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Growth Responses of Co-occurring Dryland Woody Species to Climate Variability in Southeastern Ethiopia

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Abstract

The objective was to understand the growth ring formation and climate growth relationships of two species, namely Acacia senegal and Commiphora africana. Wood disc samples of 30 trees belonging to the species of under study site (15 samples each) were used to develop climate sensitive ring-width chronologies using standard dendrochronological techniques. The sampled tree species were analyzed both manually and microscopically to check the occurrence of growth rings. The results showed that both studied species form distinct growth boundaries, while differences in distinctiveness were revealed between the species. Thin parenchyma bands define growth rings of Acacia senegal. In contrast, growths rings of Commiphora africana were delineated with a transition from fibers with thicker cell wall (latewood) to fibers with thinner cell wall (early wood). Apart from wood section analysis, ring patterns were investigated on standing trees of both species based on the concept of cambial marking by wounding (pinning) the tree and analyzing the number of growth rings formed between the time of wounding and cutting. The result showed the formation of three growth rings after wounding within 2.6 years across the entire samples and this represented the radial growth for the years that revealed the ring formations were annual. In particular, tree ring width of Acacia senegal and Commiphora africana showed strong and significant relationships with average rainfall of the rainy season ($r = 0.53$, and $r = 0.40$, $p < 0.05$) respectively. It is believed that the outcome of this study has importance in restoration of degraded lands; thereby contributing to the conservation and management of forest ecology of the study area.

Introduction

Acacia Commiphora and *Combretum Terminalia* woodlands are the two dominant vegetation types that cover large parts of the dry land areas in Ethiopia (Eshete, 2011).

Acacia-Commiphora, a small leaved deciduous woodland vegetation type, is predominantly found in the Southern and Central Rift Valley and Eastern lowlands of the country at altitude below 1900 m.a.s.l (Lemenih and Kassa, 2011).

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A number of species of the genera, *Acacia* and *Commiphora*, yield commercial plant gums and resins that have been traded for many decades (EFAP, 1994; Lemenih *et al.*, 2003). *Acacia senegal* (L.) willd var. Senegal and var. kerensis and *Commiphora africana* (A. Rich.) Engl. are the species that produce gum arabic and Myrrh, while the major and quality Myrrh is produced from Commiphora Myrrh (Tadesse *et al.*, 2007). These resources are of high economic importance because of their aromatic gum resins like gum arabic and myrrh, which are used as raw material in several industries (Lemenih *et al.*, 2003; 2007). They also have economic and ecological significances. Accordimg to Woldeamanuel (2011), gum and resin collection contributes for 30% of the total household income and 36% of cash income and is the second most important means of household livelihoods in Southern Ethiopia.

Tropical forests are being threatened by global changes in climate. Temperature across tropical forest regions is currently increasing and is expected to continue to increase with an associated decrease in precipitation (Wagner *et al.*, 2014). Tropical dry forests are under threat of deforestation (Lemenih *et al.*, 2011; Mulugeta *et al.*, 2017). Trees in arid area are sensitive to climate variability (Lingnan *et al.*, 2018). Therefore, there is a need to establish options or strategies for sustainable management of these resources so as to ensure the continuity of its economic, social as well as ecological services. To develop sound forest management and conservation strategies of such resources, knowledge of growth response of tree species to variations in climatic variables is vital; and this helps to estimate forest management criteria (Worbes, 2002; Fichtler, 2003; Rozendaal and Zuidema, 2010). Such knowledge and/or information can be gained through the conduct of research works particularly in the field of dendrochronology (tree ring studies), a powerful tool to develop high-resolution and exactly dated proxies for climate reconstruction and understanding of the spatial and temporal characteristics of climate influences on tree growth (Stahle *et al.*, 1999; Worbes, 1999; Brauning and Burckhardt, 2005).

In many parts of the world, especially in arid environments, precipitation is the most important climatic factor that determines the growth of woody plants (Worbes, 2002; Nicolini *et al.*, 2010) and changes in rainfall patterns, reduction in rainfall quantity, and changes in seasonal variation affect semi-arid plant community (Miranda *et al.*, 2011). Several dendrochronological studies revealed that changes in rainfall over seasons (temporal variation of rainfall) is a growth limiting factor, mainly the growth of trees is exceedingly limited in extreme droughts (Zeppel *et al.*, 2014; Mulugeta *et al.*, 2018; Lingnan *et al.*, 2018). In a nut shell, growth of tree species is primarily influenced by water availability during the growing season (Belay, 2016). Hence, climate change related shifts in precipitation can potentially affect the growth and population dynamics of trees growing in such arid environments. In fact, temperature variations also pose risks of broad scale climate-induced tree mortality (Olivia *et al.*, 2016).

Therefore, to understand the response of trees to expected changes in climate variables, relationships derived from long-term climate data and observed tree growth is important (Briffa *et al.*, 1996; Nicolini *et al.*, 2010). In this regard, as mentioned earlier, dendrochronology is a vital tool to understand climate and tree growth relationships (Fritts, 1976) and long-term dynamics of tree growth (Couralet *et al.*, 2005; Feliksik and Wilcznski, 2009).

The potential of tree species for dendrochronological research vary depending on site and climate regimes (Speer *et al.*, 2004). For instance, the growth response of *A.senegal* growing in the Central Rift Valley and Borana might differ due to differences in climate regimes. The study site, Wachile (a district in Borana zone), is characterised by two distinct rainy seasons in a year. This might trigger different growth pattern as compared to the same species growing in a unimodal rainfall pattern of the Central Rift Valley of Ethiopia.

This study examined wood anatomy and growth responses of two co-occurring tree species from Borena Acacia-Commiphora woodland. Accordingly, the objective of this study was to understand the growth ring formation and describe wood anatomy of growth ring boundaries as well as analyze climate growth relationships of two species, namely *Acacia senegal* and *Commiphora africana*.

