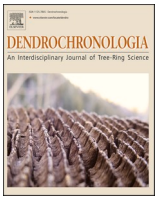
Dendrochronologia 81 (2023) 126117



Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro





Ring data provide management clues and pinpoint climate drivers of growth in two species of miombo trees (*Brachystegia spiciformis*, *Julbernardia paniculata*)

Abilio Santos-Malengue [a,b], David Ariza-Mateos [c], Rafael Navarro-Cerrillo [c], Antonio M. Cachinero-Vivar [c], J. Julio Camarero [d,*]

[a] Forest Research Centre, School of Agriculture, University of Lisbon, Lisbon 1349-017, Portugal
[b] Faculty of Agricultural Sciences, University José Eduardo dos Santos, Chianga, Huambo, Angola
[c] Forestry Engineering Department, ERSAF Research Group RNM-360, University of Córdoba, Córdoba, Spain
[d] Pyrenean Institute of Ecology (IPE-CSIC), Avda. Montañana 1005, 50059 Zaragoza, Spain

ARTICLE INFO

Key words:
Allowable cutting diameter
Angola
ENSO
Legume trees
Miombo woodland
Tropical dendrochronology

ABSTRACT

Tree-ring studies are still lacking in tropical African forests. This is the case in the seasonally dry miombo forests located in Southern Africa. In the Angolan miombo, subject to intense charcoal exploitation, tree-ring data is urgently needed to estimate the age at which the minimum permitted cutting diameter is reached. Further, climate-growth relationships must be also investigated to understand how major miombo tree species respond to climate constraints and teleconnections such as the El Niño Southern Oscillation (ENSO). To achieve both aims, we studied radial growth data of two miombo tree legume species (*Brachystegia spiciformis*, *Julbernardia paniculata*) in wet (Bailundo) and dry (Caála) Angolan sites using dendrochronological methods. Both species have diffuse porous wood and conspicuous ring boundaries delimited by terminal parenchyma in latewood. Sampled individuals had ages (at 1.3 m) between 28 and 34 years with ring widths ranging 3.8–4.3 and 5.5–6.0 mm in dry and wet sites, respectively. In the wet (dry) site, *Brachystegia* and *Julbernardia* reached maximum diameter increment rates of 1.05–1.32 (0.74–0.91) cm yr^{-1} at an age of 12 (14–20) years. Both species took 12–15 years to reach a minimum cutting diameter of 15 cm. The growth variability among conspecific individuals was lower in the dry (mean standard error, 1.4 cm) than in the wet site (mean standard error, 2.7 cm). We also found that wet conditions from November to February, often linked to El Niño events, enhanced growth for both species, with greater growth consistency among individuals and higher sensitivity to climate found in the dry site. This information may help to estimate the optimal age for minimum cutting diameter that guarantees the sustainable use of charcoal and fuelwood.

1. Introduction

Africa is the continent where long climatic records and related proxies such as tree-ring series are less numerous, particularly in the tropics (Zuidema et al., 2022). Therefore, tropical African forests and woodlands should be further studied to improve the continent presence in pantropical tree-ring networks and to fill related research gaps. In the case of tropical African tree species, legume tree species located in tropical dry regions have a high potential for building tree-ring chronologies (e.g., Höhn, 1989; Trouet et al., 2001). However, we are still lacking information on how tree-ring data of these species can be used: (i) to improve the management of timber resources, and (ii) to determine the main climate drivers of their radial growth rates and the related relevance of teleconnections such as the El Niño Southern Oscillation (ENSO) (but see Trouet et al., 2001).

In Angola, tree-ring studies are scarce. However, these data are necessary to better manage and use seasonally dry miombo woodlands, which are exploited by extracting charcoal and fuelwood (Chiteculo et al., 2018; Mendelsohn, 2019). In this country, 53% of the total area are drylands (Prăvălie, 2016), and increasing anthropogenic pressures are leading to degradation and deforestation of the miombo (Kutsch et al., 2011; Miapia et al., 2021). The miombo are seasonally-dry,

* Corresponding author.
E-mail address: jjcamarero@ipe.csic.es (J.J. Camarero).

https://doi.org/10.1016/j.dendro.2023.126117
Received 1 June 2023; Received in revised form 11 July 2023; Accepted 17 July 2023
Available online 18 July 2023
1125-7865/© 2023 The Author(s). Published by Elsevier GmbH. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

briefly-deciduous woodlands (experiencing a short, drought-triggered leaf fall period; cf. Trouet et al., 2012), with tree cover usually exceeding 40%, and appear in south African regions with mean annual precipitation above 600 mm (Campbell, 1996; Ryan et al., 2016). Miombo occurs on geologically old substrates forming nutrient-poor soils and are subjected to frequent wildfires. They are dominated by Fabaceae (legume) genera such as *Brachystegia* and *Julbernardia* and occupy ca. 2.5–3.6 million km^2 from southwestern Angola to north-eastern Tanzania (Fig. 1). Therefore, they represent one of the largest extensions of tropical dry forests and woodlands in the world (White, 1983; Millington et al., 1994; Ribeiro et al., 2015). Open miombo woodlands are subjected to stronger pressure from drought, fire and deforestation than closed miombo woodlands, usually located in wetter regions.

Miombo woodlands provide many ecosystem services supporting rural communities including non-timber forestry products (charcoal, fuelwood, medicines, food) and timber for construction (Gumbo et al., 2018). Charcoal is among the main miombo products, but its use has changed from local extraction by households to large-scale exploitation through the felling of living trees and trading over longer distances due to growing urban fuel demand (Zulu, 2010). Charcoal production has often resulted in large cleared areas, particularly near cities, with slow recovery rates (Miapia et al., 2021). Therefore, assessments of growth rates of the main miombo tree species are needed to sustainably manage these exploited woodlands and to forecast their recovery times. In the case of Angolan miombo, the National Institute for Forest Development considers that the allowable minimum cutting diameter of the main tree species is around 15–20 cm, which can be attained in 25–40 years (Chiteculo and Surovy, 2018). However, these estimates are often based on growth models, whereas a rigorous study of tree-ring patterns through dendrochronology would offer more reliable data on growth rates and merchantable age for charcoal production. Considering individual and temporal growth and age variability using reliable tree-ring data improves predictions of future timber yield, which is critical for sustainable management (Worbes et al., 2003; Brienen and Zuidema, 2007). In the miombo, few studies have been carried out following this approach (but see Therrell et al., 2007).

