Precipitation as the Main Driver of the Radial Growth of *Cupressus lusitanica* (Mill.) at Wondo Genet, Ethiopia

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Abstract

There is a wide range of literature on the failure of tropical trees to form clearly visible annual growth rings, especially where there is an extended rainy season. Most southern parts of Ethiopia have a bimodal rainfall distribution with varying degrees of distinction between rainy seasons. We measured the ring-widths of *Cupressus lusitanica* which is the second most important plantation species in Ethiopia and has not been utilised in many other dendrochronological studies. Cross-dating of 30 radii ensured that the trees were absolutely-dated and that its growth rings were annual. The association with climate was investigated over the 30 years meteorological records from Wondo Genet in Ethiopia. The standardized ring-width index was significantly correlated (r = 0.59; p < 0.05) with the amount of precipitation. Even though the distribution of precipitation was not clearly unimodal, this study demonstrates that exotic species growing in far from optimal dendrochronological conditions still have the potential for dendrochronological studies by forming clearly visible annual growth rings.

Keywords: Tropical dendrochronology, climate-growth relationship, absolutely-dated, rainy seasons, short dry season.

Introduction

Tree growth depends on the amount and distribution of precipitation, temperature and other climatic variables over a certain time (Fritts 1976, Gebrekirstos et al. 2009). The signature of all these patterns is recorded on their annual growth rings with resolution of one year (Fritts 1976, Speer 2010). A tree-ring of conifers begins with early-wood which is lighter in colour due to the thin-walled tracheids followed by late-wood which extends to the end of the annual ring and it is characterized by darker colour from thick-walled tracheids. Tree-ring width holds the value of the radial growth in that year the cells are formed (Kozlowski and Pallardy 1997, Fritts 1976). Tree-ring information has multiple applications in many fields of study such as climate reconstruction, forest management, archaeology, ecology and others (Harvey 2012, Popa and Cheval 2007). Not all trees are suitable for dendrochronology because the visibility, clarity of boundary, annual nature and other important characteristics of tree rings vary with the tree species, age and site conditions (Schongart et al. 2006). The main growth limiting and ring formation initiating factors in temperate region is temperature (Cherubini et al. 2003) whereas in dry tropical forests moisture is the main growth limiting factor (Speer 2010).

Although, dendrochronology has been successfully adopted in temperate regions, it is still relatively new and less developed field in the tropics (Worbes 2002, Kozlowski and Pallardy 1997). Tropical dendrochronology faced strong challenges from a number of scientists against its reliability after some unsuccessful studies (Gebrekirstos et al. 2014, Rozendaal and Zuidema 2011, Worbes 2002). Amongst the reasons that made tropical dendrochronology challenging are possession of anatomically indistinct tree-ring boundaries by tropical trees (Stahle et al. 1999) which mainly occurs due to absence of distinct seasonality of the climate which did not make the trees to stop their growth in response to water stress on some part of the year (Tomlinson and Longman 1981, Jacoby 1989, Détienne 1989, De Ridder et al. 2014). Intra-annual ring boundaries were observed on some of the very wide rings of *Juniperus procera* trees from the Arsi highlands of Ethiopia (Couralet et al. 2007, Wils et al. 2010). However, there are numerous recent studies demonstrating the advantages of adopting a dendrochronological approach in tropics. For example, observation made on twelve tropical tree species showed that tree growth and phenology is highly dependent on the amount and duration of water availability (Reich and Borchert 1984). *Juniperus procera* samples formed strictly annual tree-rings which was confirmed by radiocarbon date results at Gonder, Ethiopia (Wils et al. 2011, Wils et al. 2009). The successful climate-growth relationship works on *Acacia* species from different arid and semi-arid regions of Ethiopia paved the way for many similar studies towards building and strengthening chronologies throughout the country (Eshete and Stahl 1998, Gebrekirstos et al. 2009).

