

Climate–growth relationships of the dominant tree species from semi-arid savanna woodland in Ethiopia

Aster Gebrekirstos · Ralph Mitlöhner ·
Demel Teketay · Martin Worbes

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Abstract Long-term climate–growth relationships, were examined in tree rings of four co-occurring tree species from semi-arid *Acacia* savanna woodlands in Ethiopia. The main purpose of the study was to prove the presence of annual tree rings, evaluate the relationship between radial growth and climate parameters, and evaluate the association of El Niño and drought years in Ethiopia. The results showed that all species studied form distinct growth boundaries, though differences in distinctiveness were revealed among the species. Tree rings of the evergreen *Balanites aegyptiaca* were separated by vessels surrounding a thin parenchyma band and the growth boundary of the deciduous acacias was characterized by thin parenchyma bands. The mean annual diameter increment ranged from 3.6 to 5.0 mm. *Acacia senegal* and *Acacia seyal* showed more enhanced growth than *Acacia tortilis* and *B. aegyptiaca*. High positive correlations were found between the tree-ring width chronologies and precipitation data, and all species showed similar response to external climate forcing, which supports the formation of one tree-ring per year. Strong declines in tree-ring width correlated remarkably

well with past El Niño Southern Oscillation (ENSO) events and drought/famine periods in Ethiopia. Spectral analysis of the master tree-ring chronology indicated occurrences of periodic drought events, which fall within the spectral peak equivalent to 2–8 years. Our results proved the strong linkage between tree-ring chronologies and climate, which sheds light on the potential of dendrochronological studies developing in Ethiopia. The outcome of this study has important implications for paleoclimatic reconstructions and in restoration of degraded lands.

Keywords Tree-ring width · *Acacia* species · *Balanites aegyptiaca* · Climate change · Dendrochronology

Introduction

The open savanna woodlands in Ethiopia, which have been estimated to cover 30% of the total land area of the country (FAO 1981), have suffered from deforestation (Argaw et al. 1999; Gebrekirstos 2006). In this connection, there are many visible symptoms of the adverse effects on the livelihood of the local population today. Restoration of the degraded landscapes will play a vital role in facilitating sustainable development (Lemeneh et al. 2004) and is therefore highly desirable. Management of woodlands on a sustainable basis is a challenge for people living in many arid and semi-arid areas of the world. For the development of sustainable silvicultural systems, for instance, knowledge of the long-term diameter increment growth of tropical forest trees and their reaction to climate is essential (Worbes 1999). However, knowledge of growth rates of tropical trees in general is extremely poor (Worbes et al. 2003). Despite their practical importance, the growth rate

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A. Gebrekirstos (✉) · R. Mitlöhner
Institute of Silviculture, Sect. II: Tropical Silviculture,
Georg-August University of Göttingen, Büsgenweg 1,
37077 Göttingen, Germany
e-mail: agebrekirstos@yahoo.com; agebrek@gwdg.de

D. Teketay
Forest Stewardship Council, African Regional Office,
P.O. Box UP 805, Kumasi, Ghana

M. Worbes
Institute of Agronomy in the Tropics, Georg-August University
of Göttingen, Grisebachstrasse 6, 37077 Göttingen, Germany

of woodland species in arid and semi-arid conditions are even dismissed as being low in comparison with most forest types (Gourlay 1995) and less documented than the closed forest (Eshete and Ståhl 1999). Hence, this study will provide growth rate data for managing important open savanna trees.

Furthermore, the effects of deforestation and land degradation are compounded by recurrent droughts. Severe droughts are the principal climate-related disaster in Ethiopia and their impact, i.e., in the form of famine and human migration, has been felt for a long time. Drought periods in Ethiopia were related to El Niño Southern Oscillation (ENSO) (Tesfaye 1988; Bekele 1993). Hence, information on ENSO has been used to forecast drought after the catastrophic 1983–1984 event. By making use of such information, for example, the Ethiopian Government managed to reduce the consequences of severe drought on people due to the 1987/1988 ENSO (Bekele 1993). However, the absence of long-term meteorological information in various parts of the country has been one of the major problems hindering effective long-term weather forecasting (Tesfaye 1988). This problem calls for urgently identifying potential proxies that can provide information about past climatic events.

Since tree rings have long been acknowledged as indicators of annual climatic information, radial growth responses can indicate the reaction of trees to past periodic droughts (Orwig and Abrams 1997), an eco-physiological record of past climate and ecological conditions (Sass and Eckstein 1995) and ENSO events (Cook 1992). Hence, long-term series of tree-ring width chronologies could be used as a proxy to reconstruct past climatic events. For example, dendrochronology has been widely applied in paleoclimate studies in the temperate climates, where the strong climate seasonality induces annual ring formation (e.g., Schweingruber et al. 1990). However, it has been widely assumed that tropical trees do not form annual wood rings (Lang and Knight 1983; Lieberman et al. 1985; Whitmore 1998). Contrary to this assumption, many authors have succeeded in using tree-ring measurements on tropical trees to determine tree age, understand growth dynamics and support ecological and climate studies, e.g., in the Amazon (Vetter and Botosso 1989; Worbes et al. 1992; Schöngart et al. 2004), Africa (Gourlay 1995; Stahle et al. 1999; Eshete and Ståhl 1999; Worbes et al. 2003; Eshetu and February 2003; Fichtler et al. 2004, Schöngart et al. 2006, Therrell et al. 2006), Central America (Enquist and Leffler 2001) and Asia (Pumijumnong 1999). This was possible since many tropical areas have at least two months of arid conditions, which induce cambial dormancy and trigger formation of growth boundaries (Worbes 1995). Formation of two rings per year was reported in areas with two distinct dry seasons (Jacoby 1989; Wayant and Reid 1992; Gourlay 1995) and fewer rings

