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TREE RING ANALYSIS OF BRACHYSTEGIA SPICIFORMIS AND ISOBERLINIA TOMENTOSA: EVALUATION OF THE ENSO-SIGNAL IN THE MIOMBO WOODLAND OF EASTERN AFRICA

by

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SUMMARY

The value of growth rings as proxy data for climate reconstruction was studied in two miombo woodland species in eastern Africa. Growth rings, marked by terminal parenchyma, were visually detectable on carefully prepared stem discs of *Isoberlinia tomentosa* and *Brachystegia spiciformis*, dominant species of the miombo woodland in north-western Tanzania. However, the presence of multiple growth ring anomalies rendered cross-dating of the growth ring series between trees difficult. Cross-dating succeeded for eight out of thirteen samples for *Isoberlinia tomentosa*, but was unsuccessful for *Brachystegia spiciformis*. A mean series of 38 years was calculated for *Isoberlinia tomentosa* only. Monthly precipitation, monthly maximum air temperature and monthly SOI-value (Southern Oscillation Index) correlated significantly with tree ring widths of the mean series. These correlations are strong indicators of the annual character of the growth rings. They also suggest that *Isoberlinia tomentosa* provides an appropriate paleoclimatic record for dendroclimatic reconstruction.

Key words: Dendrochronology, miombo woodland, ENSO, *Brachystegia spiciformis*, *Isoberlinia tomentosa*, growth ring anomalies.

INTRODUCTION

In equatorial eastern Africa a strong teleconnection exists between the regional climate and the El Niño Southern Oscillation (ENSO) (Nicholson & Entekhabi 1986; Janowiak 1988; Ropelewski & Halpert 1988; Nicholson & Kim 1997). The first phase of the cycle (El Niño) corresponds with an increase in both temperature and precipitation in the region. The second phase (La Niña) is associated with a decrease of both.

The understanding of ENSO-cycles and their variations can only be based on research of the long-term ENSO-signal. Climatic time-series, as provided by instru-

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ment-acquired records, are not extensive enough to encompass multiple realisations of decadal variability (Stahle et al. 1998), especially not in Africa. Proxy data offer a potential solution. Tree ring data in particular often have a fixed annual resolution and can produce absolute time-series, two important characteristics for historical ENSO-reconstruction (Cook 1992).

In the northern hemisphere dendrochronological ENSO-research has already been conducted based on time-series from areas with strong teleconnections with ENSO (D'Arrigo & Jacoby 1992; Stahle et al. 1998; Stahle et al. 1999). The reconstruction of the local characteristics of ENSO, however, can only be derived from information acquired in the centre of the relevant ENSO impact region and therefore proxy data need to be acquired locally (e.g. growth ring measurements).

The occurrence of annual rings in the tree species of equatorial Africa is restricted to regions with alternating wet and dry seasons (Worbes 1992). The main vegetation type of these regions is miombo woodland (White 1983).

This research had as its main objective an examination of the potential of tree ring series of two species of the miombo woodland (*Brachystegia spiciformis* Benth. and *Isoberlinia tomentosa* (Harms) Craib et Stapf) for climate reconstruction.

MATERIALS AND METHODS

Study sites

The study sites were located in the north-western part of Tanzania, in the Kigoma region. This region is characterised by a tropical seasonally dry climate and is covered by miombo woodland. Noteworthy is the fact that other proxy data have been examined in this region (e.g. sediments in Lake Tanganyika, Plisnier 1998). Allthough temporal resolution of different time-series varies, a comparison of time-series based on different proxy data is feasible.

Isoberlinia tomentosa (Harms) Craib et Stapf was sampled in Myovosi, about 20 km to the northeast of Kasulu (30.4° E, 4.4° S, 1490 m), *Brachystegia spiciformis* Benth. in Kazuramimba (30° E, 5° S, 970 m), 60 km east of Kigoma. The sites were about 100 km apart, the vegetation-type (miombo woodland) and the climatic regime (tropical seasonally dry) remained constant.

Specimens

Isoberlinia tomentosa and *Brachystegia spiciformis* offer good prospects for the presence of annual growth rings. They belong to the seasonally dry forest type where the dry season (precipitation < 60 mm) lasts longer than 3 months (Worbes 1995). Another important characteristic is the macro- and microscopically distinctive character of their growth rings, marked by terminal parenchyma (Stahle 1999) and a decreasing frequency of paratracheal parenchyma bands towards the latewood (Fig. 1a, b).