Materials and Methods

Description of the study area

As mentioned earlier, the study was conducted in Wachile (also called Dhas) District in Borana Zone of Oromia National Regional State of Ethiopia, bordering Kenya (Figure 1). Topographically, the area is characterized by semi-arid lowlands with some mid-altitude areas, including mountain ranges, scattered volcanic cones, craters and gently undulating and flat plains. The altitudinal range varies from 1,100 to 1,450 m.a.s.l.

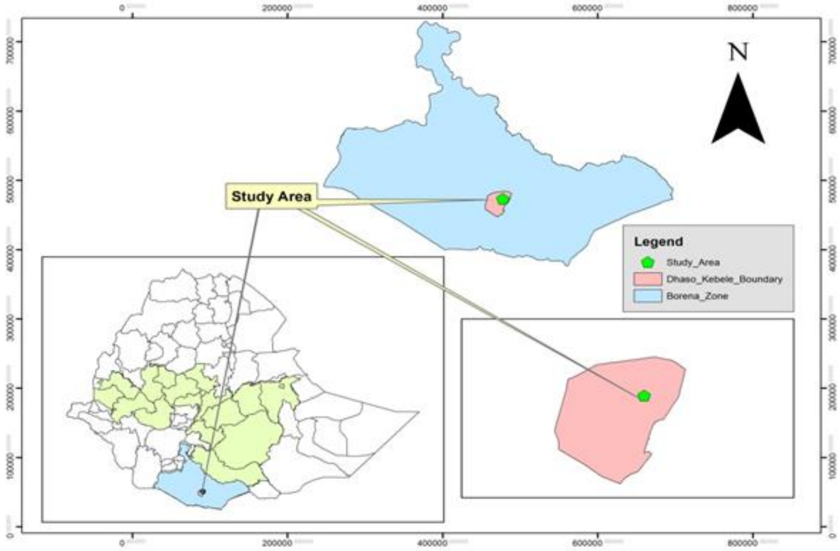


Figure 1. Map of the study area

The climate of the area is characterized by bimodal rainfall distribution. The main rainy season (locally known as 'Ganna') extends from March to May, whereas the short rainy season (locally klnown as 'Hagaya') lasts from October to November, followed by the long dry season (locally known as 'Bona'), which extends from December to February. The actual length of the rainy season is getting shorter and shorter over time and the area is highly prone to more frequent drought (Figure 2).

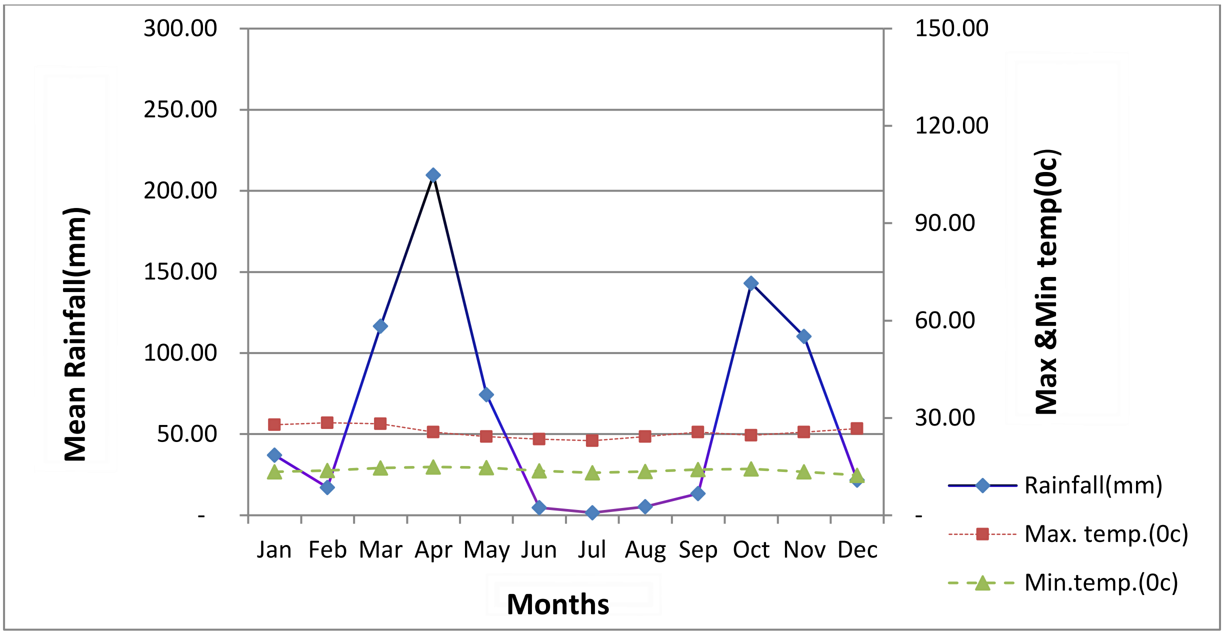


Figure 2. Climate diagram of the study area drawn based on meteorological data obtained from the nearest stations Chew-bet

Sample collection and preparation

The wood samples (discs) were collected from 20 living trees (8 from *A. senegal* and 12 from *C. africana*) distributed through the study area. The sample discs were collected using handsaw and a fresh chainsaw blade cutting with some required care to avoid crumbling of the sections. Therefore, growth ring analysis was based on 20 stem discs, collected from a total 20 dry land woody species with no noticeable stem and crown damage. After the samples were air-dried, the stem discs were sanded and polished progressively using sandpaper with an increasing grit size between 60 and 1200 to ensure the visibility of growth ring and wood anatomical features.