than their age in moist conditions (Eshete and Ståhl 1999). Eshete and Ståhl (1999) who evaluated the growth periodicity of acacia in Ethiopia, demonstrated statistically significant precipitation-growth relationships for 12 years (1982–1994). According to Pilcher (1990), to gain reliable results with regard to climate growth relations, the overlap of cross-dated time series should reach a minimum of 40 years. Apart from the acacias, a recent dendrochronological study on *Juniperus procera* in a dry Afromontane forest (Couralet et al. 2005) indicated the dendrochronological potential of this species for reconstructing precipitation and studying forest growth and population dynamics in Ethiopia. Other dendrochronological pilot studies on *Juniperus procera* and *Prunus Africana* reported yearly river discharge reconstructed from tree-ring width (Wils and Eshetu 2007). In light of these early studies, our purpose is to demonstrate, on the basis of long time-series, that tree rings in tropical Africa can be used as a tool for dendroclimatic and dendroecological applied research.

Hence this study focused on the dominant trees growing in arid and semi-arid Ethiopia, namely: *Acacia tortilis* (Forssk.) Hayne, *Acacia seyal* Del, *Acacia senegal* (L.) Wild., and *Balanites aegyptiaca* (L.) Del. The specific objectives of the study were to: (a) prove the presence of annual tree rings and understand tree growth dynamics of four naturally co-occurring tree species; (b) evaluate long-term growth patterns and the relationship between radial growth and climate parameters; and (c) evaluate the association of ENSO and drought/famine years in Ethiopia with tree-ring pointer years.

Materials and methods

Study area and species

The study was undertaken in the *Acacia* woodland in Abernosa, which is located within the upper Rift Valley lakes sub-region about 170 km south of Addis Ababa, 7°51' N, 38°42' E at an elevation of about 1,600 m. It is characterized by a distinct dry season, with no or erratic rain of less than 40 mm per month between October and February. The major and minor rainfall periods are from June to September and March to June, respectively, and the wettest month is July (142 mm). Average annual precipitation, measured at Adami Tulu Research Center Metrological Station about 5 km away from the study area, was 760 mm and ranges between 550 and 900 mm (Fig. 1). The mean annual temperature is 20.7°C and varies little from year to year. The underlying parent material of the study area is characterized by acidic lava, ash and pumice interbedded with lacustrine siltstone and sandstones (Makin et al. 1975). The soils are sandy loam with pH of 6.75.

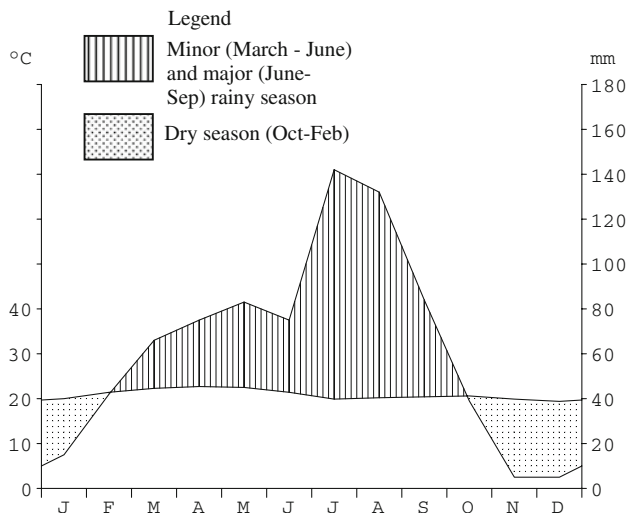


Fig. 1 Climatic diagram of the study site (in Abernosa) drawn according to Walter (1973). Rainfall (mm) and temperature (°C) data (1980–2002) were obtained from Adamitulu Research Station, which is situated at about 5 km from Abernosa

The area is classified as a semi-arid ecoclimatic vegetation zone (Makin et al. 1975), and is a major part of the country's *Acacia* woodland and savannah region (Argaw et al. 1999). Large areas of the woodlands have been deforested and converted to arable and grazing lands. However, there was a cattle ranch protected from open access to grazing, tree cutting and settlement inside the boundary as a reference site of relatively undisturbed vegetation. The density of the trees was comparatively higher with a relatively closed canopy compared to the surrounding communal lands with an open access to grazing and cultivation. The communal and cultivated lands were part of the ranch until 1994. The most dominant tree species in the study area are *A. tortilis*, *A. seyal*, *A. senegal* and *B. aegyptiaca* (Gebrekirstos et al. 2006).