Thirteen samples of *Isoberlinia tomentosa* were collected in Myovosi and have been incorporated in the xylarium of the Royal Museum for Central Africa, accessions Tw 55682 to Tw 55694. The eleven samples of the species *Brachystegia spiciformis*, collected in Kazuramimba, have the numbers Tw 55697, Tw 55698, Tw 55700 to Tw 55707 and Tw 55710.

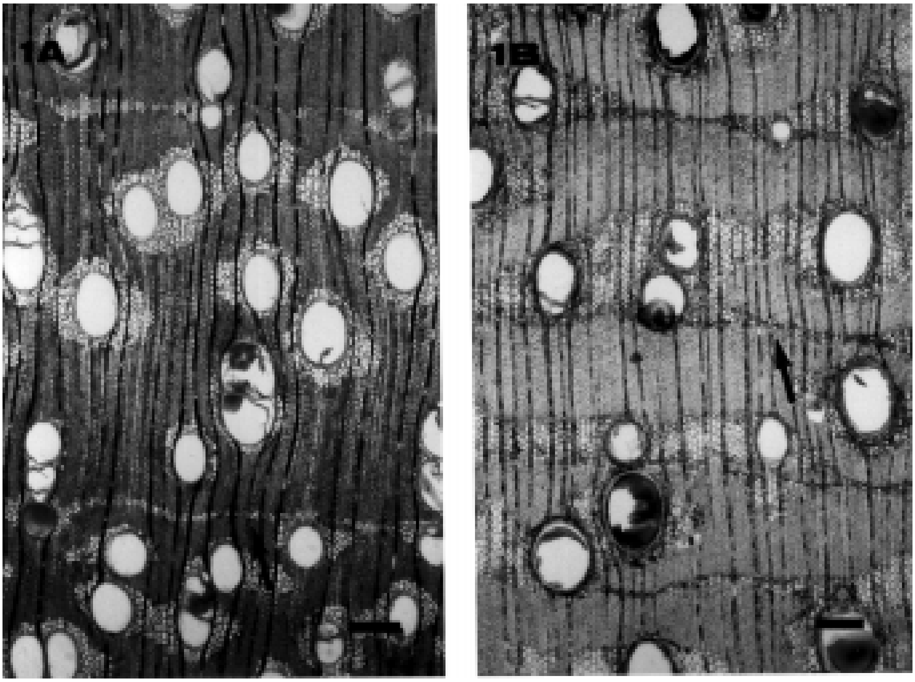

Fig. 1. Growth rings. – a: *Brachystegia spiciformis*, marked by terminal parenchyma (arrow); b: *Isoberlinia tomentosa*, marked by terminal parenchyma (arrow). — Scale bars = 100 μm.

The samples taken were full stem discs, as core collection was impracticable because of the occurrence of wedging rings. To minimise damage to living trees, disc samples were taken from stumps of trees (80–100 cm height) that were cut earlier on in the same year for other purposes (logging, charcoal production).

Climatic data

Precipitation data were available for Kasulu and Kigoma. The mean annual precipitation in Kasulu was 1380.7 mm (1964–1997), in Kigoma 997 mm (1968–1998). The dry season (no rainfall) lasted four months (June to September) in both localities. Temperature data were only available for Kigoma (1965–1994).

Sample preparation and measurements

In order to optimise growth ring detectability, transverse surfaces of all stem discs were sanded and polished (grain 180 to 1200) and observed under oblique lighting conditions. Before carrying out any measurements, all stem discs were analyzed microscopically (stereo microscope) to carefully delineate and positionally register the presence of any wedging rings. Growth ring widths were then measured using LINTAB equipment and TSAP software (Rinn & Jäkel 1997), for four to six radii (from bark to pith) per sample disc.

Statistical analysis

Cross-dating of the radii data was carried out at tree level using SYSTAT cross correlation functions (Wilkinson 1997). In order to detect any trends, the average growth ring series of individual trees were subjected to an autocorrelation analysis (SYSTAT, Wilkinson 1997). When present, the trend was removed applying a moving-average or differentiation-technique, referred to as standardisation (Schweingruber 1996). Average growth ring series of different trees on the same site were then cross-dated.