Quantifying climate-growth relationships is also needed for understanding the dynamics of miombo woodlands since more arid conditions would constrain growth rates (Ryan et al., 2016). The ENSO impacts inter-annual precipitation variability over South Africa because, in general, the region receives below normal seasonal rainfall amounts during warm ENSO phases (El Niño years), whereas positive anomalies are associated with cold ENSO phases (La Niña years) (Ropelewski and Halpert, 1989; Plisnier, 1998; Ratnam et al., 2014). The ENSO effect on rainfall variability is strongest during the wettest months, mainly from January to March (Camberlin et al., 2001; Hoell et al., 2021). However, ENSO explains a relatively small fraction of seasonal rainfall anomalies

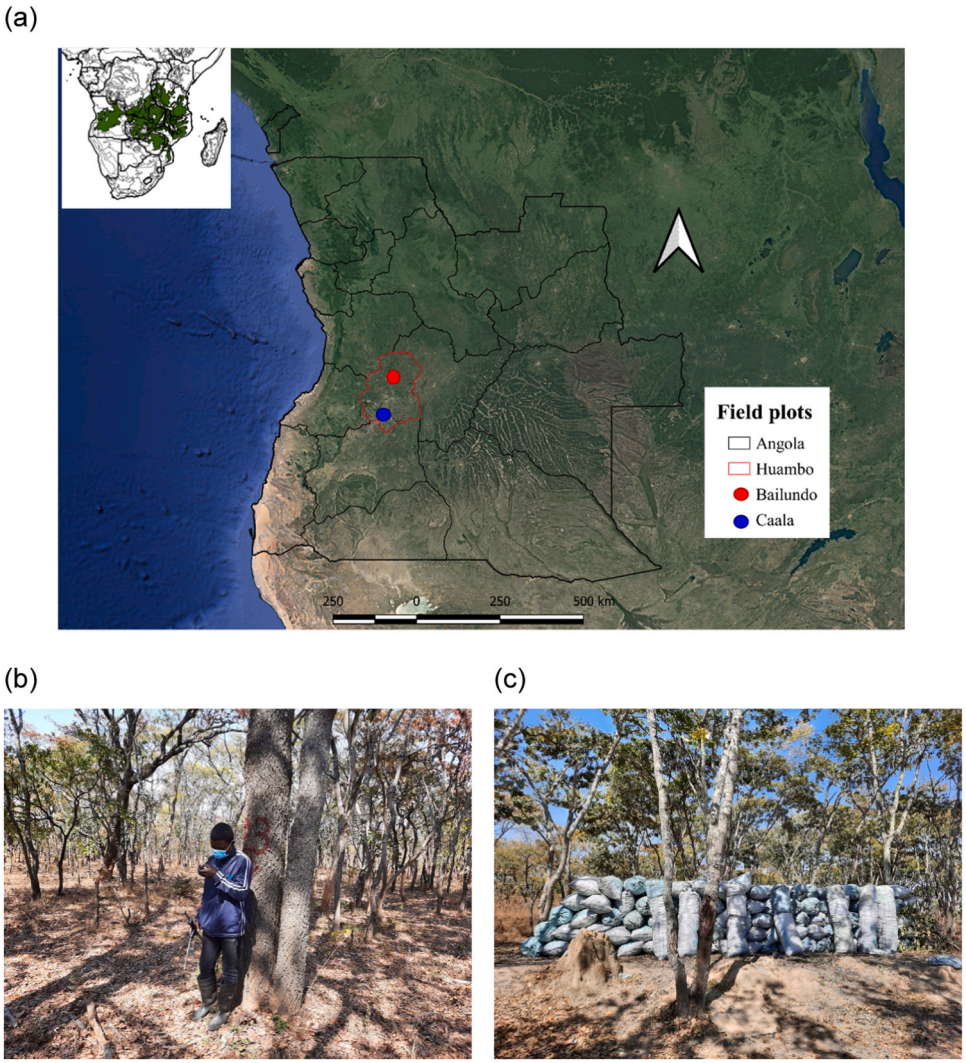


Fig. 1. (a) Distribution of miombo woodlands in Southern Africa (green patches, inset map) and location of the two study areas (Bailundo, Caála) in Huambo province, Angola. (b) Views of sampled miombo woodlands and (c) charcoal exploitation.

over South Africa with the Angola low situated at about 14ºS over southeastern Angola, driving a considerable variability of precipitation from December to March independent of ENSO (Howard and Washington, 2018). Therefore, more detailed studies are needed to assess how climate and ENSO variability drive growth patterns of the main Angolan miombo tree species with potential to form annual, cross-datable rings in seasonally dry areas (Worbes, 2002; Mendivelso et al., 2013; Zuidema et al., 2022).

Several studies have already analyzed climate-growth relationships of miombo tree species using cross-dated series of tree-ring width data including *Brachystegia spiciformis* Bent, *Isoberlinia tomentosa* (Harms) Craib & Stapf and *Pericopsis angolensis* (Barber) Meeuwen (Fichtler et al., 2004; Trouet et al., 2001, 2006, 2010; Munalula et al., 2020). However, they have not jointly addressed the study of growth curves and climate-growth relationships. Here, we propose using tree-ring data of two major miombo tree species (*B. spiciformis*, *Julbernardia paniculata* (Bent.) Troupin) considering a wet (Bailundo) and a dry (Caála) site: (i) to estimate the time needed to reach the allowable minimum cutting diameter, and (ii) to quantify climate- and ENSO-growth relationships. We expect both species to show the lowest radial growth rates in the dry site and that their growth series respond more to precipitation variability and the ENSO in that site. Additionally, this information may help to estimate the optimal age for minimum cutting diameter that guarantees the sustainable use of charcoal and fuelwood in Angolan miombo woodlands.

2. Material and methods

2.1. Study sites

The study was carried out in two municipalities of Huambo province, located in the central plateau of Angola (Fig. 1): Caála (15.551 ºE, 12.895º S, 1682 m a.s.l.) and Bailundo, (15.812 ºE, 12.188º S, 1491 m a.s.l.). The study region is subjected to a dry tropical climate with a mean annual temperature of 17–20 °C and annual precipitation ranging from 900 to 1300 mm (data from: Chianga station, 15.633 ºE, 12.551º S, 1516 m, period 1942–2019; and Huambo airport station, 15.750 ºE, 12.803º S, 1707 m, period 1941–1980). According to local climate data, the Caála site is drier (annual precipitation ca. 950 mm) than the Bailundo site (annual precipitation ca. 1200 mm). The wet season lasts from November to March, whereas the dry season (monthly precipitation < 20 mm) lasts from May to September. The dominant soils are nutrient-poor ferrosols (Chiteculo et al., 2022).

To characterize the stand structure at each site, tree species were identified and their diameter at breast height (dbh) was measured at 1.3 m within randomly located circular plots (10 m in radius). In total, 25 plots were measured per site. In Bailundo and Caála, the total basal area was 0.414 and 0.372 $m^2\ ha^{-1}$, respectively. In total, 28 tree species were identified and 10 of them belonged to the Fabaceae family.

In both sites, the highest values of basal area corresponded to *B. spiciformis* (local name "omanda") with values of 0.031 and 0.020 $m^2\ ha^{-1}$ recorded in Bailundo and Caála, respectively. In Bailundo, *Brachystegia boehmii* Taub (local name "ussamba") was also a very abundant species (basal area 0.030 $m^2\ ha^{-1}$, density 4361 stems ha^{-1}), followed by *J. paniculata* (local name "olumue"; basal area 0.018 $m^2\ ha^{-1}$, density 3215 stems ha^{-1}). Here, *B. spiciformis* and *J. paniculata* had a mean dbh of 15.4 cm, whereas *P. angolensis* ("omako") reached the highest basal area value (0.053 $m^2\ ha^{-1}$). In Caála, *J. paniculata* was also abundant (basal area 0.017 $m^2\ ha^{-1}$, density 5539 stems ha^{-1}). These woodlands often show bimodal diameter distributions with a main peak around 20–30 cm, often found in open miombo sites, and a second peak from 40 to 50 cm, often found in closed miombo sites (Chiteculo and Surovy, 2018).

