ITCZ). During the peak of the growing season (March–August), the ITCZ is located north of the study site. Therefore, air-parcel trajectories run predominantly from the south to the north. Hence, tree-ring $\delta^{18}O$ is affected more strongly by 'rainout' processes south than north of the study area.

4.3 . Indirect proxies for regional climate variability

Although the correlations between tree-ring $\delta^{18}O$ and precipitation covered vast spatial scales, the resulting correlation coefficients are relatively low (Pearson's r between −0.2 and −0.5; Fig. 6), and become much weaker when including the years before 1930. This result could, at least partially, be caused by the quality of the CRU dataset, which is known to be relatively unreliable and inconsistent in regions with limited meteorological stations (Harris et al., 2014). We therefore also correlated tree-ring $\delta^{18}O$ with several indirect proxies for regional climate variability.

The first is river discharge data. A significant negative correlation was found between tree-ring $\delta^{18}O$ and discharge of two major river systems in Central and South Cameroon (Fig. 5), underpinning the capacity of this species to record the precipitation amount on regional to sub-continental scales. We also found a strong positive correlation between tree-ring $\delta^{18}O$ and sea surface salinity (SSS; Supplementary Fig. C). Sea surface salinity is strongly determined by freshwater input (e.g. from rivers; Dessier and Donguy, 1994). A low salinity suggests a high input of freshwater and thus reflects a relatively wet year. This is recorded in *E. utile* with a low $\delta^{18}O$ value, which is in line with the negative correlations found between tree-ring $\delta^{18}O$ and precipitation amount (Fig. 6). The highest correlations between tree-ring $\delta^{18}O$ and SSS were found with months in the second half of the calendar year. This result is probably due to the time it takes for continental rain to be transported by rivers and to affect sea salinity, causing the correlation between tree-ring $\delta^{18}O$ and SSS to be strongest after the peak of the growing season.

Another proxy for regional climate variability is sea surface temperature (SST). Rainfall variability in West and Central Africa is profoundly influenced by the sea surface temperature of the tropical Atlantic Ocean (Chang et al., 1997). A high SST in the Gulf of Guinea is associated with high precipitation over large parts of West and Central Africa during the peak of the wet (growing) season (Balas et al., 2007). We correlated tree-ring $\delta^{18}O$ to sea surface temperatures and found a significant negative correlation between tree-ring $\delta^{18}O$ and SST in the Gulf of Guinea (Supplementary Fig. C). This negative correlation confirms expectations given the positive effect of SST on precipitation and the negative effect of precipitation amount on rainwater $\delta^{18}O$ (and so tree-ring $\delta^{18}O$). Although the found correlations between tree-ring $\delta^{18}O$ and SST were significant over a vast area, the correlation coefficients were not very high. Partially, this result might also be cause by the accuracy of the SST dataset, which is affected by the strong lack of historical data from this region (Ingleby and Huddleston, 2007).

Lastly, we assessed the relation between tree-ring $\delta^{18}O$ and outgoing longwave radiation (OLR) over West and Central Africa, measured by NOAA satellites (Liebmann and Smith, 1996). Outgoing longwave radiation is often used to distinguish areas of convection. For example, high OLR indicates a suppressed convection and thus a low cloud cover. Conversely, a low OLR indicates enhanced convection and high cloud cover. We found a strong and highly significant correlation between tree-ring $\delta^{18}O$ and OLR from 1974–2011 (the period for which OLR data are available; Fig. 6). This correlation again confirms the precipitation signal in tree-ring $\delta^{18}O$ in *E. utile*, because years with a high OLR are years with a relatively low cloud cover and tend to be years with low precipitation. Such years are recorded in trees by high $\delta^{18}O$ values. Oppositely are years with a low OLR indicative of thick cloud cover (thus representing cool, wet years) and recorded by low $\delta^{18}O$ values in *E. utile*. Similar to the correlations with precipitation (Fig. 6), the strongest correlation between tree-ring $\delta^{18}O$ and OLR were found with areas south of the study site (Supplementary Fig. C). As discussed above, this is because of the location of the ITCZ during the growing season, being north of the study site. Therefore, the main convection areas that affect the $\delta^{18}O$ signature of the rain falling in the study region are located to the south.