Ultimately, a response function analysis was performed between growth ring data and climatic data. Growth ring data encompassed both the average series from each individual tree and the average series of the site. Climatic data comprised monthly amount of precipitation, monthly maximum and minimum temperature, monthly mean temperature, monthly air-humidity and monthly Southern Oscillation Index (SOI) value. The SOI value is the normalised difference between the air pressures of Tahiti and Darwin and a quantification of the ENSO-cycle in the Pacific (McGregor & Nieuwolt 1998).

Three different response function analysis methods were implemented to ensure the significance of the response functions found. Redundancy Analysis (RDA) and Set Correlation Analysis (SCA) are canonical ordination methods and thus have the power to reveal trends in complex ecological datasets, consistent of predictor and predicted variables (Fritts et al. 1971). RDA, executed under CANOCO (Ter Braak 1994) is an eigenvector method that does not presuppose an upper limit for the ratio between variables (specimens and/or chronologies) and objects (growth rings) (Beeckman & Vander Mijnsbrugge 1993). SCA (Cohen & Wilkinson 1997), used as a second canonical ordination method to verify the results of RDA, was executed under SYSTAT. The third method applied is multiple linear regression (MLR), executed under SYSTAT (Wilkinson 1997). MLR is generally used for the examination of the relation between tree growth and climate (Fritts 1962).

The tree ring series of *Isoberlinia tomentosa* were analyzed against the precipitation data of Kasulu and the temperature data of Kigoma. The precipitation dataset consisted of the data of the growth year itself (year 0) and the months September to December of the previous year (year –1), as these months are part of the rainy season (running from September to May). The dataset was reduced by leaving out the months with high multicollinearity. The inflation factor calculated during RDA was used as a parameter for this multicollinearity.

The temperature dataset consisted of the mean monthly temperatures and maximum and minimum temperatures of the weather station at Kigoma. The dataset was restricted to data collected during the growth year, again excluding months with high multicollinearity.

The relation between the growth ring series and the SOI values was examined over a time-period from 1929 to 1998 (length of the longest growth ring series).

The precipitation and temperature data of Kigoma were used for correlation analysis of the tree ring series of *Brachystegia spiciformis*.

Table 1. Total number of rings and number of locally absent rings for the specimens of *Isoberlinia tomentosa* and *Brachystegia spiciformis*.

Isoberlinia tomentosa	Total	Locally absent	*Brachystegia spiciformis*	Total	Locally absent
Tw 55682	37	6	Tw 55697	38	4
Tw 55683	35	3	Tw 55698	44	4
Tw 55684	44	10	Tw 55700	54	4
Tw 55685	54	11	Tw 55701	46	4
Tw 55686	70	16	Tw 55702	47	5
Tw 55687	36	3	Tw 55703	47	10
Tw 55688	38	0	Tw 55704	41	0
Tw 55689	35	6	Tw 55705	37	0
Tw 55690	34	7	Tw 55706	42	15
Tw 55691	35	8	Tw 55707	25	3
Tw 55692	69	9	Tw 55710	34	4
Tw 55693	38	3			
Tw 55694	49	2			

RESULTS

Locally absent rings

Of the thirteen samples of *Isoberlinia tomentosa*, only one was free of locally absent rings (ring wedging). This sample was therefore used as a cross-dating reference. For *Brachystegia spiciformis*, two of the eleven stem discs did not show ring wedging (Table 1).

Because of the occurrence of locally absent rings (Fig. 2), ring counting over different radii of a sample often gave different results.

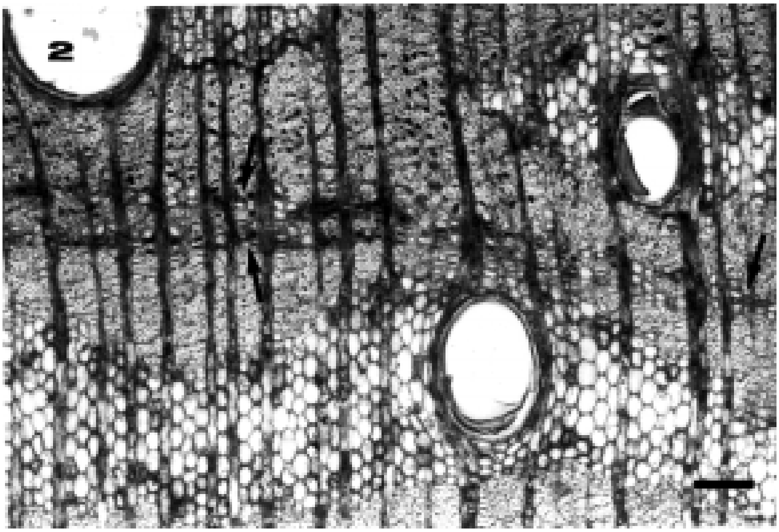

Fig. 2. Growth ring anomalies (arrows) in *Isoberlinia tomentosa*. — Scale bar = 100 µm.