Rising demands for new agricultural land and, particularly, charcoal production for cooking and heating in urban areas (Huambo, Luanga) have been the main causes of deforestation in the study area (Chiteculo et al., 2018, 2019; Miapia et al., 2021). The unsustainable exploitation of open miombo for charcoal, fuelwood or timber production has caused local extinction or reduction of the most valuable timber species such as *P. angolensis* (Kalaba, Gonçalves et al., 2013, 2017).

2.2. Study species

The two study legume tree species (*B. spiciformis* –hereafter *Brachystegia*, and *J. paniculata* –hereafter *Julbernardia*) belong to the Caesalpinioideae subfamily and they were selected because they are abundant and intensively used for charcoal production by local communities. Further, they show good potential for the formation of annual growth rings since they appear in seasonally dry, semi-deciduous to deciduous forests with a dry season (precipitation < 60 mm) longer than 3 months (Détienne, 1989; Worbes, 1995). They form diffuse-porous wood with ring boundaries marked by terminal parenchyma in the latewood (Fig. 2) as it is usual among the Caesalpinioideae species (Worbes, 1989; Höhn, 1999; Stahle, 1999). In dry tropical forests, deciduousness depends on species but also on site conditions and it is usually linked to the formation of annual growth rings (Borchert, 1999).

2.3. Field sampling and tree-ring analyses

We took wood disks at 1.3 m from 40 individuals per species at each site. Samples were air dried and sanded with sandpapers of increasing grit until ring boundaries were conspicuous. Then, they were visually cross-dated under the binocular scope and scanned at 1200 dpi (Epson Expression 10000XL). The ring widths were measured with a 0.001 mm resolution along two radii per sample using the CooRecorder-CDendro software (Larsson and Larsson, 2018; Maxwell and Larsson, 2021). The visual cross-dating was checked using the COFECHA software which calculates moving correlations between individual tree-ring width series and the mean series of each site (Holmes, 1983). Calendar dates were assigned to rings following the southern Hemisphere convention that assigns an annual ring to the calendar year in which the ring formation stars (Schulman, 1956).

To calculate the individual diameter growth curves the annual ring-widths measured on two cores were averaged and summed for every tree from pith to bark. Then, a mean diameter curve was calculated for every species in the two sites and a sigmoidal function was fitted to characterize the relationship between tree age and dbh (Schöngart et al., 2007; Worbes and Schöngart, 2019):

$$dbh = \frac{a}{(1 + b \times e^{-c \times age})} \quad (1)$$

where a, b and c are parameters corresponding to the upper asymptote, slope (growth rate) and the time of maximum growth, respectively. Tree age at 1.3 m was estimated by counting the number of rings from bark to pith along the two radii of each section. Differences in tree age or ring-width statistics between sites were checked using Mann-Whitney tests.

To remove size- or disturbance-related trends in tree-ring width data and emphasize high-frequency growth variability, the series were detrended and standardized using the dplR package (Bunn, 2010) in R (R Development Core Team, 2022). We fitted 32-year cubic smoothing splines with a 50% frequency response cut-off to individual ring-width series and obtained ring-width indices by dividing observed by fitted values. Then, we fitted autoregressive models to remove most of the first-order autocorrelation in series of dimensionless ring-width indices. The residual or pre-whitened individual series were averaged using a bi-weight robust mean to obtain mean residual series for each site (Fritts, 1976). These mean series or chronologies were correlated to monthly climate data or drought indices using the Treeclim R package (Zang and Biondi, 2015).

Lastly, we calculated several statistics for the common, best-replicated 1997–2022 period. This period was defined based on the

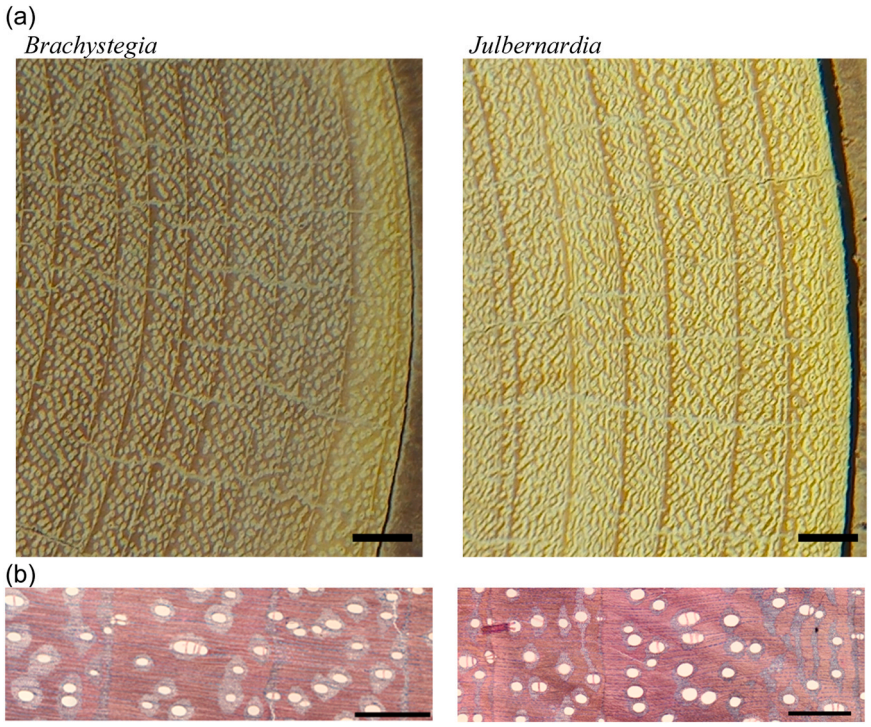


Fig. 2. Macroscopic (a) and microscopic (b) views of *Brachystegia spiciformis* and *Julbernardia paniculata* wood samples and cross-sections, respectively. Scale bars in (a) and (b) measure 5 mm and 1 mm, respectively.

values of the Expressed Population Signal (EPS) (Wigley et al., 1984). We considered the period with EPS > 0.75 as the one in which the calculated chronologies approached the theoretically perfect chronologies, instead of the widely used 0.85 threshold, because in tropical tree species EPS values are usually low. In addition, to characterize the mean site chronologies we calculated: the mean and standard deviation (SD) of tree-ring width values, the mean first-order autocorrelation of ring widths (AR1) which accounts for year-to-year persistence in growth, the mean sensitivity (MSx) of ring-width indices, which measures relative changes in growth between consecutive years, and the mean correlation between series (rbar), which is a measure of coherence of the site chronology (Fritts, 1976; Briffa and Jones, 1990).