Ethiopia as a tropical country has also been considered to be an inconvenient place for dendrochronological studies (Conway et al. 1998). Contrary to this, many dendrochronological studies conducted in semiarid zones of the northern and rift valley areas of Ethiopia showed the great potential for further studies in the field (Gebrekirstos et al. 2008, Eshete and Stahl 1998, Wils et al. 2009, Gebrekirstos et al. 2009). For instance, *Juniperus procera* formed strictly annual growth rings at Gonder due to distinct seasonality of rainfall while it showed multiple rings a year at Doba forest where there is indistinct rainfall seasonality (Wils et al. 2010).

Cupressus lusitanica is the second most common plantation tree species to Ethiopia, which grows in agro-climatic zones characterized by various precipitation levels, i.e. dry, moist, wet, WeynaDega and Dega. It is a highly abundant yet exotic species in east Africa (Tesfaye 1998, Jacoby 1989). It originated from the moist montane forests of Mexico and Central America. It has tremendous uses such as construction, fuel wood, hedge, furniture manufacture, and many more. It propagates by seedlings and it can produce poles in 10 years and general-purpose timber in 20 years age (Azene and Tengnäs 2007, Tesfaye 1998). One of the reasons to target this species for this study is that it has wide geographic distribution as a standing or dead tree throughout Ethiopia (Tesfaye 1998) which could give us opportunity to build a tree-ring chronology network which can be extended back in time by using samples from wooden constructions and furniture since there are many of them from different eras. It has been used for dendrochronological studies in Kenya (David et al. 2014) but not in its country of origin, i.e. Mexico (Acosta-Hernández et al. 2017).

As in most parts of Southern Ethiopia, Wondo Genet has two slightly distinct rainy seasons with a short dry season between them (Figures 1 and 2). In the scientific literature, it is often described as having a bimodal rainfall pattern (Eriksson et al. 2003, Hunde et al. 2003); from March to May (the so-called ‘short rains’ or *Belg* in Amharic) and July to October (the ‘long rains’ or *Kiremt* in Amharic). But we hypothesise that the gap between the two rainy seasons is not long enough to form double growth rings. As a result of this, we expect to observe clearly visible annual growth rings. The main aim of this study is to investigate the relationship between the annual growth of *Cupressus lusitanica* and precipitation at Wondo Genet.

Materials and Methods

Description of the Study Area

The *Cupressus lusitanica* trees were collected from the plantation forest that cover 14.3% of the total area of Wondo Genet College of Forestry and Natural Resources (WGCFNRs), (7°06’N; 38°37’E) (Figure 1). The topography of Wondo Genet is mountainous (44%) with some flat areas (36%) and the remaining land generally consists of undulating terrain with an overall elevational range of 1600-2580 m a.s.l (Teklay et al. 2006).

The Wondo Genet Meteorological Station is geographically located in the central rift valley of Ethiopia, 265 km south of Addis Ababa (7º5’30”N; 38º36’48”E). It is the longest available and the closest instrumental climate record to the study site. Analysing the climate data from this station through the period 1981-2013, the study area received approximately bimodal rainfall (Figure 2, Eriksson et al. 2003, Hunde et al. 2003) the short rainy season took place between March and May which supplied 30.7% of the total annual rainfall and the long rainy season took place from July to October supplying 47.3% of the annual rainfall. June is considered as a drier month