Cambial marking/wounding

The cambial marking was carried out at about 30cm above ground level and was successfully applied to the two selected tree species at documented time intervals in order investigate periodicity of growth ring formation between the time of wounding and time of cutting (Tolera *et al.*, 2013; Mokria *et al.*, 2017). After drying, the stem discs were cut a few millimeters above the actual place of cambial wounding and sanded until the full wound became visible. The wound tissue was carefully investigated to locate the position of the cambial initials at the time of pinning and the number of growth rings formed thereafter. Then, the growth rings after the pin marks were studied in specified scanned image of thin section prepared from the ring formed between times of pin marking, June 2010 and cutting January 2013, so as to confirm annual character of detected growth rings and evaluate periodicity of wood growth.

Growth ring formation, width measurement and cross-dating

Growth rings on the smoothened sample discs were detected following concentric features around the stem circumference, and then identified when all rings on a disc and ring numbers and characteristics matched along different radii.Then, growth rings were marked and counted under stereo-microscope on four radial directions of the sample discs.Visual cross-dating was conducted by comparing and distinguishing characteristics of rings among radii of the same tree and followed by matching the series from different trees of the same species.

The widths of each growth ring were measured to develop first tree level and then sspecies level chronology for each species of the study site. The inter-annual ring width variability within each mean tree series was compared against all other series both with statistical and graphical programs (e.g., TSAP, Rinn, 2003). In order to identify locally absent rings, eliminate measurement errors and ensure relative and absolute dating accuracy, the quality of cross-dating was checked with the program COFECHA (Grissino-Mayer *et al.*, 2005). It enhances reliability of dating. Subsequently, it was concentrated on the output such as tree ring series correlation with master chronology, mean sensitivity (a measure of the year-to-year ring variability within a sample), number of "A" flagged segments (e.g. Maxwell *et al.*, 2011). These COFECHA output obtained by using the default analysis settings, examination of 32-years segments lagged 16 years with 0.4093 critical levels in the correlation analysis (Grissino-mayer, 2001).

Then, Tree ID and beginning year were first entered into the Measuring interface. The distance between the growth rings was automatically measured and recorded for the four radii of each dated tree discs with an accuracy of 0.001mm under LEICA ^{TM}5 LINTAB, Rinn, Tech, and Heidelberg Germany with moveable device connected to personal computer associated to TSAP-dos software and registered in a computer using Tree ring Series Analysis Program (TSAP, Rinn 2003) and these processes were repeated for all rings.

Tree rings were measured under a binocular scope using a LINTAB measuring device (Rinntech, Heidelberg, Germany). Then, the previous visual cross-dating was checked using the COFECHA program which calculates the correlation between individual ring-width series and a master series for each species. Following the above procedures, Tree rings Series Analysis Program (TSAP) was used for the Tucson tree ring data format and for graphic capabilities option for cross-dating and standardization.

Standardization and chronology development

Tree ring series were standardized using the software program called ARSTAN (Holmes, 1983). To standardize the tree ring curves, a cubic smoothing spline of 50% wavelength cutoff for filtering of selected frequency response portion of variance to preserve examined segment 32 years to lag 16 years was used. Double detrending was used in the tree ring series for removing age effect due to biological growth trend and other low frequency variations, and to enhance the frequency variance that concentrates on climatically related environmental signals. The standardized values were averaged into a mean value function by adjusting the series for different growth rates that may be due to differing tree ages and differences in the overall rate of growth (Schulman, 1945).

Climate data

The instrumentally recorded climate data ranged from 1983 to 2012 was taken from Ethiopian National Meteorological Agency (ENMA) for the analysis of the climate-growth relationship of the study species. Hence, these data were, then, analyzed to gain reliable climate–growth related information. All climate-related information was calculated from the data obtained from Chewbet which is nearest stations of the study site.

Analysis Climate-Radial Growth Relationships

The Pearson product-moment correlation coefficient (r) was used to test the association between observed climate data (rainfall and temperature) and radial growth of trees. This method of analysis is appropriate as it inspects the linear association between growth of tree rings and climate and it avoids the subjectivity of the interpretations, as well (Andreu *et al.*, 2008).