2.4. Climate data and indices

Due to the lack of long-term, homogeneous climate series in the study sites we used monthly 0.5°-gridded data from Climate Research Unit dataset (CRU TS 4.03; Harris et al., 2014), which were downloaded from the Climate Explorer webpage (http://climexp.knmi.nl/). We acknowledge that using local climate series may render more specific results regarding climate-growth relationships. However, the available local series were too short, heterogeneous or interrupted by the Angolan Civil War (1975–2002), which affected the study area. The CRU monthly climate data (mean temperature and total precipitation) were complemented and compared with precipitation data from the "Climate Hazards group Infrared Precipitation with Stations" dataset (Funk et al., 2015). Lastly, monthly data of shallow (0–10 cm) soil moisture, available up to 2018, were also obtained from the 0.1°-gridded Land Data Assimilation Systems dataset (Rodell et al., 2004). We avoided using drought indices since there was a lack of reliable, homogeneous data and long series due to the aforementioned problems.

We also calculated the responses of growth indices to the ENSO signal, as defined by the Southern Oscillation Index (SOI; Ropelewski and Jones, 1987). The SOI is tightly linked to the sea surface temperature index for the Niño 3.4 region (5° N – 5° S; 120° – 170° W), located in the equatorial Pacific (Trenberth and Stepaniak, 2001). Long periods of negative (positive) SOI values coincide with abnormally high (low) sea surface temperatures across the eastern tropical Pacific typical of El Niño (La Niña) events. Monthly SOI data was retrieved from the CRU webpage (https://crudata.uea.ac.uk/cru/data/soi/).

2.5. Climate- and drought-growth relationships

The relationships between monthly climate variables or the SOI indices and the site chronologies were quantified using Pearson correlations from June of the prior year to June of the following year following previous studies because the wet season (November to March) includes the main growing season (Trouet et al., 2001, 2012). Correlations were calculated for the common period 1997–2022 in the case of mean temperature, total precipitation and SOI, and for the period 1997–2018 in the case of soil moisture.

3. Results

3.1. Tree-ring width data

Both species formed diffuse-porous wood with conspicuous ring boundaries delimited by terminal parenchyma (Fig. 2). The mean age at 1.3 m of sampled individuals was 31 years, and the mean first-order autocorrelation and sensitivity values were 0.41 and 0.32, respectively (Table 1). In both species, growth rates were significantly ($p < 0.05$) lower in Caála than in Bailundo (*Brachystegia*, mean values of 3.76 vs. 6.04 mm; *Julbernardia*, mean values of 4.28 vs. 5.51 mm). The resulting site mean series or chronologies were well replicated with rbar and EPS values ranging 0.28–0.37 and 0.78–0.85, respectively. The EPS values were higher in Caála than in Bailundo. In Caála, the two species' chronologies were highly correlated considering the common period 1997–2022 ($r = 0.57$, $p = 0.002$), whereas the correlation was lower in Bailundo ($r = 0.40$, $p = 0.05$) (Fig. 3).

Table 1
Size and tree-ring width statistics of the two study species in Bailundo and Caála sites. Data correspond to cross-dated and measured individuals and statistics were calculated for the common, best-replicated interval 1997–2022. Values are means ± SD. Different letters indicate significant ($p < 0.05$) differences between sites according to Mann-Whitney tests.

Species	Site	No. measured trees (No. radii)	Age at 1.3 m (years)	Tree-ring width (mm)	AR1	MSx	rbar	EPS
Brachystegia	Bailundo	24 (48)	29 ± 4	6.04 ± 2.32b	0.30 ± 0.12	0.31 ± 0.06	0.30	0.81
	Caála	15 (30)	34 ± 5	3.76 ± 1.54a	0.44 ± 0.23	0.36 ± 0.08	0.31	0.84
Julbernardia	Bailundo	30 (60)	28 ± 3	5.51 ± 2.40b	0.40 ± 0.27	0.31 ± 0.06	0.28	0.78
	Caála	17 (34)	32 ± 4	4.28 ± 1.75a	0.50 ± 0.21	0.30 ± 0.04	0.37	0.85

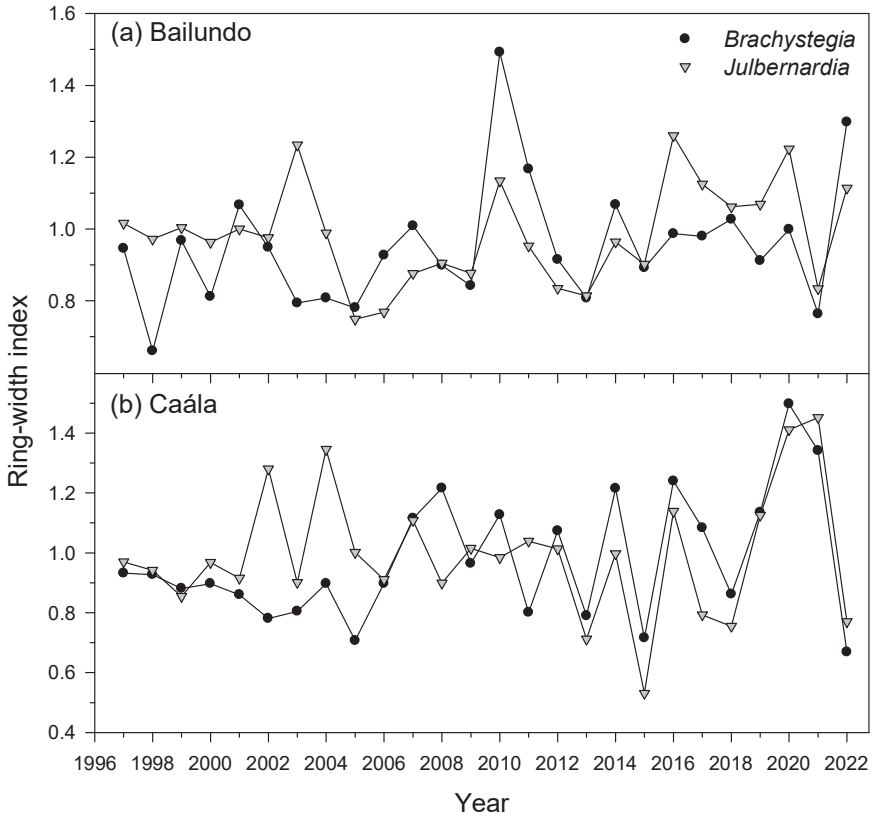


Fig. 3. Mean series of ring-width indices (chronologies) of the two study species (*Brachystegia* and *Julbernardia*) obtained in the (a) Bailundo and (b) Caála study sites.

3.2. Age-diameter relationships and cumulative growth curves

The cumulative diameter curves showed a higher tree-to-tree variability in the wet Bailundo site than in the drier Caála site (Figs. S1 and S2). In Bailundo, the mean standard errors of *Brachystegia* and *Julbernardia* were 3.64 and 1.83 cm, respectively, whereas in Caála they were 1.13 and 1.70 cm. In *Brachystegia*, the standard error of cumulative diameter was significantly higher in Bailundo than in Caála (Mann-Whitney test, $p < 0.001$).