4.4. Plant physiological controls

Sea surface salinity, sea surface temperature and OLR do not only reflect inter-annual variation in precipitation amount (wet vs. dry years), but also in temperature (cool vs. hot years). Although the first can affect tree-ring $\delta^{18}O$ through rainwater $\delta^{18}O$, the latter can strongly affect plant physiology (i.e. leaf evaporation) and thereby also modify tree-ring $\delta^{18}O$ values (Barbour, 2007). To study to what extent inter-annual variation in $\delta^{18}O$ is influenced by plant physiological controls, we correlated tree-ring $\delta^{18}O$ to locally recorded temperature, gridded temperature and gridded water-vapor pressure. Both temperature and water-vapor pressure can strongly drive leaf evaporation, leading to changes in the ^{18}O signature of leaf assimilates (Roden et al., 2000).

We found no significant correlation with temperatures measured at the four stations closest to the study site (meteorological station of Mamfé, Douala and Nkongsamba in Cameroon and Calabar in Nigeria; results not shown). We also did not find a significant correlation between tree-ring $\delta^{18}O$ and gridded temperature and water-vapor pressure during the growing season (of a 2° × 2° grid centering the study location; CRU TS 3.21 dataset; results not shown). These results suggest that leaf physiological controls on tree-ring $\delta^{18}O$ values are likely small and that the $\delta^{18}O$ variability in tree rings predominantly reflects variations in regional precipitation amount.

4.5. Long-term variability in the $\delta^{18}O$ chronology

A period of higher $\delta^{18}O$ values from 1970–1990, coincided with the occurrence of the Sahel drought (Fig. 5), a series of severe droughts in the 1970s and 1980s in the Sahel region and parts of sub-Saharan Africa (Zeng, 2003). A similar pattern of relatively high $\delta^{18}O$ values during this period has been found in corals from the Island of Principe in the gulf of Guinea (Swart et al., 1998; Supplementary Fig. B) and lake sediments in Ghana (Shanahan et al., 2009; Fig. 3B). These results suggest that tree-ring $\delta^{18}O$ values in *Entandrophragma* also recorded decadal drought periods.

The occurrence of the Sahel drought has been related to changing sea surface temperatures, that may reflect a natural cycle of SST variability, termed the Atlantic Multidecadal Oscillation (AMO; Schlesinger and Ramankutty, 1994; Shanahan et al., 2009). Although higher tree-ring $\delta^{18}O$ values from 1970 to 1990 coincide with the Sahel drought period, we did not find a significant correlation between tree-ring $\delta^{18}O$ and the AMO index, which is based on patterns of SST variability in the North Atlantic (data not shown). Discussion also remains on the extent of influence of the El Niño-Southern Oscillation (ENSO) on precipitation variability in west and central Africa (Joly and Voldoire, 2009). We did not find a significant correlation between tree-ring $\delta^{18}O$ and ENSO indices, a similar result has been found in a tree-ring study by Schöngart et al. (2006) in West Africa.

We found a significant long-term trend in the $\delta^{18}O$ chronology, amounting to a 0.5‰ increase of $\delta^{18}O$ values over the period 1860–2011 ($p < 0.001$; result not shown). Interestingly, an equal 0.5‰ increase since 1850 has been found in trees from Bolivia (Brienen et al., 2012). Because similar trends in $\delta^{18}O$ value since 1850 were also found in Andean ice cores (Thompson et al., 2006) and Andean lake sediments (Bird et al., 2011), Brienen et al. (2012) suggested this trend is not caused by the ontogeny (i.e. size development) of trees. In Southeast Asia, a stronger increase of tree-ring $\delta^{18}O$ values since 1950 has been reported and was related to a drying of the Asian Monsoon (Poussart and Schrag, 2005; Xu et al., 2011). In our study, the Sahel drought period (1970–1990; Fig. 5) contributed to the observed long-term increase in $\delta^{18}O$ values, as no trend was found when excluding the last 40 years of the $\delta^{18}O$ chronology.

5 . Conclusions and perspectives

Tree-ring $\delta^{18}O$ in *E. utile* from North-western Cameroon correlated to precipitation at regional to sub-continental scales. This relation is confirmed by several indirect proxies for regional climate variability: river discharge data, outgoing longwave radiation, sea surface salinity and sea surface temperatures in the Gulf of Guinea.