Hence, these species were analyzed for this study. The acacias are drought deciduous and are members of Fabaceae family, while the evergreen *B. aegyptiaca* belongs to Balanitaceae (Table 1). All the species are economically important, found all over Africa in arid, semi-arid and sub-humid savannah. The ecology, morphological description, and use of the study species are described elsewhere (Azene Bekele et al. 1993; Hedberg and Edwards 1989) as is their leaf shedding behavior and adaptation to water stress (Gebrekirstos et al. 2006).

Tree-ring sampling

For each species two wood cores per tree were collected exclusively from the ranch in 2002 from ten trees, using an increment borer. Up to seven stem disks were collected for each species from fallen trees of known felling age from the ranch, adjacent community grazing and cultivated lands as well. However, the growth bands were extremely difficult to detect in the increment cores, in most cases, due to wedging rings and/or the presence of dark heartwood. About 60% of the stem disks collected from communal grazing lands and agricultural lands were not cross-datable as well. This was due to possible missing rings caused by human disturbances. Thus, the increment cores of all the species and the problematic stem disks were excluded. Instead, additional stem disks were collected exclusively from the ranch in 2003. The number of stem disks investigated, for each species, are indicated in Table 1.

Tree-ring analysis

Standard dendrochronological methods were used to prepare the samples for measurement. The surfaces of the stem disks were sanded gradually using sand paper of grit

Table 1 List of studied species with summary of their habit and annual growth increment

Species	Habit	N	Range in ages and time span	dbh (cm)	Annual radial growth (mm)		
					Mean	Maximum	Minimum
<i>A. senegal</i>	Deciduous shrub/tree, up to 10–15 m	8 (6)	28–69 (1937–2003)	12.4–34.3	2.53 ± 0.35 (a)	9.12 ± 0.92 (a)	0.30 ± 0.15 (a)
<i>A. seyal</i>	Deciduous tree up to 9 m	7 (6)	25–67 (1939–2003)	15.8–27.7	2.32 ± 0.66 (a)	7.89 ± 1.85 (a)	0.27 ± 0.13 (a)
<i>A. tortilis</i>	Deciduous tree, 4–21 m	9 (8)	35–93 (1927–2003)	12.2–34.8	1.81 ± 0.46 (a)	5.25 ± 1.64 (b)	0.34 ± 0.29 (a)
<i>B. aegyptiaca</i>	Evergreen small tree up to 8 m	6 (4)	50–70 (1936–2003)	19.4–27.2	1.93 ± 0.30 (a)	4.58 ± 0.74 (b)	0.40 ± 0.14 (a)

N = number of stem disks investigated with successfully cross-dated trees in parenthesis (Note: from the successfully cross-dated trees, for *A. senegal* (2), *A. seyal* (1), *A. tortilis* (3) trees are from the community areas, while for *B. aegyptiaca* (4) of them are from the ranch); age range in years and time span in parenthesis; diameter range of the stem disk (dbh); annual radial increment (mean, maximum and minimum) with standard deviations calculated from tree ring measurements (number of trees used in parenthesis). Within a column, means followed by different letters were statistically different at $P < 0.05$

size 80–600. To improve visibility of the growth zone boundaries, the wood dust was removed with compressed air. Tree-ring width was measured to the nearest 0.01 mm with a semi-automatic device (LINTAB, Rinn tech, Heidelberg, Germany), which consists of a stereomicroscope and a moveable board linked to a distance measuring device and a personal computer. To produce mean curves for each sample, ring width curves of individuals, from 2 to 4 radii, were cross-dated visually using pointer years (extreme wide or narrow rings). The pointer years allowed possible errors due to missing rings or false rings to be corrected (checked), hence the conditional dates were shifted in some cases to obtain a maximal similarity (match) between different curves. Furthermore the similarity of individual curves were tested statistically with the computer program Time Series Analysis and Presentation (TSAP) (Rinn and Jäkel 1997), which allowed: (a) the measurement of “Gleichläufigkeitskoeffizient” (GLK): the percentage year-to-year harmony in the fluctuation of two curves within the overlapping period (Schweingruber 1988); (b) the calculation of student’s *T*-values that convey the degree of similarity of two curves (Baillie and Pilcher 1973); these statistics (a and b) were used in selecting the best correlated series to include for building mean chronologies; and (c) indexing: the removal of individual and long-term growth trends from the mean curves by division of a running mean of 5 years (Baillie and Pilcher 1973; Schweingruber 1988), which is indispensable to obtain an interpretable correlation coefficient with climate data (Cook and Briffa 1990).

Using the same method, successfully cross-dated mean ring width series of different sample trees were averaged to build species-specific mean chronologies. A master site chronology, with a length of 68 years, was further constructed by building the mean of the four species. In constructing species mean chronologies, the juvenile part of the wood (3–6 years) was excluded for two reasons. As mentioned by Worbes (2002) and others, it is the experience of most dendrochronological studies that compared to the mature part of the wood, juvenile wood reacts differently to drought physiologically due to competition. Moreover, browsing effects at seedling and sapling stages could be significant in the present study area, which may mask climate related signals in the tree rings.

Growth analysis

Tree-ring measurements were carried out on the longest radii. To minimize over or under-estimation of tree diameter annual radial increments were corrected by multiplying their values with the correction factor using the following formula:

$$\text{Correction factor} = (\text{Provisional diameter/actual diameter}) \times 100,$$

where provisional and actual diameters were measured from tree rings and a measuring tape, respectively.