The sigmoidal models were satisfactorily fitted to the cumulative diameter curves (Table 2). They allowed deriving the estimated maximum diameter increments and their corresponding ages. For instance, *Brachystegia* reached maximum diameter increment rates of 1.32 and 0.74 cm yr^{-1} at ages of 12 and 20 years in Bailundo and Caála, respectively (Fig. 4). In the case of *Julbernardia*, maximum diameter increment rates of 1.05 and 0.91 cm yr^{-1} were reached at ages of 12 and 14 years in Bailundo and Caála, respectively. To reach a minimum cutting diameter of 15 cm, *Brachystegia* took 12 or 15 years in Bailundo and Caála, respectively, whereas *Julbernardia* took 13 or 15 years in those two sites.

3.3. Growth responses to climate and the ENSO

Growth of the two study species was enhanced by high precipitation from November to February and elevated soil moisture from December to February as indicated the positive correlations (Table 3). The highest

Table 2
Statistics and parameters corresponding to the sigmoidal functions fitted to mean diameter growth curves as a function of tree age at 1.3 m.

Species	Site	*a*	*b*	*c*	R^2	*p*	Standard error
Brachystegia	Bailundo	30.700	7.608	0.172	0.992	0.001	0.781
	Caála	32.666	6.163	0.091	0.993	0.001	0.569
Julbernardia	Bailundo	28.814	5.698	0.146	0.987	0.001	0.813
	Caála	27.643	6.096	0.132	0.987	0.001	0.848

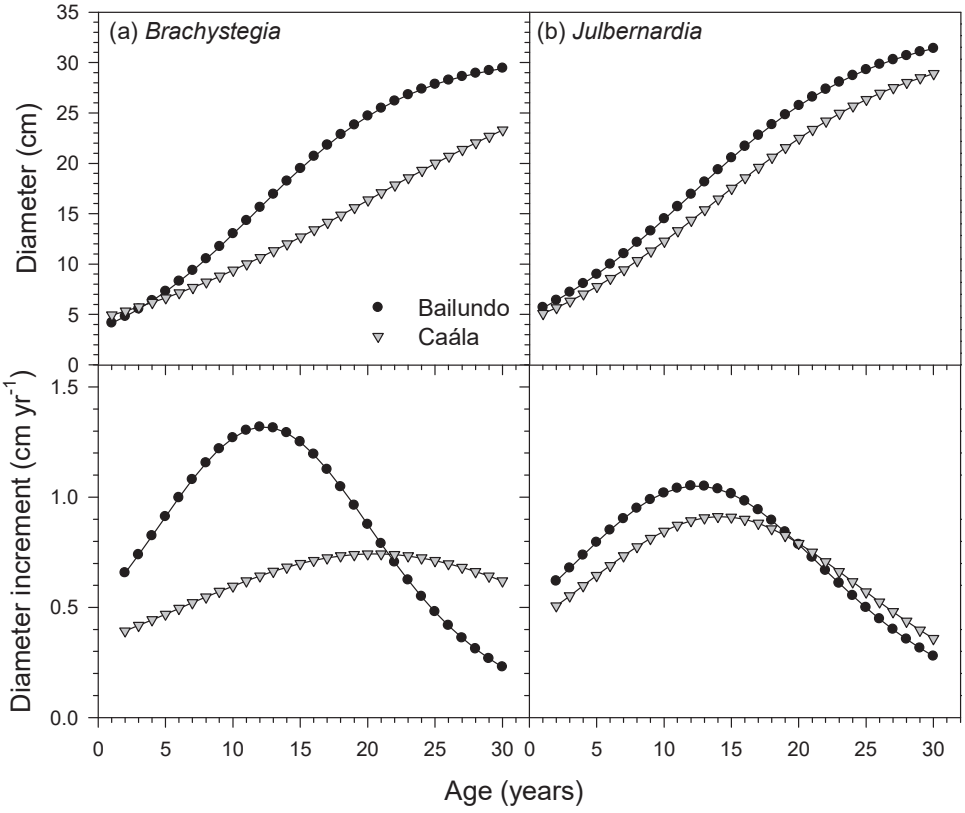


Fig. 4. Fitted diameter growth curves of (a) *Brachystegia* and (b) *Julbernardia* in the Bailundo and Caála study sites and derived diameter increment rates.

Table 3
Climate-growth relationships based on the correlations calculated between monthly climate variables and the series of ring-width indices of the two species studied in Bailundo and Caála sites. Significant ($p < 0.05$) correlations are shown with bold characters.

Species	Site	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
		Mean temperature											
Brachystegia	Bailundo	0.23	-0.04	-0.06	0.03	-0.28	**-0.53**	0.21	0.10	-0.22	0.05	-0.28	-0.26
	Caála	0.25	0.07	0.18	-0.27	-0.31	-0.36	-0.11	0.19	0.04	0.04	0.06	-0.08
Julbernardia	Bailundo	0.17	0.12	0.14	0.02	-0.15	-0.42	0.05	0.03	-0.16	0.08	-0.04	0.01
	Caála	0.12	0.09	0.28	-0.25	-0.32	-0.37	-0.22	0.11	0.23	0.10	-0.11	0.05
		Precipitation											
Brachystegia	Bailundo	0.14	0.12	0.21	-0.26	0.13	**0.51**	0.26	**0.71**	0.10	-0.16	0.11	0.09
	Caála	0.14	0.10	0.09	-0.11	**0.51**	**0.54**	0.33	0.15	0.12	0.30	-0.11	0.10
Julbernardia	Bailundo	0.18	0.11	0.15	-0.32	0.10	**0.53**	**0.58**	-0.20	0.07	0.20	0.10	0.12
	Caála	0.12	0.08	0.10	-0.27	0.46	**0.62**	0.44	-0.14	0.21	0.14	0.13	0.20
		Soil moisture											
Brachystegia	Bailundo	0.04	0.30	0.17	0.33	0.26	0.18	**0.56**	**0.58**	0.07	-0.28	0.18	0.10
	Caála	0.38	0.16	0.22	0.08	0.25	0.34	**0.55**	0.25	0.18	0.14	0.11	0.18
Julbernardia	Bailundo	0.20	0.19	0.19	0.11	0.29	**0.54**	0.40	0.35	0.24	0.14	0.02	0.19
	Caála	0.24	0.18	0.27	0.07	0.28	0.38	**0.67**	0.20	0.23	0.18	0.12	0.13
		SOI											
Brachystegia	Bailundo	0.14	0.11	0.10	0.31	0.22	**0.53**	0.17	0.40	0.27	0.16	0.06	0.01
	Caála	0.20	0.13	0.09	0.12	**0.55**	0.06	0.16	**0.54**	0.30	0.26	0.02	0.05
Julbernardia	Bailundo	0.23	0.25	0.33	**0.49**	0.29	0.25	0.23	0.26	0.21	0.20	0.08	0.12
	Caála	0.17	0.20	0.15	0.15	**0.51**	0.19	0.21	0.47	0.27	0.17	0.05	0.15

positive correlations of ring-width indices with precipitation and soil moisture were found for *Julbernardia* and they were larger in Caála than in Bailundo. Regarding temperature, we only found a significant ($p < 0.05$) and negative correlation with December data in the case of *Brachystegia* from Bailundo. The correlations between ring-width indices and the SOI were mostly positive, with maximum values reached from October to December. These analyses were in agreement with spatial correlations showing a positive link between the *Julbernardia* chronology from Bailundo and January precipitation (Fig. S3).