Results and Discussions

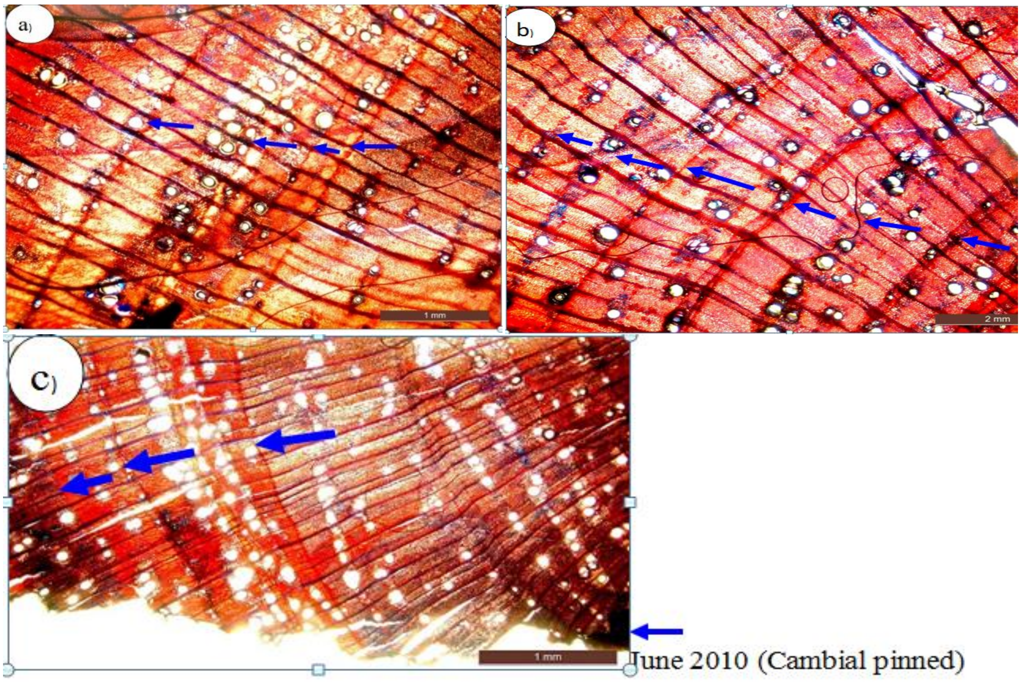
Growth ring formation

Microscopic analysis of wood sections of both species revealed the formation of distinct growth rings in both study species (Figure 3a and b). A closer anatomical investigation into the wood thin sections showed differences in anatomical features that depict growth ring boundaries of the two study species. Growth rings of *A.senegal* are defined by thin parenchyma bands, where as that of *C.africana* is delineated with a transition from fibers with thicker cell wall (latewood) to fibers with thinner cell wall (earlywood). This is also supplemented with shifts in vessel size, i.e., vessels in the latewood cells are smaller in size as compared to that ofearlywood vessels. In general, growth ring boundaries of *A. senegal* are more distinct as compared to *C. africana*.

In the case of *C. africana*, the abrupt shift in vessel diameter was difficult to distinguish particularly at the sapwood (Figure 3b). Even if the distinctiveness of growth ring for *A.senegal* had visible parenchyma bands, its narrowness made visual inspection of rings and cross-dating difficult. This was not the case in *C.africana*. Both studied tree species showed annual growth rings. Growth boundaries of A. senegal were characterized by parenchyma bands (Figure 3a), whereas that of C. africana are characterized by fiber cell wall thickness that is supplemented by vessel size and distribution (Figure 3b). These growth ring boundaries and formationsare common features of tropical tree species as studied by many scholars (Worbes, 1989, 2001; Tarhule and Hughes, 2002; Verheyden et al., 2004; Schongart et al., 2006; Gebrekristos et al., 2008; Steenkamp et al., 2008; Tolera et al., 2013). The findings of this study indicated that formations of growth ring boundaries are influenced by alternating variations in climatic factors, such as rainfall and temperature. This finding corroborates with the findings of many similar studies(Fritts, 1974; Whitmore, 1998;Worbes, 1995, 1999, 2002; Shinta et al., 2009). On the other hand, missing and wedging growth rings were observed in the growth ring patternof both study species. These irregular ring characters were successfully detected through differences in the anatomy of the ring and by checking the continuity of rings over the entire stem discs. Such ring characters might be caused by rainfall deficit, which consequently results in discontinuous growth in response to low cambial activity (partial ring formation); and as soon as the climatic condition gets favorable, tree ring growth starts yet again, resulting in false rings formation. These irregular ring characters were also detected in other tropical species as studied by various researchers (Gebrekristos et al., 2008; Maxwell et al., 2011; Tolera et al., 2013).

Despite a ring is normally formed every growing season, in some years of unfavorable climatic conditions, a tree may not develop an annual ring (missing ring). In other circumstances, a ring may be absent at some point on the tree, and therefore is only seen when a cross-section of the tree is taken (locally absent). In some cases, two rings may be formed during a favorable growing season (False rings or double rings). These missing, locally absent, and false rings can be detected in both studied trees species by cross-dating these growth formations of the study species with other species from the same region. This is apparent in other studies (Eshete and Stahl, 1999; Worbes, 2002; Gebrekirstos et al., 2008; Wils et al., 2009, 2011). This implied that tree ring analysis and cross-dating is challenging in similar regions with the study site, as seasonal changes in environmental conditions are often less pronounced in timing and intensity. Despite this, in this study, such challenges were controlled by investigating visual detection of the growth rings, monitoring growth rhythms, and testing the climate signal with tree ring features.

Individual ring width patterns of tree species in the study site were successfully cross-dated and showed significant relationships with seasonal rainfall, proving the existence of annual tree rings (Stahle, 1999). This finding is also supported by cambial marking analysis (Figure 3c). This finding is in agreement with the formation of annual growth rings reported for other woodland species growing under bi-modal rainfall patternin Ethiopia and Eastern Africa (Eshete and Stahle, 1999; Menezes et al., 2003; Verheyden et al., 2004; Gebrekiristos et al., 2008; Tolera et al., 2013).



June 2010 (Cambial pinned)

Figure 1. Growth boundaries in A.senegal(a) and C.africana(b) (Arrows indicate the annual growth

Periodicity of growth ring formation

It was understood from the cambial wounding experiment that three growth rings were noticed across the entire period between time of wounding and time of cutting representing the radial growth for the years 2011, 2012 and a half year of uncompleted growth ring for 2013 as seen in Figure 4