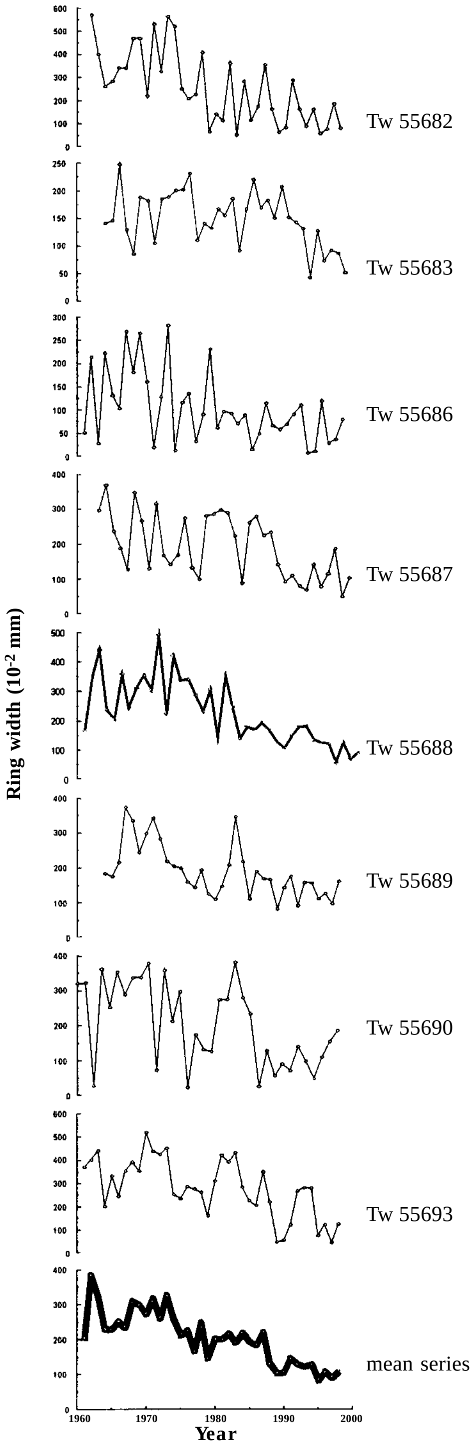

Fig. 3. Eight individual and one mean growth ring series of *Isoberlinia tomentosa* on the Myovosi-site.

In order to cross-date the different radii, two methodologies were developed to compare the rings of the same year. For the first method, ring wedging is accepted as the hypothesis for the appearance of locally absent rings. During several years, strong radial growth takes place in some segments of the tree, while in other segments growth is absent or extremely slow (Norton et al. 1987). Using this method, every ring, locally absent or not, was considered to be an annual ring and where it was locally absent, its width was considered to be the average of the widths on the radii were it was present. This meant that the mean sample growth ring width was not impacted by the absence of the ring in one or more radii.

The second method assumes the formation of more than one ring per year in some segments of the tree, but not in others (locally false rings). The explanation for this phenomenon could be a dry period during the wet season causing a growth stop. After the continuation of the rainy season, growth can be resumed in some segments of the tree. In this case, multiple rings are individually counted as they occur in the different segments. The width of locally false rings is added up to the width of the previously formed complete growth ring. The total number of rings on every radius is the number of rings that has no local absence on any segment.

The two methods have been applied on all samples. The second method gave slightly better results during the cross-dating between trees of *Brachystegia spiciformis*. However, cross-dating remains statistically insignificant. For the samples of *Isoberlinia tomentosa*, the two methods gave the same results during the cross-dating. After standardisation, however, cross-dating was more successful using the first method. For this reason, the hypothesis of ring wedging has been accepted.