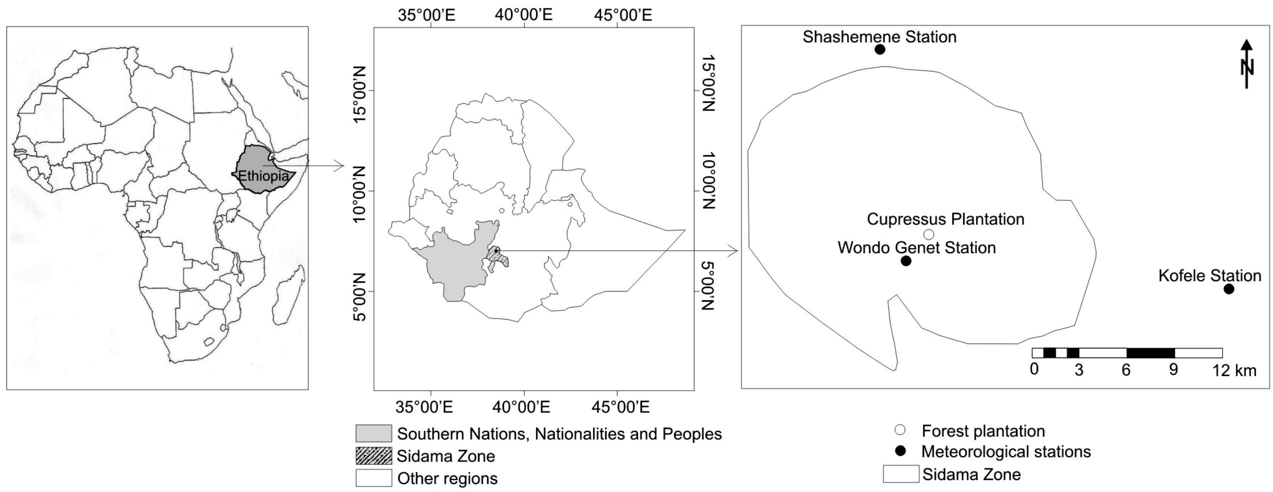

Figure 1. Map of the study area Wondo Genet (7° 5'50.58"N, 38°37'56.87"E) and the meteorological stations (7°5'30"N; 38°36'48"E) available nearby. As it can be seen on the map, the *Cupressus lusitanica* plantation is located at Wondo Genet College of Forestry and Natural Resources (WGCFNRS) in Sidama zone, southern Nations, Nationalities and Peoples Region (SNNPR), Ethiopia

due to the relatively lower rainfall and high minimum temperature (Krepkowski et al. 2013).

Sampling, sample preparation and ring-width measurement

Twelve trees were selected for this study from the oldest available compartment of known age in the plantation forest of WGCFNRs by simple random sampling. Discs were obtained at stump height and dried in the open air (Baillie and Pilcher 1973). Dried sample discs were prepared using progressively finer grades of abrasive paper ranging from 40-360 µm. Wood dust was removed with compressed air to increase visibility of boundaries between growth rings (Baillie and Pilcher 1973, Eshete and Stahl 1998). Temporary thin sections were prepared following standard methodology (Gartner and Nievergelt 2010). Some portion of wood was soaked in to cold water for 24 hours followed by slicing 25 µm thick thin sections using a Microtome. The slides were placed on glass transparency slides and bathed with a solution of Sufrenel and Astrablue for three to five minutes (Fritts 1976). The samples were then washed with deionized water, and lubricated with Glycerin to displace any water. Finally, the samples were covered with a slide cover and pressed gently to remove any water. The slides were observed and photographed under a stereo microscope at 10x magnification. The cell wall and lumen characteristics, near the annual growth ring boundaries, were examined (Speer 2010, Fritts 1976).

Identification of ring boundaries (Worbes 1989) was performed on all the four radii marked on each sample disc. Visual cross-dating was performed on all samples by checking the occurrence of every tenth ring on all radii with the help of a stereo microscope (Fritts 1976). Ring widths were determined on each radius using a LINTAB measuring stage (Rinntech Heidelberg, Germany) and cross-dated (Cook and Holmes 1986) using TSAP-Win (Rinn 2003).