4. Discussion

We used tree-ring analysis in a tropical dry forest located in Southwest Africa considering two major Angolan miombo tree species (*Brachystegia spiciformis*, *Julbernardia paniculata*) and two climatically different sites. We were able to derive growth curves which allowed estimating the time required to reach cutting diameter of the two tree species. Notably, growth rates exhibited considerable variation between species and sites achieving a minimum cutting diameter at distinct ages. Furthermore, age variability within species was also found to be

significant. This finding is critical for a more sustainable use of these seasonally dry ecosystems which are severely exploited for charcoal production (Chiteculo et al., 2018).

4.1. Age-diameter relationships and cumulative growth curves

According to growth models, *B. spiciformis* is considered to reach the minimum allowable cutting diameter in 15–30 years (Chiteculo and Surovy, 2018). Using tree-ring data of this species we found that a minimum diameter of 15–20 cm can be attained in 12–20 years depending on site climate conditions. These ages are significantly lower than those used (25–40 years) by the Angolan Institute for Forest Development (Chiteculo and Surovy, 2018). Such discrepancy may be explained by the relative low age of sampled *Brachystegia* individuals (31 years, on average) and by their high growth rates (5.1 mm), particularly in the wet Bailundo site. Interestingly, the growth rates observed in our study align with those reported for other tree species in various tropical dry forests (Wils et al., 2011; Mendivelso et al., 2013; Paredes-Villanueva et al., 2013). For instance, our results are similar to those obtained for *P. angolensis* by Stahle et al. (1999) in several South African countries, who reported mean tree-ring widths ranging between 2.6 and 4.0 mm but mentioned higher growth rates (5.0–6.0 mm) in other studies carried out in wetter sites. Syampungani et al. (2010) and Chidumayo (1988) also reported similar growth rates of miombo species (5.1–5.4 mm for *J. paniculata, Bachystegia floribunda* and *Isoberlinia angolensis*; 3.6 and 4.8 mm for *Brachystegia* and *Julbemardia*, respectively). Such growth variation may be caused by additional factors: population dynamics (such as regeneration or sprouting pulses), local factors (such as soil depth and water table), or competition dynamics (Bowman et al., 2013). Overall, the high growth rates observed, especially in the wet Bailundo site, indicate that trees could reach 15 cm in diameter in 12–15 years.

4.2. Growth responses to climate and the ENSO

As expected, we found that the growth of these species was enhanced by wet conditions linked to low SOI values. The growth sensitivity to winter precipitation and soil moisture was higher in the dry (Caála) than in the wet (Bailundo) site. The growth variability among co-occurring individuals of the same species was also lower in the dry than in the wet site, which explains that the age (15 years) to reach a minimum cutting diameter of 15 cm was similar between the two species in Caála. Our findings concur with those of Therrell et al. (2007), who found that *P. angolensis* showed radial growth rates which: (i) greatly varied among stands and individuals, and (ii) increased as seasonal rainfall did. Furthermore, in previous studies on *B. spiciformis*, growth was also found to increase as December precipitation did (Trouet et al., 2001, 2006). The presented results support our hypothesis, as indicated by the high correlation values obtained between growth and monthly climatic variables, confirming the relationship between diameter growth and rainfall. Elevated temperatures hinder tree growth due to water deficit conditions, as water resources act as a limiting factor for growth in tropical dry forests (González et al., 2021).

In general, wet conditions during winter or high annual precipitation enhanced radial growth of major miombo tree species such as *B. spiciformis*, *P. angolensis* and *Burkea africana* (Stahle et al., 1999; Trouet et al., 2001, 2006; Fichtler et al., 2004; Munalula et al., 2020), although those studies were developed in Namibia, Tanzania and Zambia. To the best of our knowledge, this is one of the first tree-ring studies carried out in Angola. These correlative findings are supported by studies on wood phenology showing that the cambial growth season corresponded to the core of the rainy season (December to February), when 75% of the annual precipitation falls and trees show maximum photosynthetic capacity (Trouet et al., 2012). In drier sites than those studied here, a negative correlation of growth indices with winter temperature was also found (Fichtler et al., 2004; Trouet et al., 2006), which could be related to higher respiration and consumption of assimilated non-structural carbohydrates (Wagner et al., 2016). In a tropical rain forest from Costa Rica dominated by *Pentaclethra macroloba*, a negative correlation of tree growth and daily night minimum temperature was also detected by Clark et al. (2010). This could explain why we only found a negative growth-temperature association in *Brachystegia* from the wet Bailundo site which could be due to increased evapotranspiration rates.

During the rainy season, the ENSO peaks in amplitude and its effects on precipitation variability in Southern Africa are the strongest (Camberlin et al., 2001), which explains the negative (positive) responses of miombo tree species to dry-warm (wet-cool) El Niño (La Niña) events (Fichtler et al., 2004). Our results agree with this because we also found positive relationships between the winter SOI values and ring-width indices, peaking in the rainy season. As stated before, not every El Niño (La Niña) year is dry (wet) over Southern Africa, so longer chronologies of the study species are needed to test ENSO-growth associations considering extreme ENSO episodes, particularly in dry miombo woodlands. These findings provide confirmation that the impacts of atmospheric circulation patterns on the growth of miombo species are likely an indirect manifestation of their influence on local precipitation patterns and drought conditions.

4.3. Silvicultural implications

Tree-ring analysis holds valuable potential for its application in tropical dry forests, enabling the acquisition of species-specific growth data and tree age information, which can greatly contribute to sustainable forest management practices. In Angola, forest management decisions, including minimum cutting diameter and logging intensities, heavily rely on the Angolan Institute for Forest Development. However, this poses two key problems when estimating future timber yields: (1) the set growth rates may be inaccurate, leading to potentially flawed regulations regarding logging intensity and cutting cycles; and (2) the neglect of persistent growth disparities among individuals when relying solely on species-average values. Such disparities between set and actual growth rates may result in excessive harvesting rates that surpass species' regrowth capacity.

On this study, we accurately identified growth rates for each managed species at the local level, considering that rates may vary within species across different regions. Growth during early stages becomes relatively more crucial for wood production compared to later stages, indicating persistent differences in growth rates within species. These variations significantly affect size-age relationships within a species and may lead to underestimations of estimated future timber yields. Therefore, timber yield calculations should incorporate this inherent variability instead of relying solely on average growth rates. The growth data obtained in our study account for such variability and can facilitate more accurate and species-specific estimations of future timber yields. From the perspective of forest management in miombo woodlands, we suggest focusing tree-ring analysis on the most harvested tree species. Tree-ring analysis possesses great potential, even in wet tropical forests, to provide crucial ecological data for sustainable forest management. Such analyses would facilitate a more accurate evaluation of the consequences of forest harvesting.