Isoberlinia tomentosa

Cross-dating and standardisation

Cross-dating between radii was successful for each tree. In order to build a chronology for the site of Myovosi, the thirteen specimens had to be cross-dated. The cross-correlations of seven out of thirteen samples were significant at lag 0. Standardisation by means of a moving average (for a period of four years) added another sample to this group, with previously found correlations remaining significant after standardisation. It was decided to continue the research with non-standardised time-series. The risk of losing important information through standardisation was considered too high (Beeckman 1992). Based on the eight samples, a Myovosi-site mean growth curve was constructed (Fig. 3).

Response function analysis

The next phase consisted of carrying out a response function analysis between, on the one hand the site mean growth curve, and on the other climatic information, using MLR and SCA. Another analysis was carried out with the group of eight individually contributing tree series using RDA. Response function analysis with the entire dataset of tree ring series was unsuccessful.

Significant relations were found only for monthly precipitation, monthly maximum temperature and monthly SOI value (Table 2).

Significant results were found for the response function analysis between the growth ring dataset and the monthly precipitation of Kasulu. The overall correlation between both datasets was strong and significant for all three methods (Table 2).

The biplot of the redundancy analysis is given in Figure 4. Emphasis must be put on the scores of samples (full bullets) and climatic data (blank bullets) along the first

Table 2. Overall response of the mean growth ring series to three climatic data sets: monthly precipitation (RF), monthly maximum temperature (Tmax) and monthly SOI-value (SOI). Three different response function analysis methods were implemented: redundancy analysis (RDA), multiple linear regression (MLR) and set correlation analysis (SCA).

	RDA		MLR		SCA	
	R^2	P-value	R^2	P-value	R^2	P-value
RF	0.391	0.01	0.768	0.057	0.824	0.046
Tmax	0.305	0.06	0.751	0.03	0.796	0.046
SOI	0.205	0.08	0.46	0.042	0.284	0.035

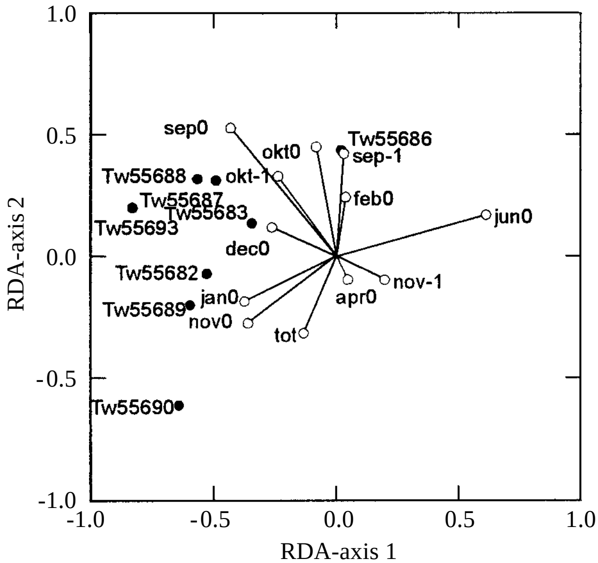

Fig. 4. Biplot of the RDA of 8 growth ring series of *Isoberlinia tomentosa* (Tw) and monthly rainfall.

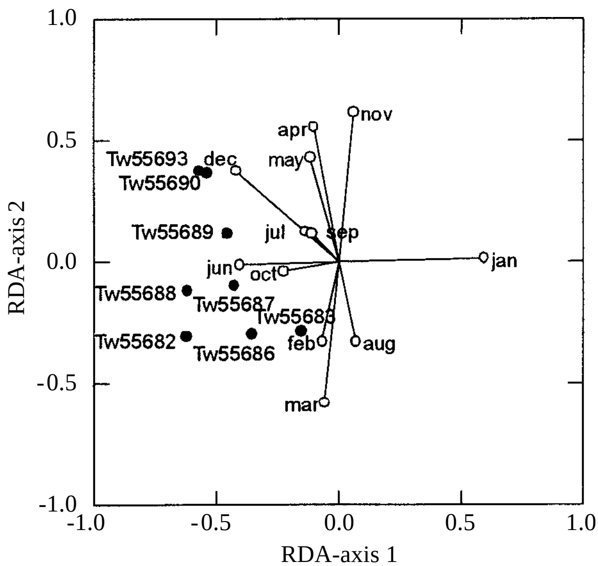

Fig. 5. Biplot of the RDA of 8 growth ring series of *Isoberlinia tomentosa* (Tw) and monthly maximum temperature.

axis, as this axis explains 39.1% of the variance between growth ring widths. All sample scores are negative along the first axis, except for the score of sample Tw 55686. This is an indication of the strong cross-correlation between the samples, which was found earlier in the cross-correlation function analysis. The precipitation of the month of June is strongly negatively related to the growth ring widths.