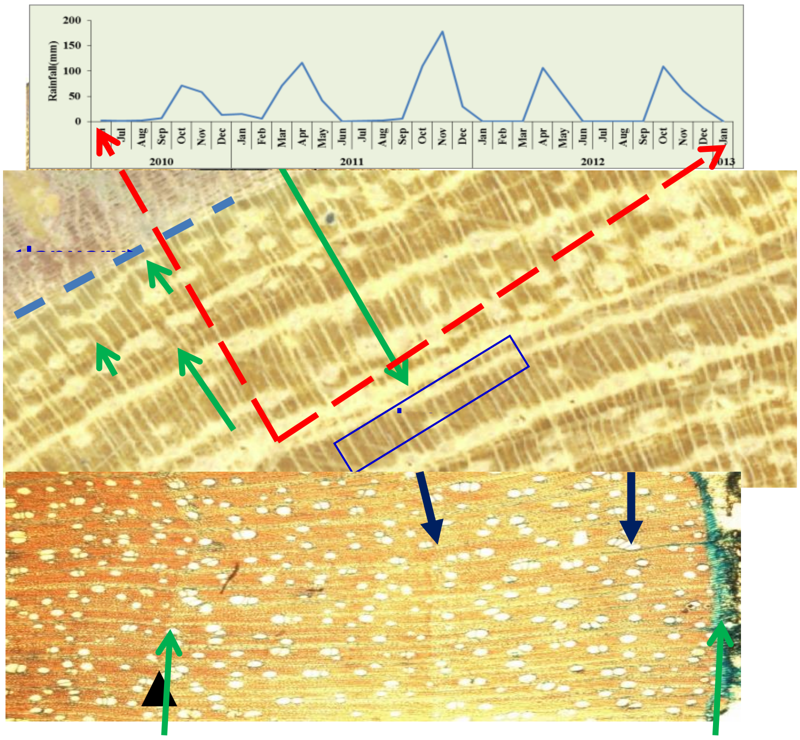


Figure 2. Tree ring growth formed by the sample species between the time of wounding (June, 2010) and cutting (January, 2013) [Arrows indicate the annual growth rings]

Cross-dating and chronology development

Ring-width series measured from different radii on the same stem discwere crossdated. This was verified from the growth pattern ofthe species, which showed the growth patterns of both species grow slowly at the beginning and then grow highly at the mid age and fall down afterwards (Figure 5a and b). The average growth rate of *A. senegal* was 0.995±0.27mm (SD = 0.617), while that of *C. africana* was 1.008±0.457mm (SD=0.601) (Table 1). Among the measured sample trees, it was possible to build a chronology for *A. Senegal* and *C. africana*, from 28 samples (87.5% of the total samples) and from 43 samples (89.6% of the total samples) with 4 and 5 flagged segments, respectively. A 53-years chronology (1957 – 2013) and 64-years chronology (1951 – 2013) were obtained for *A. senegal* and *C. africana* respectively (Figure 6a and b). The auto-correlation values were -0.017 and -0.005 for A. *senegal* and C. *africana*, respectively (Figure 5a and b and Table 1) showing lack of climate of previous year on each consecutive growth.

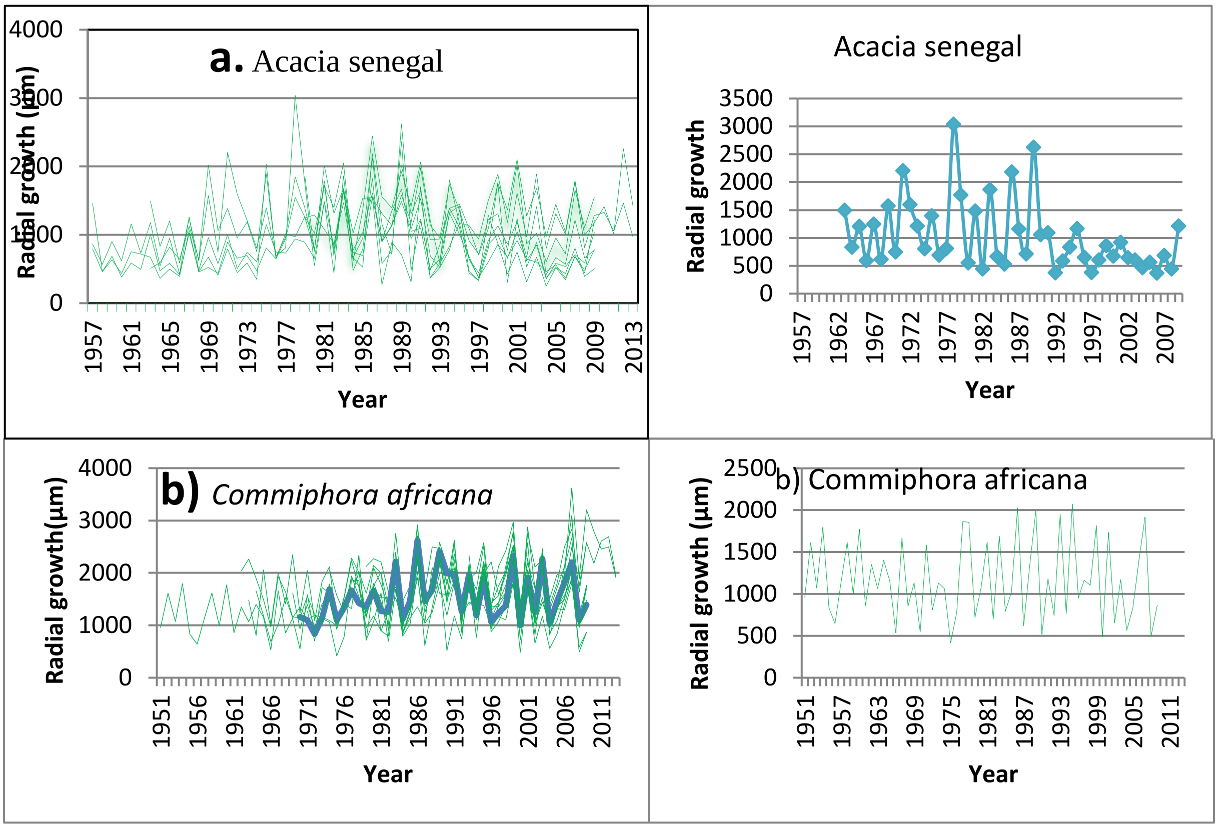


Figure 3. Ring width series variations obtained for 20 trees in study site (climate and radial growth variations) of cross-dated tree rings of A.senegal(a) and C.africana(b)