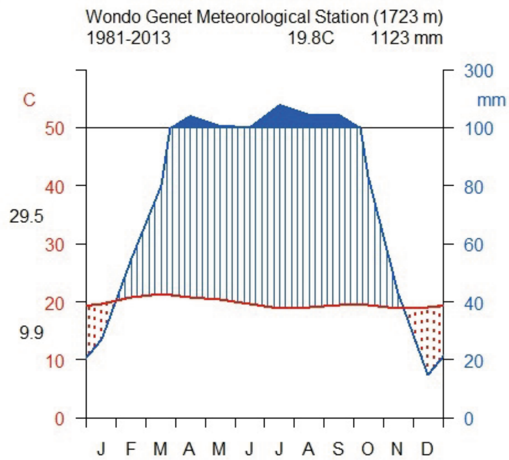

Figure 2. Climate diagram of the meteorological station in Wondo Genet. Each tick mark along the abscissa indicates one month where J represents January, F represents February etc. The blue line represents precipitation and the red line represents temperature. The mean daily maximum temperature of the warmest month is 29.5°C whereas the mean daily minimum temperature of the coldest month is 9.9°C. The annual average of temperature (19.8°C) and the annual precipitation (1,123 mm) are indicated

Statistical analysis

In order to get high frequency environmental proxy data statistical cross-dating between radii within a disc and between discs (Fritts 1976) was performed using TSAP-Win (Rinn 2003). Standard dendrochronological parameters were calculated including *t*-values, which show the degree of similarity between two curves (Fichtler et al. 2004) and, the Gleichläufigkeitskoeffizient (GLK), which measures the similarity of year-year fluctuations between two curves (Baillie and Pilcher 1973). To make sure that all the radii were correctly dated (GLK values > 75% and *t*-values > 4.0), an iterative procedure was employed, where samples were re-measured and the data quality checked using COFECHA (Holmes 1983, Grissino-Mayer 2001). Some radii were excluded from further analysis during quality checking and cross-dating and 30 radii from 12 trees, i.e. two to four radii for each disc, were included in the final chronology. The cross-dated series was prepared in .rwl format and standardized in the Dendrochronology Program Library in R (dplR) using the detrend function (Bunn 2008). The time series were standardized using the smooth spline option, since the growth pattern in all the samples decreased from pith to bark. The Expressed Population Signal (EPS) was calculated as a measure of the common signal in the chronology using R (dplR) (Wigley et al. 1984, Robertson et al. 1997, McCarroll and Pawellek 1998). Climate-growth relationships of *Cupressus lusitanica* growing at Wondo Genet was determined by comparing the indexed tree-ring width series of residual standardized chronology with the values of monthly, seasonal and annual precipitation and also various regimes of temperature recorded at the nearby Wondo Genet Meteorological Station (Figure 1). The degree of relationship between the indexed values of the standardized ring-width and mean annual temperature, annual, seasonal and monthly precipitation was investigated using TREECLIM (Zang and Biondi 2015). Indices of the residual and standardized chronologies were saved as ".csv comma delimited" file format and the various climate data were also saved in same format and uploaded in to R and got analysed using the commands described in TREECLIM (Zang and Biondi 2015).

Results

Tree ring formation

All the *Cupressus lusitanica* samples showed clearly distinct boundaries of their growth rings characterized by darker colour of tracheids due to smaller lumen and thicker cell walls. The transition between early-wood and late-wood in most rings was an abrupt change, where the size of the cell lumen decreased and the cell wall became thicker (Figure 3). The number of rings on each sample exactly matched the respective ages which indirectly means that the trees formed only one ring per year.

Ring width measurements

Throughout the period 1983 to 2012, the growth rate varied highly through the different years within and between trees with a mean annual radial growth of 4.81 mm (varying from 2.9 mm to 8.21 mm) (supplementary Table 1). The mean series inter-correlation ranged from 0.41 to 0.89 with an overall mean 0.57 and age from 28 to 32 years. The correlation of each radius with the master chronology varied from 0.48 to 0.82; with an average of 0.63 with an average first order autocorrelation of 0.46 (supplementary Table 1). The ability of the ring-width chronology to represent an external common forcing was confirmed as twelve trees were required to give an EPS ≥ 0.85 (Wigley et al. 1984) and the EPS from all 30 radii was 0.95.