The results of set correlation analysis and multiple linear regression show a significant and strong negative response of the growth ring widths to the precipitation of the month of June.

In the response function analysis with the temperature dataset, significant results were found only for the monthly maximum temperature. The overall correlation for this climatic factor was strong and significant by the three methods (Table 2).

The RDA biplot scores of growth ring series and monthly maximum temperatures are shown in Figure 5. The first axis explains 30.5% of the total variance. The sample scores are all negative along this axis. The maximum temperature of the month of January has a strong positive score, indicating a negative correlation with the growth ring width. This result is corroborated by the SCA and MLR analyses.

With the dataset containing the SOI values, significant correlations were found only for data of the year prior to the growth year (Table 2).

Figure 6 shows the biplot of the RDA between the growth ring series dataset and the SOI value dataset. The first axis explains 20.5% of the total variance between growth ring widths. The scores of the different growth ring series along this axis are all positive. The SOI value of the month of July is the only SOI value having a negative score and thus indicating a negative correlation with growth ring width. The strongest positive correlation is found for the month of June.

The results of SCA and MLR show a significant and strongly positive relation between the SOI value of June and growth ring width for both methods. A significant and strongly negative relation is found for the SOI value of July.

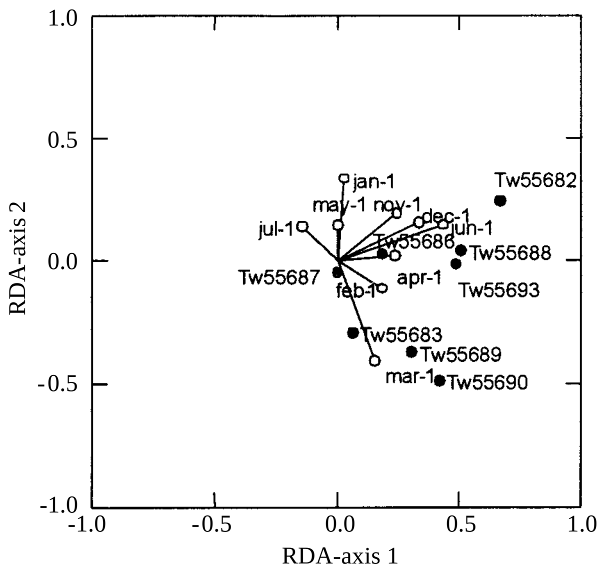

Fig. 6. Biplot of the RDA of 8 growth ring series of *Isoberlinia tomentosa* (Tw) and monthly SOI-values.

Brachystegia spiciformis

Cross-dating and standardisation

Cross-correlation between ring series of different radii, adjusted according to the hypothesis of locally false rings, was usually significant at lag 0. Sometimes a significant correlation was found at lag –1 or lag –2. After calculation of the average series for each tree, ACF-analysis revealed a significant trend for five series. Removal of the trend using differentiation was only successful for two samples. ACF-analysis after differentiation for the other three series revealed that a significant positive autocorrelation was replaced by a significant negative autocorrelation at lag 1 or lag 2. Standardisation by means of moving-average could not improve these results. Since the autocorrelations at lag 1 only exceeded the level of significance (two times standard deviation) slightly, two datasets were used in further analysis, one with and one without trend removal.

Cross-correlations between the average growth ring series of the trees were seldom significant. Only the two series without locally absent rings could be synchronised. Six other series showed a slight correlation at lag 0, but not significant. These low correlations make it impossible to build a chronology for this site.

These results were found using the second method to edit the original growth ring series. Using the first method, cross-dating between trees gave even lower correlations. Therefore only the growth ring series edited according to the second method were used for further analysis.