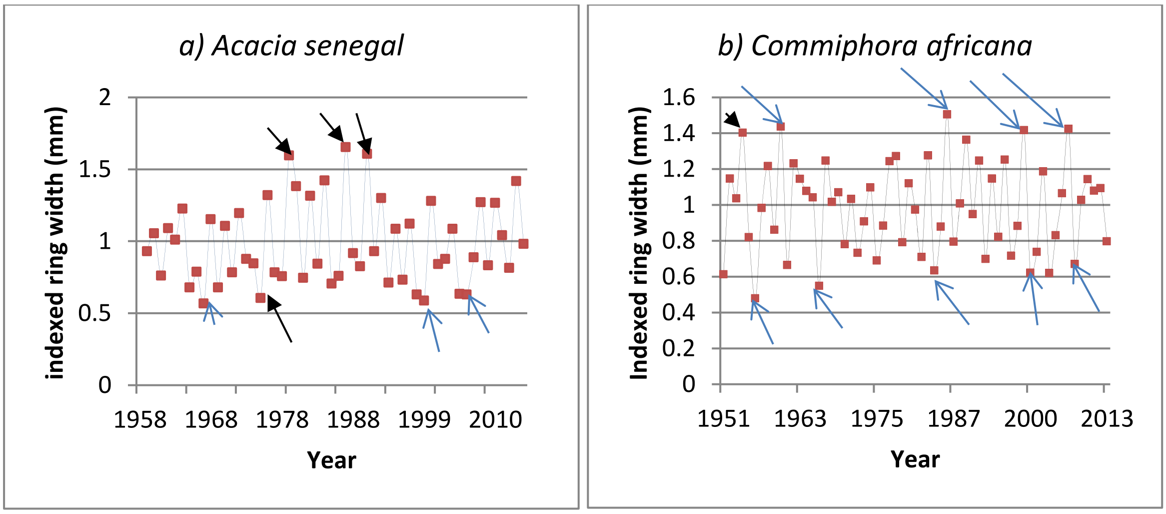


Figure 4. Chronology of indexed tree ring width from the selected cubing smoothing spline, preserved 50% of the variance contained in the measurement series at wavelength of 32-years [Arrows indicate extremely narrow and peak rings]

Table 1. Summary of chronology statistics

No.	Variables	*A. senegal*	*C. africana*
1	Number sampled trees	8	12
2	Average stem disc diameter(range)	10.5(9-12)cm	13.7(11-15)cm
3	Average age (range)	42(1957-2009)	37(1950-2013)
4	Time span (Year)	1957-2013	1950-2013
5	Average ring width(mm)±SD	0.995±0.270	1.008±0.457
6	Average correlation with Master	0.636	0.604
7	First order autocorrelations (Unfiltered)	-0.017	-0.05
8	Mean sensitivity	0.543	0.442
9	Standard deviation (Filtered)	0.617	0.601
10	Flagged Segment	4	5
11	t-values Bp	4.2-12.7	3.3-12.5
12	GLK %	65-93	70-94

Tree diameter growth in the study site is sensitive to climate variability specifically rainfall patterns and also experience high seasonal and inter-annual environmental variation (Table 1). The statistical analysis of standard chronologies from both tree species revealed high mean sensitivity (>0.4) and had significant correlation compared with Pearson (parametric, quantitative) critical level of correlation, 99% confidence level (0.3281) of program COFECHA (Holmes, 1999). The high mean sensitivity indicated a presence of high inter-annual variability in the ring widths and that the chronologies were sensitive to yearly environmental changes. Meanwhile, its low value (-0.017, -0.05) indicates that a significant portion of the observed ring width is a function of the exogenous factors (for this case Rainfall) than preceding year's growth (Table 1). The response of radial growth to climate and the climate sensitivity of tree growth at different species in different drought conditions are essential for predicting forest dynamics and making correct forest management policies. In this study, we analyzed the growth responsiveness of co-occuring dryland woody species to climate and explored the relationship climate and radial growth at the species levels.

Growth response to climate

The results showed that the studied tree species had a comparable pattern in their tree ring growth response to climatic variables (rainfall and temperature) (Figure 7 and 8). The tree ring chronology showed a statistically significant correlation ($r = 0.53$, $P < 0.05$ for *Acacia senegal* and $r = 0.40$, $P < 0.05$ for *C. africana*) with the rainfall of the main rainy seasons (March-May). Peaks of growth rings were synchronized with high rainfall years (e.g. 1953, 1960, 1979, 1989, 1990, 1999 and 2007), while extremely narrow rings fairly matched with years with below average rainfall (e.g. 1967, 1975, 1984/85, 1992, 1996-1998 2000, 2004/2005) (Figure 7). Hence, the rainfall during the major rainy season seems to be the most important climatic factor that influences ring-width growth.

Likewise, indexed tree-ring of *Acacia senegal* showed a statistically significant ($r = 0.4$; $P < 0.05$) association with peak rainfall month (April). On the other hand, *C. africana* showed a statistically significant correlation (r = 0.48; P < 0.05) with rainfall of the month of March (that is beginning of major rainfall season). On the other hand, *A, senegal*hada negative correlation (r = -0.31) with the average minimum rainfall of spring seasons (October and November); while *C. africana* showed a positive association for most of the months of the year (January, February, July, August, September and December). *C. africana* also had a negative correlation with the month of May (end of major wet seasons) and November (end of minimum rainfall seasons). As a result, the correlation analysis between indexed tree ring width and monthly and seasonal rainfall revealed some differences between the two studied species (Figure 7).