Climate data

Precipitation and temperature data recorded since 1980 were obtained from a weather station at Adamitulu. Since the period covered by this station and others close to the study area was too short to gain reliable climate–growth related information, precipitation data during the period of 1930–1980 were obtained from the National Center for Atmospheric Research (<http://ncardata.ucar.edu/datasets>) for Region 27 as defined by Nicholson (2001). Nicholson (2001) regionalized the African continent according to climatic homogeneity with respect to the inter-annual variability of rainfall. Each region contains enough overlapping years to generate a long-term record. Therefore, mean monthly precipitation data from six identical climate areas (Region 27) for the period of 1930–1980 were calculated to obtain composite long-term mean monthly and annual precipitation series.

Data analyses

To evaluate and determine climate–growth relationships, the indexed mean ring width curves of each species and the master chronology were compared with indexed values of precipitation data from Adamitulu (22 years) (hereafter referred to as Adamitulu precipitation), and the long time series (66–73 years) derived from Nicholson (2001) (hereafter referred to as NCAR precipitation). We used correlation coefficients obtained between the tree-ring index and Adamitulu precipitation values for the purpose of species comparisons, since the Adamitulu precipitation data were collected close to the study site. Indexed values of annual and major rainfall period (June–September) precipitation were separately checked for correlations with indexed ring width mean curves. Single spectrum analysis of the master chronology was also carried out to examine periodic events in time series (Jenkins and Watts 1968). Radial growth comparisons among the species were determined using one-way analysis of variance (ANOVA). When significant variations in the ANOVA were revealed, means were ranked using Tukey’s test (Fowler et al. 1998). STATISTICA for Windows (Version 6.0) was used for the data analysis. Unless stated otherwise, results are statistically significant at $P < 0.05$.

Results

Tree-ring formation

All studied tree species form distinct tree-ring boundaries. The growth ring boundary of the acacias are characterized by thin parenchyma bands, which run around the entire stem disc (Fig. 2a–c). A thin parenchyma band and the accumulation of vessels characterize tree-rings of *B. aegyptiaca*. Additionally, when the rings are crossed with rays, the rays appear broader (Fig. 2d). The distinctiveness of the growth rings vary among the species. Among the deciduous species, *A. seyal* shows less distinct growth rings than *A. senegal* and *A. tortilis*. In *A. seyal* the vessels often mask the finer marginal band, which makes identifying the growth zones complicated. The growth rings of *B. aegyptiaca* are the least distinct. All the species show wedging rings, though the wedging rings are more apparent on *B. aegyptiaca*.

Radial growth

The width of rings varied considerably between years and among the species (in average maximum ring widths). Mean ring width differed regardless of their age class. Individual ring width of *A. senegal* and *A. seyal* range from 0.27 to 9.12 mm with overall means of 2.53 ± 0.35 and 2.32 ± 0.66 mm, respectively. *A. tortilis* and *B. aegyptiaca* showed significantly narrower ring width ranging from 0.34 to 5.25 mm with overall means of 1.81 ± 0.46 and 1.93 ± 0.30 mm, respectively (Table 1).

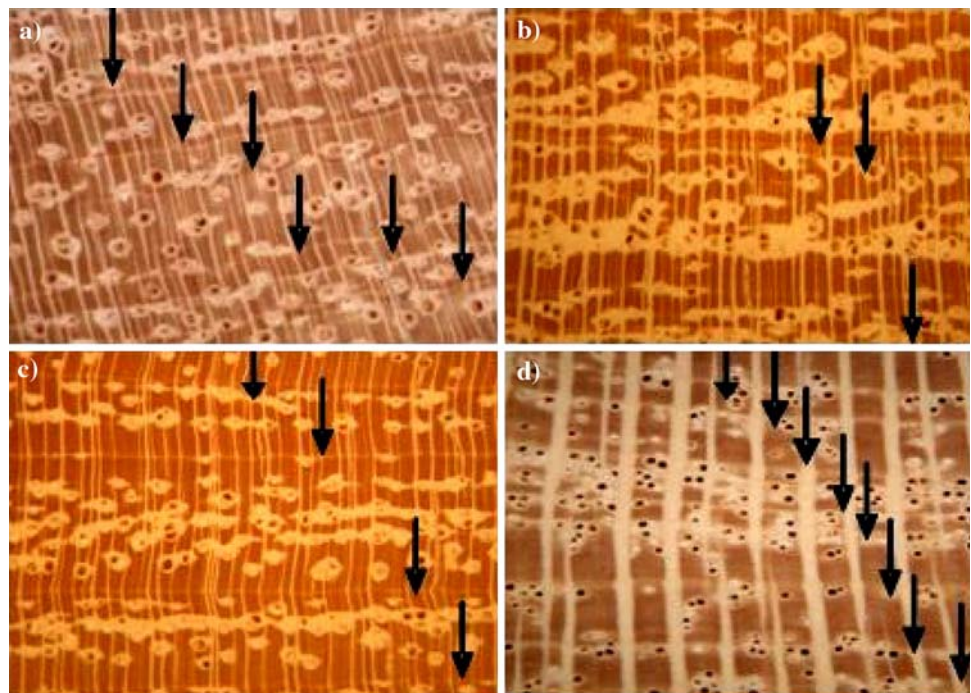
Cross-dating

Cross-dating between radii of the same disks and of different trees was successful in most cases. However, some stem disks collected from communal grazing lands and agricultural lands were not cross-datable. Cross-dating was successful for six out of eight trees for *A. senegal* and six out of seven trees for *A. seyal*, ranging in length between 25 and 69 years (Table 1). For *A. tortilis*, eight out of nine trees, ranging in length between 35 and 93 years, were cross-datable. The mean chronology for *A. tortilis* was constructed with a length of 73 years since the longest (93 years) was contributed only from one tree. *B. aegyptiaca* had the lowest number of cross-datable individual disks, i.e., four out of six trees (Table 1). Cross-dating of the four different species was successful for 22 out of 30 trees with a mean (GLK %) range of 61–75%.