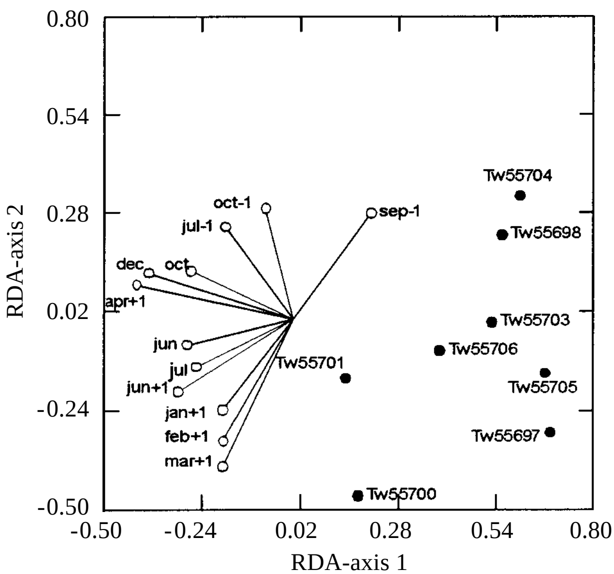

Fig. 7. Biplot of growth ring series of *Brachystegia spiciformis* (Tw) and monthly SOI-values.

Response function analysis

Although no chronology could be built for the site, theoretically individual trees could bear some climatic information. Therefore a matrix of eight growth ring series was made. These eight series show mutual, although low and not significant, correlation. Using RDA-analysis, combined with a Monte Carlo-test, a remarkable correlation was found between the SOI values and the ring width series. Though the overall test was not significant (p = 0.28), the first axis explained 32% of the variation in a significant way (p = 0.01). A biplot (Fig. 7) suggests a negative correlation between cambial activity and SOI-values.

The RDA-analyses using monthly data of relative humidity and average temperature gave similar results, but were not significant for the overall test (0.09 and 0.12). Visualising the biplots of these analyses did not reveal any clear relations, but the canonical regression coefficients of the first axis of these two RDA-analyses were similar. The months with significant t-values for the canonical regression coefficient on the first axis are in both cases November (year –1), April and June (Fig. 8a, b).

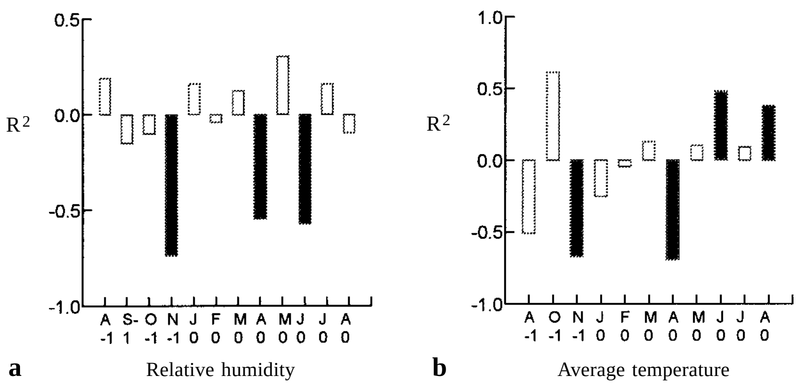

Fig. 8. Canonical regression coefficients of the first axis of the RDA-analysis with growth ring series and monthly values of (a) relative humidity and (b) average temperature.

Although these analyses gave similar results, it remained impossible to draw definite conclusions.

DISCUSSION

Although it was possible to build a representative mean growth curve based on eight out of thirteen samples for *Isoberlinia tomentosa*, the cross-dating of eleven samples of *Brachystegia spiciformis* proved impossible. A key aspect could be degree of deciduousness. Temporal correlations between phenology and cambium activity of tropical and subtropical trees have been described in an early study by Coster (1927/1928) in Indonesia. A clear seasonal segregation of leaf flush and leaf fall is an important condition for the formation of annual growth rings (Borchert 1999). Most species of the miombo woodland are, however, semi-deciduous, shedding the old leaves simultaneously with the flushing of the new leaves, and this a few weeks before the start of the wet season (Campbell 1996).

Deciduousness is not only species-dependent, but also site-dependent (Borchert 1999). *Brachystegia* is known to be semi-deciduous under good conditions and deciduous under dry conditions. The total sample not only encompassed two species, but also two sites. Both factors could have caused differences in deciduousness and thus in cross-dating potential. Moreover, deciduousness also shows a year-to-year variability. The same trees can flush after the onset of the wet season one year and weeks before the onset of another year. This year-to-year variability could be a contributing factor to the appearance of growth ring anomalies.