The statistical analysis of standard chronologies from both tree species revealed high series inter-correlation and higher mean sensitivity that implies strong response to common external environmental factor like climate (Grissino-Mayer, 2001). Mean annual diameter growth increment increased predictably with total major rainy seasons (Worbes, 2004; Gebrekristos, 2008). This findingindicates that rainfall during the rainy season (P<0.05) influences annual growth patterns more than total annual rainfall (Figure 7). The reason is, in these dry climates, food supply largely depends on the amount of rainfall. What is more, in cases where the rainfall amount is limited, the width between growth rings becomes narrower signifying that the life struggle of the tree during water stress is against drought rather than competing vegetation (Worbes, 2004; Cherubin *et al.*, 2003). To sum up, for such co-occurring dryland species, the study implied that radial growth is strongly influenced by the climate variability, particularly by the amount of rainfall during the rainy season. Hence, this study provides a basis for using short-term growth data to make long-term growth projection with growth adjusted to long-term climatic conditions.

Chronologies of both species are statistically significant and correlated with monthly rainfall in the major wet season (of March, April and May) and this observation is in agreement with other studies in Ethiopia (Gebrekritos *et al.*, 2008). Among these major rainfall months, March and April are the most important to the tree radial growth. In general, the positive correlation of tree ring width and major rainfalls indicates that more growth is likely to occur with higher levels of rainfall, whereas smaller rings develop in years with limited moisture and similar observations were made previously for other tropical tree species (Worbes, 1999). Both chronologies for the two selected dryland species are significantly correlated (r) with seasonal rainfall for the major wet season.

In contrast, the study revealed that there is a negative correlation between tree growth and rainfall amount during the minimum rainfall season, spring (October and November); and this may be the result of low and inaccessible soil moisture, loss of water through evapo-transpiration. Consequently, less water availability makes the uptake of water difficult to support the secondary growth, and this might result leaves to shade before end of rainfall.

This finding is also in agreement with other studies in tropics (Orwig and Abrams, 1997; Wils *et al.*, 2010). From the field observation, *C.africana* might take the advantage of having green barks during the dry season that might carry out photosynthesis to support growth in these dry seasons. In this study, *A.senegal* demonstrated more differential responseto climatic variations than *C.africana.*

Figure 5. Indexed tree ring width indices of A.senegal (a) and C.africana (b) and rainfall of the major rainy season (March-May)

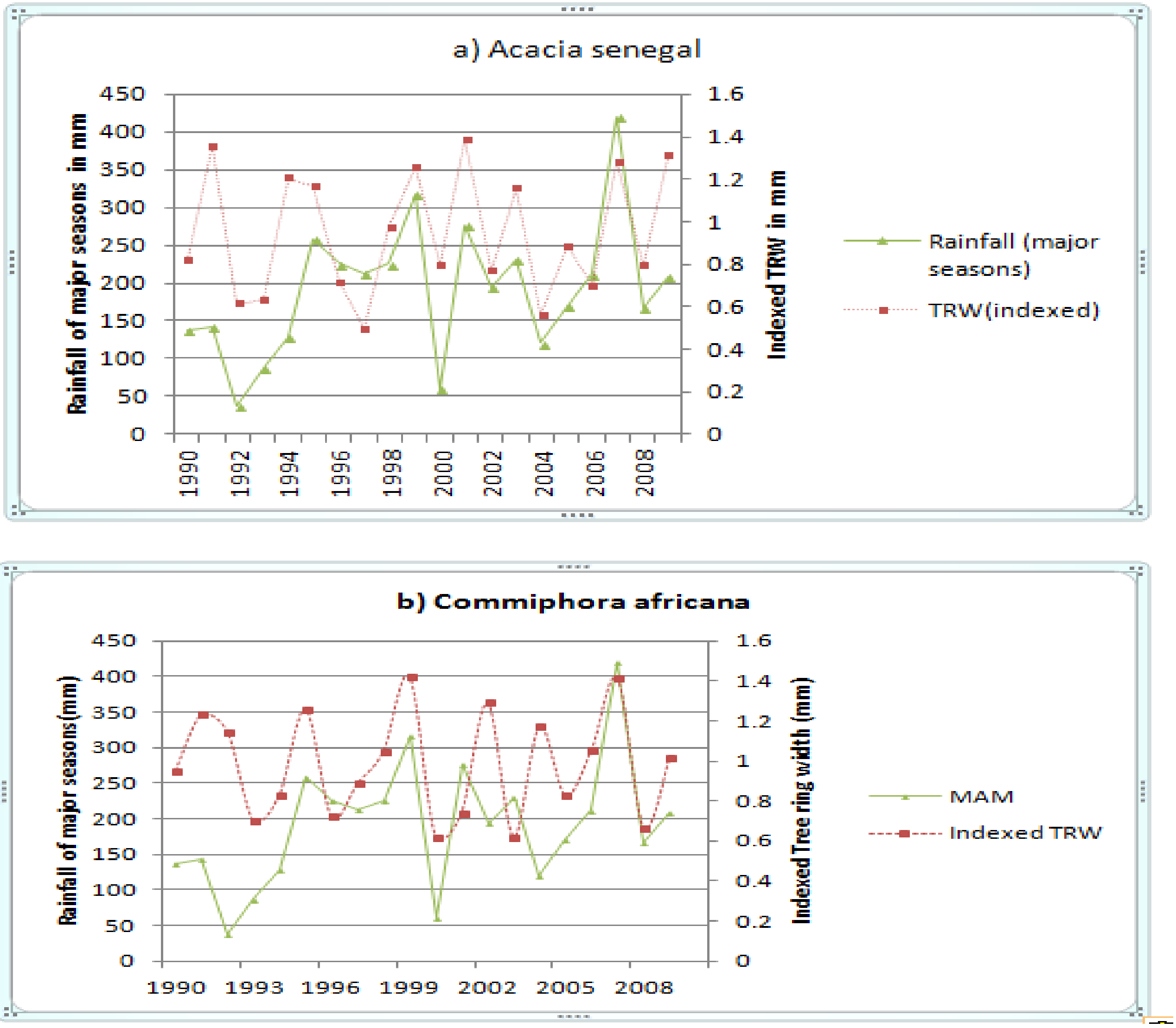
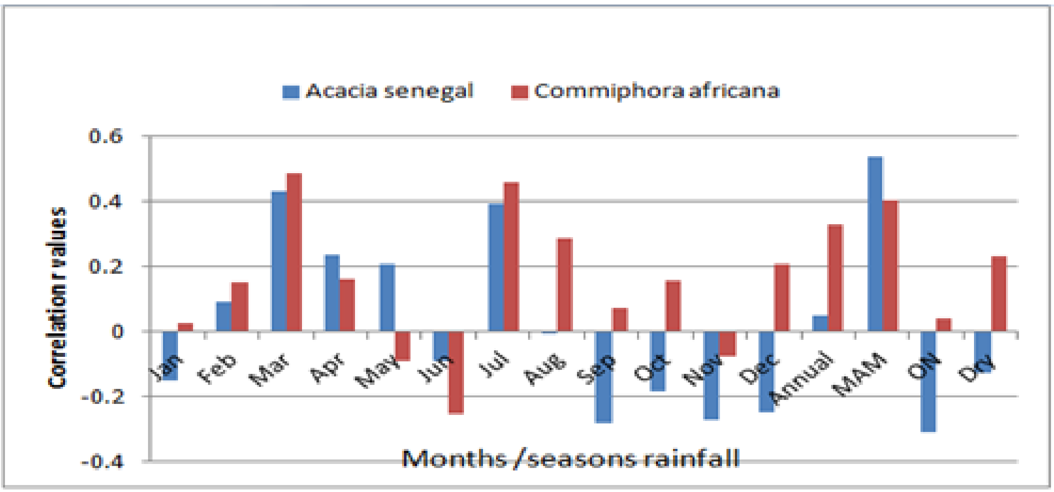
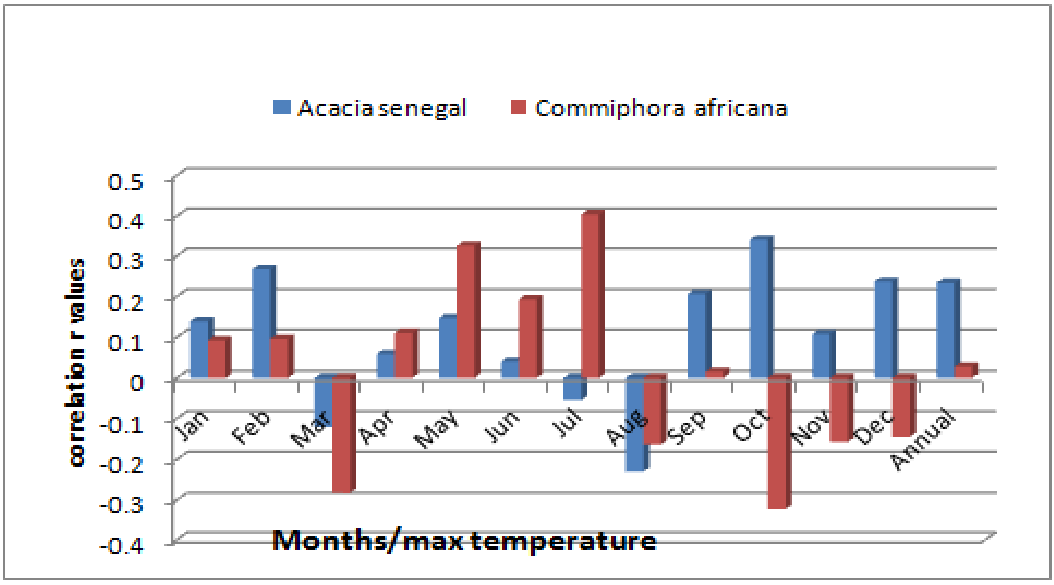