Species response to precipitation

The individual (species) mean ring width curves showed annual patterns similar to seasonal precipitation. The high similarities are evident in the graphs between indexed major rainfall season precipitation data and mean ring width series (Fig. 3). In general, all the species showed high GLK % and *T*-values with both annual and major rainfall season precipitation (June–September) and notably with Adamitulu precipitation. Further, simple regression analyses indicated significant positive relationships between annual radial increments and both annual and

Fig. 2 Cross-sections of **a** *A. senegal*; **b** *A. seyal*; **c** *A. tortilis*; and **d** *B. aegyptiaca*. The arrows indicate annual growth boundaries



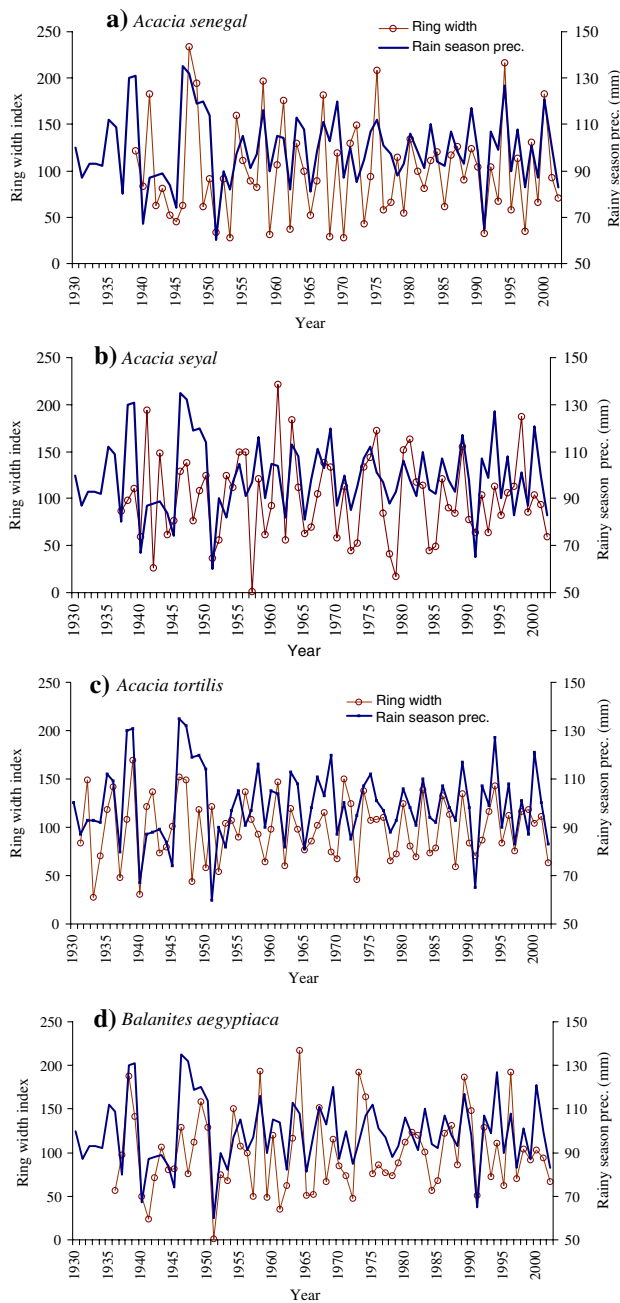


Fig. 3 Ring width indices of **a** *A. seyal*; **b** *A. senegal*; **c** *A. tortilis*; **d** *B. aegyptiaca* and major rainy season precipitation (June–September)

major rainfall season precipitations for all the species. For the deciduous species, except *A. senegal*, annual radial growth correlated more strongly with major rainfall season than annual precipitation recorded at Adamitulu. Of all the species, *A. seyal* appeared most sensitive to major rainfall season fluctuations with the highest correlation coefficient ($r = 0.77$), while *B. aegyptiaca* revealed the highest correlation ($r = 0.66$) with annual precipitation (Table 2).

Site master chronology, tree-ring pointer years, drought periods and ENSO events

The master chronology showed strong similarity to major rainy season precipitation (Fig. 4). The percentage of parallel run (GLK%) and T -values between the master chronology, and both annual and major rainy season precipitation were higher than mean curves of the individual species. The master chronology also showed strong positive significant correlation with major rainy season and annual precipitation, particularly with Adamitulu precipitation (Table 3).