5. Conclusions

To conclude, cross-dating of Angola miombo tree species sampled in wet and dry sites allowed quantifying the time they require reaching a minimum cutting diameter and their climate- and ENSO-growth correlations. Tree-ring data show that the study species (*Brachystegia* and *Julbernardia*), which are heavily exploited for charcoal production, show high growth rates in wet sites. They show maximum growth rates (0.74–1.32 cm yr^{-1}) at ages from 12 to 20 years and can reach a minimum cutting diameter of 15 cm in 12–15 years. Their growth rates are

constrained by dry-warm conditions during the rainy season associated with low SOI values. We hope this study will encourage further dendrochronological research in understudied Angolan tropical forests, and contribute to establishing a stronger knowledge foundation for sustainable forest management in Southern Africa.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was funded by Instituto Nacional de Gestão de Bolsas de Estudos da República de Angola. The first author would like also to acknowledge the staff of FCA and UJES in Huambo province. Special thanks go to Francisco Cachama and Fernando Hequele for their support during the field work in Angola. We thank Michele Colangelo for preparing the wood cross-sections. We also thank two anonymous reviewers and the editor for their constructive comments and careful editing of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2023.126117.

References

Borchert, R., 1999. Climatic periodicity, phenology and cambium activity in tropical dry forest trees. IAWA J. 20, 239–247.
Bowman, D.M., Brienen, R.J., Gloor, E., Phillips, O.L., Prior, L.D., 2013. Detecting trends in tree growth: not so simple. Trends Plant Sci. 18, 11–17.
Brienen, R.J.W., Zuidema, P.A., 2007. Incorporating persistent tree growth differences increases estimates of tropical timber yield. Front. Ecol. Environ. 5, 302–306.
Briffa, K.R., Jones, P.D., 1990. Basic chronology statistics and assessment. In: Cook, E.R., Kairiukstis, L.A. (Eds.), Methods of Dendrochronology. Kluwer, Dordrecht, pp. 137–152.
Bunn, A.G., 2010. Statistical and visual crossdating in R using the dplR library. Dendrochronologia 28, 251–258.
Camberlin, P., Janicot, S., Poccard, I., 2001. Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO. Int. J. Climatol. 21, 973–1005.
Campbell, B. (Ed.), 1996. The Miombo in Transition: Woodlands and Welfare in Africa. CIFOR, Bogor, Indonesia.
Chidumayo, E.N., 1988. Estimating fuelwood production and yield in regrowth dry miombo woodland in Zambia. Ecol. Manag. 24, 59–66.
Chiteculo, V., Surovy, P., 2018. Dynamic patterns of trees species in miombo forest and management perspectives for sustainable production-case study in Huambo Province. Angola For. 9, 321.
Chiteculo, V., Lojka, B., Surový, P., Verner, V., Panagiotidis, D., Woitsch, J., 2018. Value chain of charcoal production and implications for forest degradation: case study of Bié Province, Angola. Environments 5, 113.
Chiteculo, V., Abdollahnejad, A., Panagiotidis, D., Surový, P., Sharma, R.P., 2019. Defining deforestation patterns using satellite images from 2000 and 2017: assessment of forest management in miombo forests-A case study of Huambo Province in Angola. Sustainability 11, 98.
Chiteculo, V., Abdollahnejad, A., Panagiotidis, D., Surový, P., 2022. Effects, monitoring and management of forest roads using remote sensing and gis in angolan miombo woodlands. Forests 13, 524.
Clark, D.B., Clark, D.A., Oberbauer, S.F., 2010. Annual wood production in a tropical rain forest in NE Costa Rica linked to climatic variation but not to increasing CO_2. Glob. Change Biol. 16, 747–759.
Détienne, P., 1989. Appearance and periodicity of growth rings in some tropical woods. IAWA Bull. 10, 123–132.
Fichtler, E., Trouet, V., Beeckman, H., Coppin, P., Worbes, M., 2004. Climatic signals in tree rings of *Burkea africana* and *Pterocarpus angolensis* from semiarid forests in Namibia. Trees. Struct. Funct. 18, 442–451.
Fritts, H.C., 1976. Tree Rings and Climate. Academic Press,, London.
Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 150066. https://doi.org/10.1038/sdata.2015.66.
Gonçalves, F.M.P., Revermann, R., Gomes, A.L., Aidar, M.P., Finckh, M., Jürgens, N., 2017. Tree species diversity and composition of Miombo woodlands in south-central Angola, a chronosequence of forest recovery after shifting cultivation. Int. J. Res. 6202093.
González, -M., R., Posada, J.M., Carmona, C.P., Garzón, F., Salinas, V., Idárraga-Piedrahita, Á., Salgado-Negret, B., 2021. Diverging functional strategies but high sensitivity to an extreme drought in tropical dry forests. Ecol. Lett. 24, 451–463.
Gumbo, D.J., Dumas-Johansen, M., Muir, G., Boerstler, F., Xia, Z., 2018. Sustainable Management of Miombo Woodlands. Food Security, Nutrition and Wood Energy. FAO,, Rome, Italy, p. 64.
Harris, I., Jones, P., Osborn, T., Lister, D., 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS 3.10 Dataset. Int. J. Climatol. 34, 623–642.
Hoell, A., Gaughan, A.E., Magadzire, T., Harrison, L., 2021. The modulation of daily Southern Africa precipitation by El niño–southern oscillation across the summertime wet season. J. Clim. 34, 1115–1134.
Höhn, A., 1999. Wood anatomy of selected west African species of Caesalpinioideae and Mimosoideae (Leguminosae): a comparative study. IAWA J. 20, 115–146.
Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. 43, 69–78.
Howard, E., Washington, R., 2018. Characterizing the synoptic expression of the Angola low. J. Clim. 31, 7147–7165.
Kalaba, F.K., Quinn, C.H., Dougill, A.J., Vinya, R., 2013. Floristic composition, species diversity and carbon storage in charcoal and agriculture fallows and management implications in Miombo woodlands of Zambia. Ecol. Manag. 304, 99–109.
Kutsch, W.L., Merbold, L., Ziegler, W., Mukelabai, M.M., Muchinda, M., Kolle, O., Scholes, R.J., 2011. The charcoal trap: miombo forests and the energy needs of people. Carbon Balance Manag. 6, 5. https://doi.org/10.1186/1750-0680-6-5.
Larsson, L.A., Larsson, P.O., 2018. CDendro and CooRecorder (v. 9.3.1). Cybis Elektronik and Data AB,, Saltsjöbaden, Sweden.
Maxwell, R.S., Larsson, L.-A., 2021. Measuring tree-ring widths using the CooRecorder software application. Dendrochronologia 67, 125841.
Mendelsohn, J.M., 2019. Landscape changes in Angola. In: Huntley, B., Russo, V., Lages, F., Ferrand, N. (Eds.), Biodiversity of Angola. Springer, Dordrecht, pp. 123–137.
Mendivelso, H.A., Camarero, J.J., Royo Obregón, O., Gutiérrez, E., Toledo, M., 2013. Differential growth responses to water balance of coexisting deciduous tree species are linked to wood density in a Bolivian tropical dry forest. Plos ONE 8, e73855.
Miapia, L.M., Ariza-Mateos, D., Lacerda-Quartín, V., Palacios-Rodríguez, G., 2021. Deforestation and biomass production in miombo forest in Huambo (Angola): a balance between local and global needs. Forests 12, 1557.
Millington, A.C., Critchley, R.W., Douglas, T.D., Ryan, P., 1994. Estimating woody biomass in SubSaharan Africa. The World Bank,, Washington DC.
Munalula, F., Seifert, T., Meincken, M., 2020. Inter-annual growth response of three Miombo tree species to climatic effects. South. For. 82, 135–147.
Paredes-Villanueva, K., Sánchez-Salguero, R., Manzanedo, R.D., Sopepi, R.Q., Palacios, G., Navarro-Cerrillo, R.M., 2013. Growth rate and climatic response of *Machaerium scleroxylon* in a dry tropical forest in southeastern Santa Cruz, Bolivia. Tree-Ring Res. 69, 63–79.
Plisnier, P.-D. 1998. Lake Tanganyika: recent climate changes and teleconnections with ENSO. In: G. Demarée, J. Alexandre & M. De Dapper (eds), Proceedings of the International conference 'Tropical Climatology, Meteorology and Hydrology', Brussels, May 1996, Brussels, pp. 228–250.
Prävälie, R., 2016. Drylands extent and environmental issues. a global approach. Earth Sci. Rev. 161, 259–278.
R Development Core Team, 2022. R: A Language and Environment for Statistical Computing.
Ratnam, J.V., Behera, S.K., Masumoto, Y., Yamagata, T., 2014. Remote effects of El Niño and Modoki events on the austral summer precipitation of southern Africa. J. Clim. 27, 3802–3815.
Ribeiro, N.S., Syampungani, S., Matakala, N., Nangoma, D., Barros, A., 2015. Miombo Woodlands Research towards the Sustainable Use of Ecosystem Services in Southern Africa. In: Yueh-Hsin, L., Blanco, J., Shovonlal, J. (Eds.), Biodiversity in Ecosystems-Linking Structure and Function. InTech, Rijeka, Croatia, pp. 475–491.
Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., Toll, D., 2004. The global land data assimilation system. Bull. Am. Meteor. Soc. 85, 381–394.
Ropelewski, C.F., Halpert, M.S., 1989. Precipitation patterns associated with the high indices phase of the southern oscillation. J. Clim. 2, 268–284.
Ropelewski, C.F., Jones, P.D., 1987. An extension of the Tahiti-Darwin Southern Oscillation Index. Mon. Weather Rev. 115, 2161–2165.
Ryan, C.M., Pritchard, R., McNicol, I., Owen, M., Fisher, J.A., Lehmann, C., 2016. Ecosystem services from southern African woodlands and their future under global change. Philos. Trans. R. Soc. B Biol. Sci. 371, 20150312.
Schöngart, J., Wittmann, F., Worbes, M., Fernandez Piedade, M.T., Krambeck, H.-J., Junk, W.J., 2007. Management criteria for Ficus insipida Willd. (Moraceae) in Amazonian white-water floodplain forests defined by tree-ring analysis. Ann. Sci. 64, 657–664.
Schulman, E., 1956. Dendroclimatic change in semiarid America. University of Arizona Press,, Tucson, USA.
Stahle, D.W., 1999. Useful strategies for the development of tropical tree-ring chronologies. IAWA J. 20, 249–253.