Figure 8. Correlation functions of indexed tree ring width of the studied species (A. senegal and C. africana) with the mean monthly and seasonal rainfall (a) and with average monthly maximum temperature (b) (P<0.05).





Conclusion and Recommendation

This study was aimed to verify whether the growth rings are annual in nature or not, describe wood anatomical features of growth ring boundaries, and examine the relationship between climate and growth patterns of the study species. By so doing, this study attempted to investigate the response of tree species to varying climatic conditions and examined the potential and applications of tree ring research in climate science. It is strongly believed that this research can be used for further studies aimed at climate reconstruction and climate prediction.

It was found out that both studied species form annual growth ring. This indicates that the two semi-arid species are an important tree species for dendrochronological research in Ethiopia and may be useful elsewhere. The significant relationship between growth and climatic variables of the studied species also implied the potential of these species for climatic reconstruction, where long-term climatic records are rarely available. It also showed the potential of predicting the possible scenarios in growth conditions of the studied species in the prospect of changing climatic condition.

In general, Understanding the growth response and their interactions with climate in such region is fundamental for developing adequate strategies in environmental reclaim actions, there, where deforestation due to over utilization of gum and resin begun. Similarly, it is crucial to ultimately implement practices that restore, preserve and manage forest ecology in general and the remaining fragments of the semi-arid forests in particular. In addition, it indicates tree rings long-term growth chronologies are an appropriate source for understanding several aspects of tropical tree growth. Once more, the result provides additional support for views that tropical trees are sensitive to variation in rainfall.

Furthermore, Radial growths responses may be helpful in elucidating tree responses to past droughts because tree rings have long been recognized as indicators of annual climatic information such as precipitation and temperature. For example, early researchers observed drought impacts in many species by the presence of narrow rings produced during years of low moisture availability (Stewart 1913; Douglass 1914; Stickel 1933; Lyon 1936). Tree-ring patterns from arid sites shown to be climatically sensitive, or more strongly limited by precipitation (Fritts 1976).

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Conflict of Interest

The authors declare that there is no conflict of interest.

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