A close look at the master ring width curve (Fig. 4) indicated that tree-ring width was depressed from 1942 to 1945. In contrast to the decline in tree-ring width in the extreme drought years, the ring width increased concurrent with the wet years, notably from 1946 to 1950. There were distinct pointer years with narrow rings in 1951/1952, 1955–1957, 1962 and 1965/1966. Despite some recovery in 1971, 1975 and 1980/1981, there was a slowdown in growth from 1970 to 1985 with sharp declines in 1970, 1972/1973, 1977–1979 and 1984/1985, whereas frequent narrow rings appeared every 2–3 years in the 1990s with sharp decline in 1991. When strong declines in tree-ring width were compared with past ENSO events and drought/famine years in Ethiopia, they show a remarkable correlation (Table 4; Fig. 4). Single spectrum analysis of the master chronology also revealed periodically recurring events. The peaks for the year 1937–2002 were in the frequency areas of 0.14, 0.22, 0.35 and 0.45 equivalent to periods of 7.1, 4.6, 2.7 and 2.2 years, respectively. The peaks in the frequency areas of 0.14, 0.35 and 0.45 are significant ($P < 0.05$) (Fig. 5).

Discussion

When plant water potential reaches its permanent wilting point during the dry season, drought deciduous species shed their leaves (Mitlöhner 1997; Gebrekirstos et al. 2006), and evergreen and deciduous species enter a period of cambial dormancy, which implies formation of growth boundaries (Worbes 1999). In agreement with this reasoning, both the evergreen and deciduous species showed distinct growth rings. Our results also agree with previous studies, which showed that acacias form distinct annual growth rings characterized by marginal parenchyma bands (Eshete and Ståhl 1999; Gourlay 1995, Gammadid 1989). The growth zones of *B. aegyptiaca* were separated by the accumulation of vessels associated with very thin parenchyma bands at the limits of growth zones.

Though all species showed the formation of growth rings, rings in deciduous acacias were more distinct than

Table 2 Summary of Gleichläufigkeitskoeffizient (GLK%), *T*-value (TV), Overlap period in years (OVL) and correlation coefficients (*r*) between tree ring width indices and annual and major rainy season precipitation (mm)

Precipitation periods	<i>Acacia senegal</i>				<i>Acacia seyal</i>				<i>Acacia tortilis</i>				<i>Balanites aegyptiaca</i>			
	OVL	GLK	TV	<i>r</i>	OVL	GLK	TV	<i>r</i>	OVL	GLK	TV	<i>r</i>	OVL	GLK	TV	<i>r</i>
Annual ^a	67	72	4.5	0.43	64	73	3.2	0.46	73	68	4.0	0.42	67	65	6.1	0.53
Rain ^a	67	73	4.4	0.43	64	74	3.8	0.53	73	71	4.0	0.43	67	75	6.6	0.59
Annual ^b	22	82	4.8	0.56	22	78	3.0	0.42	22	72	4.6	0.53	22	92	4.5	0.66
Rain ^b	22	85	3.7	0.46	22	85	4.4	0.77	22	80	4.2	0.64	22	90	3.6	0.60

^a NCAR precipitation

^b Adamitulu precipitation

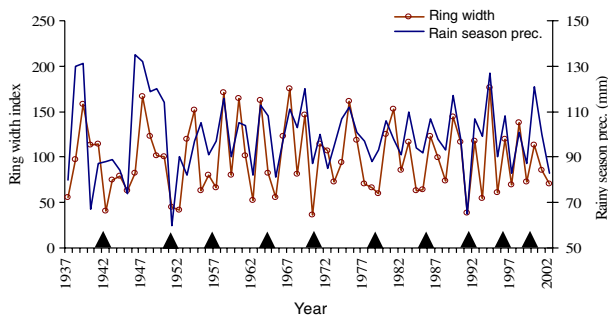


Fig. 4 Master ring width indices of the four species and major rainy season precipitation (June–September). Arrows indicate pointer years (extreme narrow rings)

Table 3 Summary of Gleichläufigkeitskoeffizient (GLK %), *T*-value (TV), overlap period in years (OVL) and correlation coefficients (*r*) between master ring width indices and annual and major rainy season precipitation (mm)

Precipitation periods	Master chronology			
	OVL	GLK	TV	<i>r</i>
Annual ^a	67	80	6.2	0.59
Rain ^a	67	76	6.1	0.61
Annual ^b	22	92	5.5	0.64
Rain ^b	22	98	6.0	0.79

^a NCAR precipitation

^b Adamitulu precipitation

the evergreen *B. aegyptiaca*. A tendency for distinct ring formation by deciduous species compared to evergreen species was reported by (Worbes 1999), and distinctiveness was related to wood structure differences, which is genetically controlled (Detienne 1989; Worbes 1995). In addition to its wood structure, the frequent occurrences of wedging rings in *B. aegyptiaca* made the determination of growth boundaries more difficult. Wedging rings are believed to result from competition of species growing under poor light conditions (Worbes 2002). Since our study

was conducted in open savanna woodlands, competition for light was unlikely. Nevertheless, competition for water resources is certain, which could cause uneven distribution of resources to initiate growth around the full circumference. Fire could have contributed to the formation of wedging rings as well. However, we did not observe fire scars in the stem disks investigated. Hence the formation of wedging rings could be attributed to genetic prerequisite (Lamarche et al. 1982) or to reduced water resources. The analyses of stem disks enhanced the detection of such ring irregularity by tracking the ring boundaries around the entire cross-section (Worbes 1995; Eshete and Ståhl 1999).