Stahle, D.W., Mushove, P.T., Cleaveland, M.K., Roig, F., Haynes, G.A., 1999. Management implications of annual growth rings in *Pterocarpus angolensis* from Zimbabwe. Ecol. Manag. 124, 217–229.
Syampungani, S., Geldenhuys, C.J., Chirwa, P.W., 2010. Age and growth rate determination using growth rings of selected miombo woodland species in charcoal and, slash and burn regrowth stands in Zambia. J. Ecol. Nat. Environ. 2, 167–174.
Therrell, M.D., Stahle, D.W., Mukelabai, M.M., Shugart, H.H., 2007. Age, and radial growth dynamics of *Pterocarpus angolensis* in southern Africa. Ecol. Manag. 244, 24–31.
Trenberth, K.E., Stepaniak, D.P., 2001. Indices of El Niño evolution. J. Clim. 14, 1697–1701.
Trouet, V., Haneca, K., Coppin, P., Beeckman, H., 2001. Tree ring analysis of *Brachystegia spiciformis* and *Isoberlinia tomentosa*: evaluation of the ENSO-signal in the miombo woodland of eastern Africa. IAWA J. 22, 385–399.
Trouet, V., Coppin, P., Beeckman, H., 2006. Annual growth ring patterns in *Brachystegia spiciformis* reveals influence of precipitation on tree growth. Biotropica 38, 375–382.
Trouet, V., Esper, J., Beeckman, H., 2010. Climate/growth relationship of *Brachystegia spiciformis* from the miombo woodland in south central Africa. Dendrochronologia 28, 161–171. https://doi.org/10.1016/j.dendro.10.002.
Trouet, V., Mukelabai, M., Verheyden, A., Beeckman, H., 2012. Cambial growth season of brevi-deciduous *Brachystegia spiciformis* trees from south central Africa restricted to less than four months. PLoS One 7, e47364.
Wagner, F.H., Hérault, B., Bonal, D., Stahl, C., Anderson, L.O., et al., 2016. Climate seasonality limits carbon assimilation and storage in tropical forests. Biogeosciences 13, 2537–2562.
White, F., 1983. The vegetation of Africa. A descriptive memoir to accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa (3 Plates, Northwestern Africa, Northeastern Africa, and Southern Africa, 1:5,000,000). UNESCO,, Paris.
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. Meteor. 23, 201–213.
Wils, T.H.G., Sass-Klaassen, U.G.W., Eshetu, Z., Bräuning, A., Gebrekirstos, A., Couralet, C., Beeckman, H., 2011. Dendrochronology in the dry tropics: the Ethiopian case. Trees Struct. Funct. 25, 345–354.
Worbes, M., 1989. Growth rings, increment and age of trees in inundation forests, savannas and a mountain forest in the Neotropics. IAWA Bull. 10, 109–122.
Worbes, M., 1995. Measuring growth dynamics in tropical trees. IAWA J. 16, 337–351.
Worbes, M., 2002. One hundred years of tree-ring research in the tropics: a brief history and an outlook to future challenges. Dendrochronologia 20, 217–231.
Worbes, M., Schöngart, J., 2019. Measures for sustainable forest management in the tropics –a tree-ring based case study on tree growth and forest dynamics in a Central Amazonian lowland moist forest. PLoS ONE 14, e0219770.
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. Ecol. Manag. 173, 105–123.
Zang, C., Biondi, F., 2015. treeclim: an R package for the numerical calibration of proxy-climate relationships. Ecography 38, 431–436.
Zuidema, P.A., Babst, F., Groenendijk, P., Trouet, V., Abiyu, A., Acuña-Soto, R., Adenesky-Filho, E., Alfaro-Sánchez, R., Aragãao, J.R.V., Assis-Pereira, G., Bai, X., et al., 2022. Tropical tree growth driven by dry-season climate variability. Nat. Geosci. 15, 269–276.
Zulu, L.C., 2010. The forbidden fuel: charcoal, urban wood fuel demand and supply dynamics, community forest management and wood fuel policy in Malawi. Energy Policy 38, 3717–3730.