Because of the easily measurable and accurately datable growth rings in *E. utile,* the presence of a strong common $\delta^{18}O$ signal and its relation to regional precipitation, we argue that $\delta^{18}O$ analysis of tree rings from this species represents a promising tool for a detailed reconstruction of climate variability over the last centuries in the region. An advantage of tree-ring $\delta^{18}O$ data relative to $\delta^{18}O$ series derived from lake sediments or scleractinian coral skeletons is that *Entandrophragma* trees are spatially much more wide-spread. In addition, *E. utile* is commercially logged throughout its range, facilitating the collection of samples (discs) from large trees. For climate reconstruction it is crucial that a set of old trees (>200 years) is collected, implying the selection of large to very large trees (roughly >150 cm dbh; Groenendijk et al., 2014). The selection of such individuals for climate reconstruction should, if possible, focus on shallow rooting species in well-drained soils as this gives the highest chance that tree-ring $\delta^{18}O$ records the $\delta^{18}O$ variability of recent rainfall. The strength of the $\delta^{18}O$ chronology could likely improve by increasing the sample size (Leavitt, 2010) and by sampling in regions with a lower annual precipitation and a stronger seasonality.

A higher temporal resolution of the variability of $\delta^{18}O$ in precipitation could be obtained from intra-annual sampling of tree-ring $\delta^{18}O$ (within one annual ring) in *E. utile*. Intra-annual sampling techniques have greatly improved during the last decade and allow a semi-automatic analysis of many very small wood samples adjacent to each other (Pons and Helle, 2011; Schollaen et al., 2013a). Such intra-annual sampling should be very well possible in *E. utile* because of its relatively fast growth, with average diameter growth of the studied trees being 0.72 ± 0.4 cm/year. The data derived could provide information on the variability of $\delta^{18}O$ in precipitation with a temporal resolution of weeks. Such information can be used to shed light on the functioning of the West African Monsoon, a major but poorly understood climatological system which may be subject to change (Roehrig et al., 2013). Thus, in addition to a reconstruction of annual variation in regional precipitation, tree-ring $\delta^{18}O$ series might further aid our understanding of important climatic drivers in West and Central Africa.

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Appendix A. Supplementary data

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References

Balas, N., Nicholson, S.E., Klotter, D., 2007. The relationship of rainfall variability in West Central Africa to sea-surface temperature fluctuations. Int. J. Climatol. 27 (10), 1335–1349.
Ballantyne, A.P., Baker, P.A., Chambers, J.Q., Villalba, R., Argollo, J., 2011. Regional differences in south american monsoon precipitation inferred from the growth and isotopic composition of tropical trees. Earth Interact. 15 (5), 1–35.
Barbour, M.M., 2007. Stable oxygen isotope composition of plant tissue: a review. Funct. Plant Biol. 34 (2), 83–94.
Bird, B.W., et al., 2011. A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. Proc. Natl. Acad. Sci. U. S. A. 108 (21), 8583–8588.
Brienen, Helle, G., Pons, T.L., Guyot, J.L., Gloor, M., 2012. Oxygen isotopes in tree rings are a good proxy for Amazon precipitation and El Niño-Southern Oscillation variability. Proc. Natl. Acad. Sci. U. S. A. 109 (42), 16957–16962.
Chang, P., Ji, L., Li, H., 1997. A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air–sea interactions. Nature 385 (6616), 516–518.
Chase, B.M., Meadows, M.E., Carr, A.S., Reimer, P.J., 2010. Evidence for progressive Holocene aridification in southern Africa recorded in Namibian hyrax middens:

implications for African Monsoon dynamics and the "African Humid Period". Quat. Res. 74 (1), 36–45.
Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16 (4), 436–468.
Dessier, A., Donguy, J.R., 1994. The sea surface salinity in the tropical Atlantic between 10°S and 30°N-seasonal and interannual variations (1977–1989). Deep-Sea Res. I 41 (1), 81–100.
Fichtler, E., Clark, D.A., Worbes, M., 2003. Age and long-term growth of trees in an old-growth tropical rain forest, based on analyses of tree rings and ^{14}C. Biotropica 35 (3), 306–317.
Gebrekirstos, A., Neufeldt, H., Mitlöhner, R., 2011. Exploring climatic signals in stable isotopes of *Sclerocarya birrea* tree ring chronologies from the Sahel region in West Africa. TRACE conference paper. vol. 9, pp. 143–148.
Gebrekirstos, A., Bräuning, A., Sass-Klassen, U., Mbow, C., 2014. Opportunities and applications of dendrochronology in Africa. Curr. Opin. Environ. Sustain. 6 (1), 48–53.
Groenendijk, P., Sass-Klaassen, U., Bongers, F., Zuidema, P.A., 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, 65–78.
Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations — the CRU TS3.10 Dataset. Int. J. Climatol. 34 (3), 623–642.
Hummel, F.C., 1946. The formation of growth rings in *Entandrophragma macrophyllum* A.Chev. and *Khaya grandifolia* C.DC. Emp. For. Rev. 25, 103–107.
IAEA/WMO, 2006. Global Network of Isotopes in Precipitation. The GNIP Database. http://www-naweb.iaea.org/napc/ih/IHS_resources_isohis.html.
Ingleby, B., Huddleston, M., 2007. Quality control of ocean temperature and salinity profiles — historical and real-time data. J. Mar. Syst. 65 (1–4 SPEC. ISS.), 158–175.
Joly, M., Voldoire, A., 2009. Influence of ENSO on the West African monsoon: temporal aspects and atmospheric processes. J. Clim. 22 (12), 3193–3210.
Kurita, N., Ichiyanagi, K., Matsumoto, J., Yamanaka, M.D., Ohata, T., 2009. The relationship between the isotopic content of precipitation and the precipitation amount in tropical regions. J. Geochem. Explor. 102 (3), 113–122.
Leavitt, S.W., 2010. Tree-ring C–H–O isotope variability and sampling. Sci. Total Environ. 408 (22), 5244–5253.
Lee, J.E., Fung, I., 2008. "Amount effect" of water isotopes and quantitative analysis of post-condensation processes. Hydrol. Process. 22 (1), 1–8.
Liebmann, B., Smith, C.A., 1996. Description of a complete (interpolated) outgoing longwave radiation dataset. Bull. Am. Meteorol. Soc. 77, 1275–1277.
Mariaux, A., 1981. Past efforts in measuring age and annual growth in tropical trees. In: Borman, F.H., Berlyn, G. (Eds.), Age and Growth Rate of Tropical Trees: New Directions for Research. Yale University School of Forestry and Environmental Studies, Petersham, Massachusetts, pp. 20–30.
Nzogang, A., 2009. Tropical forest dynamics after logging – natural regeneration and growth of commercial tree species – in southeast Cameroon. (PhD thesis), Albert-Ludwigs-Universität, Freiburg im Breisgau, Germany (220 pp.).
Pons, T.L., Helle, G., 2011. Identification of anatomically non-distinct annual rings in tropical trees using stable isotopes. Trees Struct. Funct. 25 (1), 83–93.
Poorter, L., Bongers, F., Kouamé, F.N., Hawthorne, W.D., 2004. Biodiversity of West African Forests. An ecological atlas of woody plant species. CABI International, Oxon, United Kingdom (521 pp.).
Poussart, P.F., Schrag, D.P., 2005. Seasonally resolved stable isotope chronologies from northern Thailand deciduous trees. Earth Planet. Sci. Lett. 235 (3–4), 752–765.
Rayner, N.A., et al., 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J. Geophys. Res. D Atmos. 108 (14) (ACL 2-1-ACL 2-29).
Risi, C., Bony, S., Vimeux, F., 2008. Influence of convective processes on the isotopic composition ($\delta^{18}O$ and δD) of precipitation and water vapor in the tropics: 2. Physical interpretation of the amount effect. J. Geophys. Res. D Atmos. 113 (19), D19306.