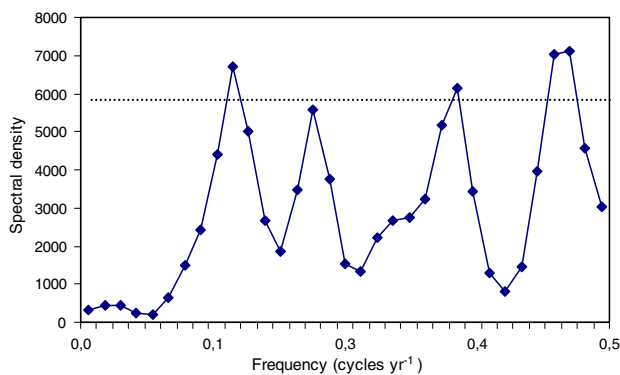
Cross-dating of the ring widths was mostly successful except for some stem discs collected from communal grazing and cultivated lands. This was due to possible missing rings. It is a common practice in the study area to prune (pollard) tree branches growing in cultivated lands to minimize competition with agricultural crops during the major rainy season and to cut branches for fuel wood and fodder from communal grazing lands. Since the photosynthetically active part of the tree would be removed by pollarding, it obviously would disrupt the normal growth of the trees. It is worth noting that the communal areas were part of the ranch until 1994, so the few trees successfully cross-dated from the communal areas (Table 1) were possibly not affected by human disturbances. Hence, our findings agree with Schweingruber (1996) that only trees from sites in undisturbed forests provide information useful for dendroclimatology.

The tree-ring chronologies presented (Fig. 2) are the first for *B. aegyptiaca* and the longest chronology, so far, for the acacias in Ethiopia. The coherent pattern of tree-ring series among the chronologies of four species suggest that an external factor, precipitation, affected the species in a similar way (Table 2). Therefore the high positive correlations found between the chronologies and the precipitation variables may substantiate the formation of one tree-ring per year (annual nature of the growth rings). This is in agreement with the findings of Eshete and Ståhl

Table 4 Tree ring pointer years compared with chronology of ENSO events and drought in Ethiopia

Pointer years	El Niño years	Drought/famine	Regions
1933–1934	1930–1932	1932–1934	Ethiopia
1942–1945	1939–1942	Not reported	
1951–1953	1951–1952/1953–54	1953	Tigray and Wollo
1955–1957	1957–1958	1957–1958	Tigray and Wollo
1962	1963	Not reported	
1965	1965/1966	1964–1966	Tigray and Wollo
1970	1969–1970	1969	
1972–1973	1972–1973	1973–1974	Tigray and Wollo
1977–1979	1976–1977	1978–1979	
1984–1985	1982–1983	1984–1985	Ethiopia
1988	1986–1987	1987–1988	Ethiopia
1991	1991–1992	1991–1992	Ethiopia
1993	1993	1993–1994	Tigray, Wollo, Addis
1995	1994–1995	Not reported	
1997	1997–1998	1997–1998	Ethiopia
1999		Not reported	
2002		2002	Ethiopia

Extreme narrow rings of the master chronology (Fig. 4) and *A. tortilis* for the year 1930–1937 (Fig. 3) were selected as pointer years. The ENSO years drought/famine and their respective regions are from literature review (Degefu 1987; Wolde-Georgis 1997; Trenberth 1997)

**Fig. 5** Single spectrum analysis of the master ring width chronology. Frequencies at which the density peaks exceed the value of the dotted horizontal line are significant ($P < 0.05$)

(1999) who reported that the acacias growing in dry sites (close to our study sites) form one ring per year, which they verified by counting tree rings of known age. In similar studies in tropical trees, successful cross-dating of individual or different species (Worbes 1995; Stahle et al. 1999; Worbes et al. 2003; Fichtler et al. 2004) and positive correlations between tree-ring width chronologies and precipitation variables (Worbes 1999) were used as evidence of the annual nature of growth rings. In light of the above discussion the annual nature of the growth rings is thus established in our study area and species.

The annual diameter increment of 3.6–5.0 mm in this study is similar to the average diameter increment of 4.2 mm per year projected by Eshete and Ståhl (1999) in the locality of our study area, which originated under similar climatic conditions, and 3.9 mm reported by

Kiyiapi (1994) with similar climatic conditions in Kenya. However, it is much lower than the 12–14 mm for *Acacia karroo* reported by Gourlay and Barnes (1994), and 10–14 mm for *A. tortilis* grown under favorable conditions reported by Lamprey et al. (1980). *A. senegal* and *A. seyal* showed enhanced growth performances compared with *A. tortilis* and *B. aegyptiaca*, especially in maximum radial growth, which seems to be associated with moist years (Table 1). This reflects their reaction to water availability, and it would be interesting to elucidate their growth performance with regard to their water-use behaviours.