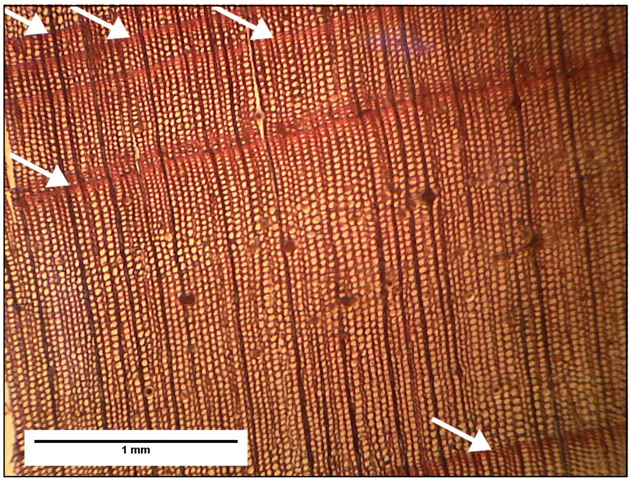

Figure 3. Tree rings of *Cupressus lusitanica*, arrows indicate the ring boundary

The relationships between climate and tree rings

The correlation (*r*) of indexed tree-ring width series of the residual chronology with monthly, seasonal and annual rainfall recorded at Wondo Genet highly varied (Figure 4). The months of February and September have the highest correlation among the months to the ring width indices (Figure 4). The minimum, maximum and average temperature records of Wondo Genet were also correlated with the standard growth index chronology using *R* (treeclim) (Zang and Biondi 2015) and no significant correlation was found.

The highest correlation was observed between the indexed tree ring chronology and the mean annual rainfall, i.e. 0.59 ($p<0.05$). Besides this, high synchrony between the dynamics of relative growth and amount of annual precipitation is clearly observed (Figure 5).

Discussion

Tree ring formation

The distinct growth boundaries in the *Cupressus lusitanica* trees from Wondo Genet demarcated by darker

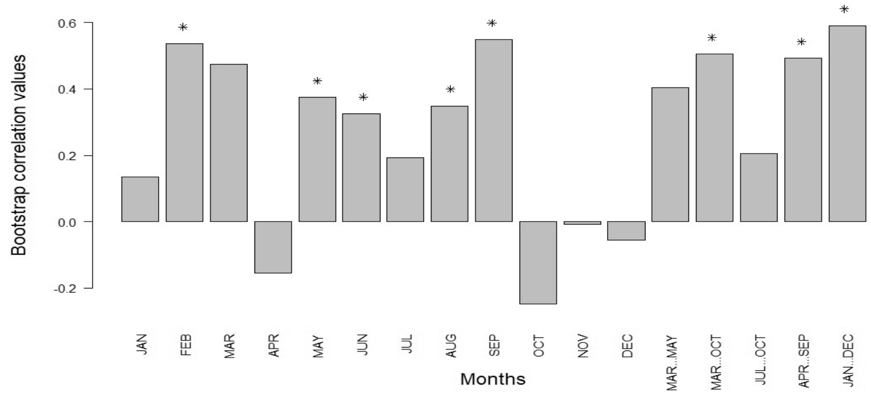

Figure 4. Relationships among the sum of precipitation in each month, selected seasons and year and indexed tree ring chronology. Asterisk (*) indicates significance at $p<0.05$

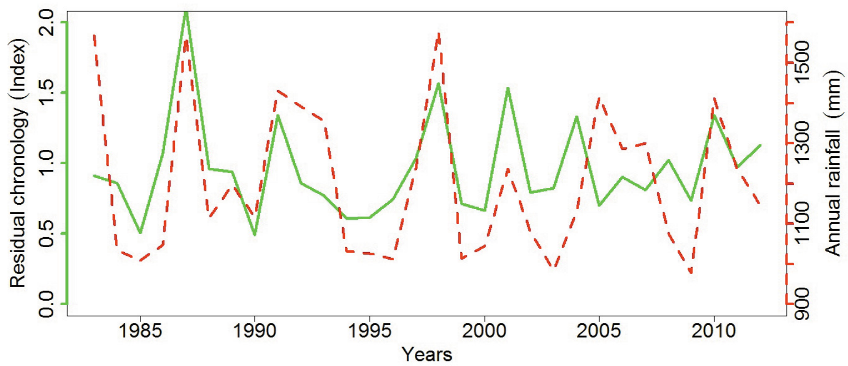

Figure 5. Comparison of the residual ring width index (solid, green line) of *Cupressus lusitanica* growing at Wondo Genet and the total annual rainfall (dashed, red line)