Growth ring anomalies appeared frequently in both species and were an obstacle for the cross-dating of the growth ring series. Glock and Agerter (1962) showed that discontinuous rings are common in summer rainfall areas, where most water becomes available after growth initiation. Local supply of carbohydrates, water, mineral elements and phytohormones (Dünisch et al. 1999) and genetic potential (Lamarche et al. 1982) can also be of high importance to the cambium. In addition to this, wood samples of stumps were used for the analyses, which often have missing rings and an atypical formation of increment zones (Table 1). Therefore, sampling at different tree heights could prove necessary for accurate annual dating of growth increments.

Ring anomalies were considered as locally absent rings in *Isoberlinia* and as false rings in *Brachystegia*. This could possibly explain the difference between the two species. However, different literature sources support the first methodology used (Norton et al. 1987; Schweingruber 1996; Povoa de Mattos et al. 1999), which is based on the theory of ring wedging.

Indications about the annual nature of growth within *Isoberlinia tomentosa* are given by the possibility to cross-date the different radii of each tree and to cross-date between trees for eight out of thirteen trees. In addition to this, significant responses were found to several annual time-series of pertinent climatic factors. For *Brachystegia spiciformis*, the indications were less clear, as they are restricted by the appearance of growth ring anomalies and by the short length of the growth ring series.

The relations found between the growth ring series of *Isoberlinia tomentosa* and several climatic factors are not mere indications of the annual character of the growth rings. The results of the transfer function analysis determine the potential for climate reconstruction. For this study, however, only few meteorological data were available, which interferes with the reconstruction of long-term climatic phenomena like ENSO.

The response of the growth ring width to the rainfall of June (the first dry month after the wet season) corresponds with the results of Pumijumnong et al. (1995). They found that the cambium activity of teak growing in monsoon forests varies strongly with interannual rainfall variation during the low-rainfall months preceding and following the heavy monsoon rains.

Growth ring widths respond significantly and in an opposite way to fluctuations in the maximum temperature of January. In Katanga, which has the same climate regime as the Kigoma region, a short dry season occasionally occurs in the month of January.

This dry period is mostly characterised by an increase in temperature (Malaisse, personal communication). According to our results, this short dry season could have a negative influence on the growth of *Isoberlinia tomentosa.*

Growth ring width responded significantly to the SOI values of the months of June and July of the year previous to the growth year. There was no direct link, however, between the significant responses to the SOI values and the responses to the other climatic variables. The absence of a direct link can be explained by the lag of 4 months in average between the occurrence of the ENSO phenomenon in the Pacific and its effects in equatorial eastern Africa (Plisnier 1998). The variability of this lag makes exact comparison with climatic data difficult. Next to this, the effects of ENSO in the Kigoma region are ambiguous. The region is in the centre of an anomaly-dipole between eastern and southern Africa, which makes unambiguous interpretation of the relations difficult.

In order to get a decisive answer to the annual character issue, cross-correlations have to be made with chronologies of other sites in the region (Stahle 1999). This can also contribute to a representative reconstruction of the climate in the region. Furthermore, cambial growth rhythms can be monitored (applying dendrometer measurements, pin-marker-techniques or microscopy of wood samples) and blind cross-dating tests can be performed to ascertain the annual nature of the rings and to interpret the relations found with climatic factors.

The response of the *Isoberlinia tomentosa* dataset was equally strong to the monthly average rainfall dataset as to the monthly maximum temperature dataset. The correlations with the monthly SOI value were considerably less strong, but still significant. Considering a lag of 4 months between the occurrence of the ENSO-signal in the Pacific and its influence in eastern Africa (Plisnier 1998), the strongest relations were found for the SOI values of the months October and November of the year –1. This agrees with the results of D'Arrigo and Jacoby (1992), who found the strongest correlation between SOI values and growth ring series for the winter prior to the growth year.

Tree ring records are especially suitable as proxy data for dendroclimatic studies, if long-time series with many repeats of trees are available (Fritts et al. 1971; Cook 1992). In this work, a limited number of samples from mainly young trees was studied. This increases the danger of uncertain results, caused by a high variability between individuals and an atypical growth dynamic of the trees, due to a high portion of juvenile wood.

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