Water relation studies on these species during the dry season in 2003 revealed that both *A. senegal* and *A. seyal* are drought sensitive (drought avoiders) while *A. tortilis* and *B. aegyptiaca* are drought tolerant (Gebrekirstos et al. 2006). The avoidance mechanism and opportunistic use of water by *A. senegal* and *A. seyal* may partially explain their growth reduction during drought years and enhanced growth performances during moist years. *A. tortilis* and *B. aegyptiaca* are conservative water users, which is consistent with their lower growth performances in moist years compared to the former species. This finding is in agreement with similar results from the study of Orwig and Abrams (1997). During drought years, drought-sensitive species show reduced growth compared to drought tolerant species, while they show enhanced growth during moist years. Similarly, one would expect the deciduous, notably the drought-sensitive species to show better correlation with climate parameters, especially with major rainy season precipitation since they are expected to be leafless during the dry season. However, as shown in Table 2, annual radial growth of *A. seyal* and *A. tortilis* showed

stronger correlation with major rainy season precipitation, while *A. senegal* and *B. aegyptiaca* strongly correlated with annual precipitation. In contrast to our results, however, Enquist and Leffler (2001) found the evergreen species (*Capparis indica*) and the deciduous (*Genipa Americana*) to be more sensitive to the peak (major) rain and minor rainfall amount, respectively. On the other hand, in agreement with our results, higher correlation of evergreen species with annual rainfall (*Terminalia guianensis* $r = 0.68$ and *Pinus caribaea* $r = 0.57$) was reported by Worbes (1999), which may indicate longer growth period activity.

The statistically significant correlation between master ring chronologies and precipitation data also provides us a high degree of confidence in the reliability of cross-dating (Table 3). Similar findings, stronger correlations of master ring chronologies than individual species curves, have been reported (e.g., Worbes 1999; Schöngart et al. 2006). Hence, it seems plausible to use the pointer years of these chronologies as an indicator of climate disturbance events. Pointer rings are conspicuously small or wide rings and show density fluctuations (Schweingruber et al. 1990), thereby enabling the cross-dating of different samples because they are formed in response to an extreme external event that affected all trees in the same way (Worbes 1995). Thus, the comparatively synchronised growth reductions shared by all species were probably the outcome of the frequent drought occurrences in Ethiopia.

A variety of historical records and proxy records provided a reference framework for assessing climatic extremes in Ethiopia, although few meteorological records can cover this period. Drought has affected millions of people in Ethiopia for a long time. The recent extreme severity of drought during 1973–1986 and its political and economic consequences were reported by different authors (Kiros 1991; Adhana 1991; Cutler 1991). Archives also demonstrate that lack of fodder during these extreme drought periods caused a heavy mortality of domestic livestock indicating the extensive influence of the severe persistent drought on woodlands and grasslands. This is evident by the high frequency of narrow rings and the incidence of large growth depressions in the 1970s and 1980s in the tree-ring chronologies. This event is more obvious in the graph of *B. aegyptiaca* (Fig. 3d).

The ENSO effect and drought years in Ethiopia are associated with the occurrence of narrow rings, i.e., pointer years (Table 4; Fig. 4). However, consistent with the occurrence of drought years in relation to the El Niño years (Wolde-Georgis 1997) some pointer years coincided with ENSO years and some followed it. ENSO years are characterized by below normal rainfall. It reduces and interrupts the major rainfall season and enhances the minor rainfall season in Ethiopia. The relationship

between ENSO and Ethiopian rainfall and atmospheric system are described elsewhere (Bekele 1993). In addition to the recognized drought years listed in Table 4, except for the year 1962, the existence of pointer years in 1940–1945, 1951/52, 1970, 1977–1979 were found to be associated with ENSO years adding to the presumption that trees are climatic event archives. The pointer year in 1962 could be due to local climatic effects. Although savanna trees are thought to be drought hardy, the lower growth increment in drought years relative to normal years revealed the impact of drought (ENSO) on the productivity of savanna woodlands.

Based on previous drought occurrences and the frequency of rainfall deviation from the average, Tesfaye (1988) reported periodic droughts every 3–5 and 6–8 years in northern Ethiopia and every 8–10 years in the whole country. This is similar to our findings of 7.1, 4.7 and 2.2–2.7 years of periodic drought events revealed by the tree rings. These peaks fall within a spectral peak equivalent to 2–8 years, which characterize the variability of ENSO-related time series (Rasmusson and Carpenter 1982; Schöngart et al. 2004, 2006). Similar to our results, correlations, mainly between tree-ring width, precipitation and ENSO in semi-arid Africa have been reported elsewhere (e.g. Fichtler 2004; Schöngart et al. 2004; Couralet et al. 2005).

There are two main outcomes of this study, which have important implications for paleoclimatic reconstructions and in restoration of degraded lands. Our results support the strong linkage between tree-ring chronologies and climate, and it appears feasible to use tree-ring width variations for climate reconstruction, a chronology of past drought and ENSO events. In addition, the growth dynamics of the species coincided with the drought tolerance characteristics of the species (Gebrekirstos et al. 2006). Hence, *A. tortilis* and *B. aegyptiaca* can be considered as suitable candidates for reforestation in drought-prone areas while the higher growth rates of *A. senegal* and *A. seyal* during moist years could make them suitable candidates in areas of less limiting water conditions. Our study sheds light on the potential of dendrochronological studies developing in Ethiopia. Further studies on long-term tree-ring chronologies are recommended to reconstruct climate fluctuations.

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