colour of tracheids due to smaller lumen and thicker cell walls (Figure 3) indicated a cessation of cambial activity caused by the alternating wet and dry seasons. Several studies have confirmed that trees growing in the tropics can form clearly visible growth rings that can be used for dendrochronological studies (Eshete and Stahl 1998; Schongart et al. 2006; Dezzeo et al. 2003; Gebrekirstos et al. 2008; De Ridder et al. 2014). *Juniperus procera* from Ethiopian highlands showed that it has high potential for dendroclimatological studies (Couralet et al. 2005); the *Juniperus procera* chronology developed in Gonder, Ethiopia successfully extended the juniper tree-ring chronology chain from Mediterranean region to eastern Africa (Wils et al. 2009); *Acacia* trees from the rift valley of Ethiopia showed clearly visible and successfully cross-dated rings (Eshete and Stahl 1998; Gebrekirstos et al. 2008). The significant correlation obtained between seasonal precipitation and ring width chronology of *Pericopsis elata* from the Democratic Republic of the Congo (De Ridder et al. 2014) and in Venezuela, clearly visible annual growth rings were observed on *Campsiandra laurifolia*, *Acosmium nitens*, *Pouteria orinocoensis* and *Psidium ovatifolium* trees (Dezzeo et al. 2003). This study found that *Cupressus lusitanica* trees from the WGCFNRs formed clearly visible and strictly annual growth rings. In tropical areas with two rainy seasons per annum, double or false rings are expected (Ogden 1981).

Although the rainfall distribution is often classified as bimodal at Wondo Genet (Eriksson et al. 2003, Hunde et al. 2003), there isn't a clear distinction between the two rainy seasons (Figure 2). In addition to this, Munesa-Shashemene, i.e. located 24 km away from Wondo Genet, was described to have short dry season between the two rainy seasons which have similar pattern as of Wondo Genet (Krepkowski et al. 2013). Even though there is moderate amount of rainfall available during the short dry period at Wondo Genet, there is also an increase in the daily minimum temperature (Figure 2) which increases evapotranspiration rate. This is the reason why Wondo Genet is categorized as it has bimodal rainfall distribution. Despite this, annual growth rings were observed. This happened because the gap between the 'short rain' (March-May) and 'long rain' (July-October) was not long and dry enough (Figure 2) to induce cambial dormancy and thereby cause the formation of false or double rings.

Ring width analysis

The number of rings per each sample was determined to be 28 to 32 years confirming the annual nature of the rings. The age of these young trees is similar to that reported in other tree-ring studies (Eshete and Stahl 1998, Schongart et al. 2006, Dezzeo et al. 2003). Although most studies recommend an overlap of at least 30 years (Cook and Holmes 1986) and ideally 100 years (Fowler and Bridge 2017, Baillie and Pilcher 1973), it is hard to find *Cupressus lusitanica* trees older than 30 years in Ethiopia. The EPS value from just twelve trees exceeded the commonly accepted threshold value of 0.85 indicating that the sample size is adequate for a dendroclimatological research (Robertson et al. 1997, McCarroll and Pawellek 1998).

The observed annual growth (Table 1), indicates that this species is fast growing with a high incremental increase in diameter every year (Ogden and West 1981). Fast growing trees with comparable growth characteristics were reported for *Pterocarpus erinaceus* and *Isoberlinia doka* growing in Benin (Schongart et al. 2006). Extreme growth rates were observed in some of the years of our chronology covered (Table 1) and most of the lowest growth rates were observed on historically known drought years (Glantz 1988). For instance, in the year of 1987, we observed wide rings (indexed ring width value of 2.46), which is directly proportional to the high amount of rainfall recorded in that year. Very narrow rings (indexed ring width value of 0.44) were formed in some of the driest years, such as 1985 (Figures 5), which was the year when the devastating drought occurred in some parts of Ethiopia and Sudan (Vadala 2009). Thus, we can confirm that our samples were successfully cross-dated in a way that allowed us to match between the obtained chronologies and records of extreme climate event years.