Roden, J.S., Lin, G., Ehleringer, J.R., 2000. A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose. Geochim. Cosmochim. Acta 64 (1), 21–35.
Roehrig, R., Bouniol, D., Guichard, F., Hourdin, F., Redelsperger, J.C., 2013. The present and future of the west african monsoon: a process-oriented assessment of CMIP5 simulations along the AMMA transect. J. Clim. 26 (17), 6471–6505.
Salati, E., Dall'olio, A., Matsui, E., Gat, J.R., 1979. Recycling of water in the Amazon Basin: an isotopic study. Water Resour. Res. 15 (5), 1250–1258.
Schlesinger, M.E., Ramankutty, N., 1994. An oscillation in the global climate system of period 65–70 years. Nature 367 (6465), 723–726.
Schollaen, K., Heinrich, I., Helle, G., 2013a. UV-laser-based microscopic dissection of tree rings — a novel sampling tool for $\delta^{13}C$ and $\delta^{18}O$ studies. New Phytol. 201 (3), 1045–1055.
Schollaen, K., et al., 2013b. Multiple tree-ring chronologies (ring width, $\delta^{13}C$ and $\delta^{18}O$) reveal dry and rainy season signals of rainfall in Indonesia. Quat. Sci. Rev. 73, 170–181.
Schöngart, J., Orthmann, B., Hennenberg, K.J., Porembski, S., Worbes, M., 2006. Climate–growth relationships of tropical tree species in West Africa and their potential for climate reconstruction. Glob. Chang. Biol. 12 (7), 1139–1150.
Shanahan, T.M., et al., 2009. Atlantic forcing of persistent drought in West Africa. Science 324 (5925), 377–380.
Speer, J.H., 2010. Fundamentals of Tree-ring Research. The University of Arizona Press, Tucson, Arizona (368 pp.).
Swart, P.K., White, K.S., Enfield, D., Dodge, R.E., Milne, P., 1998. Stable oxygen isotopic composition of corals from the Gulf of Guinea as indicators of periods of extreme precipitation conditions in the sub-Sahara. J. Geophys. Res. C Oceans 103 (C12), 27885–27891.
Talma, A.S., Vogel, J.C., 1992. Late Quaternary paleotemperatures derived from a speleothem from Cango Caves, Cape Province, South Africa. Quat. Res. 37 (2), 203–213.
Thompson, L.G., et al., 2002. Kilimanjaro ice core records: evidence of holocene climate change in tropical Africa. Science 298 (5593), 589–593.
Thompson, L.G., et al., 2006. Abrupt tropical climate change: past and present. Proc. Natl. Acad. Sci. U. S. A. 103 (28), 10536–10543.
Trouet, V., Van Oldenborgh, G.J., 2013. KNMI Climate Explorer: a web-based research tool for high-resolution paleoclimatology. Tree Ring Res. 69 (1), 3–13.
Verheyden, A., et al., 2004. Annual cyclicity in high-resolution stable carbon and oxygen isotope ratios in the wood of the mangrove tree *Rhizophora mucronata*. Plant Cell Environ. 27 (12), 1525–1536.
Voorhoeve, A.G., 1965. Liberian high forest trees. A systematical botanical study of the 75 most important or frequent high forest trees with reference to numerous related species. Centre fro Agricultural Publication and Documentation, Wageningen, the Netherlands (416 pp.).
Washington, R., James, R., Pearce, H., Pokam, W.M., Moufouma-Okia, W., 2013. Congo basin rainfall climatology: can we believe the climate models? Philos. Trans. R. Soc. B Biol. Sci. 368 (1625).
Wieloch, T., Helle, G., Heinrich, I., Voigt, M., Schyma, P., 2011. A novel device for the batch wise isolation of α-cellulose from small-amount wholewood samples. Dendrochronologia 29 (2), 115–117.
Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J. Clim. Appl. Meteorol. 23, 201–213.
Worbes, M., Staschel, R., Roloff, A., Junk, W.J., 2003. Tree ring analysis reveals age structure, dynamics and wood production of a natural forest stand in Cameroon. For. Ecol. Manag. 173 (1–3), 105–123.
Xu, C., Sano, M., Nakatsuka, T., 2011. Tree ring cellulose $\delta^{18}O$ of *Fokienia hodginsii* in northern Laos: a promising proxy to reconstruct ENSO? J. Geophys. Res. D Atmos. 116 (24), D24109.
Zeng, N., 2003. Drought in the Sahel. Science 302 (5647), 999–1000.
Zuidema, P.A., et al., 2013. Tropical forests and global change: filling knowledge gaps. Trends Plant Sci. 18 (8), 413–419.