Climatic and non-climatic factors can be responsible for the high autocorrelation which exceeded the tolerable limit, i.e. 0.4 (Baillie and Pilcher 1973) observed in this study. For instance, it could indicate one-year lag effect of rainfall on the growth of the trees (Cook and Holmes 1986) which is not the case for this study since the growth index poorly correlated with one year lagging rainfall data. Non-climatic factors such as forest management practices and ground disturbance intensity (Kojo 1987) could also be responsible. The possible non-climatic factor which could raise the autocorrelation value in this particular study site is reduced competition for resources in the plantation which has well managed tree spacing and low exposure to low physical disturbances. Within the findings of Dezzeo et al. (2003), similar possible non-climatic reasons and suggestions are believed to determine tree growth.

Table 1. Descriptive statistics of the 30 radii measurements

Measured radii ID	Period	Corr with master	Mean msmt, mm	Stdev	Mean sens1	Mean sens2	Gini	Auto corr
wong22r3	1983-2012	0.72	5.792	3.724	0.41	0.44	0.33	0.54
wong22r4	1983-2012	0.561	5.006	3.729	0.51	0.57	0.35	0.36
wong23r3	1984-2012	0.575	5.17	3.924	0.63	0.6	0.4	0.44
wong23r4	1984-2012	0.603	4.953	4.083	0.48	0.49	0.38	0.58
wong24r1	1984-2012	0.659	4.628	4.567	0.52	0.6	0.43	0.35
wong24r2	1984-2012	0.77	3.974	3.793	0.58	0.69	0.42	0.19
wong25r1	1984-2012	0.538	5.044	3.708	0.35	0.36	0.38	0.73
wong25r3	1984-2012	0.663	4.927	4.019	0.48	0.54	0.43	0.53
wong25r4	1984-2012	0.698	5.13	3.859	0.44	0.42	0.39	0.71
wong29r2	1983-2012	0.599	6.338	3.622	0.52	0.51	0.29	0.34
wong29r4	1983-2012	0.611	5.078	4.03	0.45	0.44	0.38	0.57
wong30r2	1985-2012	0.593	5.498	3.142	0.52	0.53	0.26	0.180
wong30r3	1985-2012	0.575	5.429	4.017	0.68	0.72	0.38	0.06
wong30r4	1985-2012	0.624	5.048	4.092	0.61	0.73	0.41	0.11
wong31r1	1985-2012	0.489	8.21	5.159	0.53	0.5	0.33	0.43
wong31r2	1985-2012	0.777	5.854	5.317	0.64	0.59	0.45	0.62
wong32r1	1984-2012	0.818	2.934	4.588	0.88	1.18	0.65	0.16
wong32r4	1984-2012	0.762	3.438	5.177	0.9	1.14	0.65	0.20
wong33r1	1981-2012	0.62	5.014	4.377	0.54	0.55	0.47	0.56
wong33r2	1981-2012	0.592	5.733	4.438	0.54	0.54	0.4	0.56
wong33r4	1981-2012	0.594	4.792	4.167	0.47	0.48	0.42	0.65
wong34r1	1984-2012	0.765	3.55	3.945	0.66	0.82	0.47	0.28
wong34r2	1984-2012	0.74	3.961	4.479	0.72	0.92	0.5	0.18
wong34r3	1984-2012	0.547	4.027	4.295	0.67	0.66	0.5	0.57
wong08r1	1984-2012	0.586	3.785	4.021	0.45	0.43	0.52	0.76
wong08r2	1984-2012	0.61	4.158	3.977	0.49	0.48	0.49	0.71
wong08r3	1984-2012	0.61	3.972	3.445	0.58	0.54	0.45	0.64
wong08r4	1984-2012	0.634	2.902	3.162	0.54	0.56	0.53	0.69
wong19r1	1984-2012	0.574	4.703	5.237	0.67	0.76	0.51	0.31
wong19r2	1984-2012	0.533	5.241	5.013	0.65	0.7	0.47	0.4
Mean		0.635	4.810	4.170	0.57	0.62	0.43	0.45

The relationships between climate and tree rings

Trees adopt a dormancy mode in order to save energy and minerals to survive through harsh environmental conditions thereby producing anatomical cycle in cell structure (Jacoby 1989). The main factor limiting tree growth differs based on climatic zones (Campoe et al. 2016) since tree growth is primarily influenced by climate (Dezzeo et al. 2003, Wils et al. 2011, Schweingruber 1988) and photoperiod (Stahle et al. 1999). In wet regions like the temperate zone, moisture availability is not always a factor limiting growth and it has been observed that day length (Stahle et al. 1999) and very low seasonal temperatures can limit cambial activity and the formation of growth rings (Boisvenue and Running 2006). However, there is no common consent on the factors that are responsible for causing ring formation in tropical trees (Rowland et al. 2014). The most widely stated factors are the amount of precipitation (Fritts 1976) and soil moisture availability (Campoe et al. 2016) which themselves have a seasonal distribution (Couralet et al. 2005, Schongart et al. 2006, De Ridder et al. 2014).

In this study, we demonstrated that the radial growth of *Cupressus lusitanica* was strongly correlated to the rainfall of the study area especially during wet seasons (r=0.50; p<0.05) which is in line with findings of similar studies conducted in tropical areas with seasonal moisture variability (Schongart et al. 2006, Couralet et al. 2005, Wils et al. 2011). Annual rings of *Pterocarpus angolensis* from Zimbabwe were significantly correlated with the respective year precipitation amount (Stahle et al. 1999). A study conducted in Peruvian tropical forest showed that tree growth is highly associated with the amount of moisture availability (Rowland et al. 2014). The fact that the correlation got higher in the months of February, March and September can be interpreted as during these months the most appropriate amount of water to initiate cambial growth is provided. Here, intra-annual climate-growth relationship studies can answer the question more precisely. Temperature potentially influences tree growth in areas located at high latitudes or altitudes and in regions, where the dry seasons are not long enough to initiate cambial dormancy (Boisvenue and Running

2006). The temperatures recorded at Wondo Genet were not significantly correlated with the residual growth index chronology. Similar results were observed in a study conducted in dry Afromontane forests of Ethiopia, where temperature did not have a significant association with ring widths (Couralet et al. 2007). Even though this does not mean that temperature has no role in ring formation and tree growth (Morales et al. 2004), in our study temperature did not appear as an influential factor on the growth of the *Cupressus lusitanica* trees growing at Wondo Genet.

Conclusions

Based on this study we can say that *Cupressus lusitanica* trees are suitable for dendrochronological studies in an area similar to Wondo Genet due to the character that they form clearly visible annual growth rings and they have wide abundance in a standing tree or in a dead construction or furniture wood form from different eras. Thus, it can contribute towards solving the problem of obtaining long-term forest yield and climate information. Observing the high correlation between ring-width series and the annual rainfall 0.59 ($p<0.05$) from the closest weather station with the longest available climate record to the study site, we concluded that the most determining factor which influenced the radial growth of our sample trees was the amount of precipitation. Moreover, this study showed that dendrochronology still works in sub-optimal regions without unimodal rainfall.

Cupressus lusitanica trees are the second most abundant and commercially valuable trees in Ethiopia. Tree-ring width and accurate age data entry can be the best measure of tree growth and better input for forest growth and yield estimation models. Thus, dendrochronological studies on this species will help to improve forest management by providing more reliable data quality on growth measures and yield estimation of this tree species.

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