Dendrochronologia 40 (2016) 26–35

Contents lists available at ScienceDirect

Dendrochronologia

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

Original article

Potential of dendrochronology in assessing carbon sequestration rates of *Vitellaria paradoxa* in southern Mali, West Africa

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ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 5 May 2016
Accepted 31 May 2016
Available online 7 June 2016

Keywords:
Allometric equation
Climate variability
Drylands
Parklands
Tree rings

ABSTRACT

This study aimed to investigate the applicability of dendrochronology for assessing the growth dynamics and response to climate variability and to estimate the aboveground carbon stock and carbon sequestration potential of *Vitellaria paradoxa* in southern Mali. Twenty stem disks were collected from three land-use types (parklands, fallows and protected areas) in Koutiala and Yanfolila districts. We combined a standard dendrochronological approach with biomass allometric equations to estimate the growth and carbon stocks. The results showed that *V. paradoxa* forms distinct growth ring boundaries but most of the disks from parklands did not successfully cross-date due to management operations like pruning. The tree-ring width showed a significant standardized coefficient of regression with rainfall ($r^2 = 0.66$, $p < 0.001$) but insignificant correlation with temperature. One-way analysis of variance showed no significant difference ($p > 0.05$) for C-sequestration as well as for carbon stocks in aboveground biomass for both land-use types and sites. Mean values of the amount of C-sequestered in Yanfolila were $0.112 \pm 0.0.065$ Mg C ha^{-1} yr^{-1} in parklands, 0.075 ± 0.018 Mg C ha^{-1} yr^{-1} in fallows and 0.064 ± 0.028 Mg C ha^{-1} yr^{-1} in protected areas. In Koutiala, the values were 0.068 ± 0.020 Mg C ha^{-1} yr^{-1} in the parklands and 0.053 ± 0.017 Mg C ha^{-1} yr^{-1} in the fallows. These results clearly indicate that dendrochronology can be applied to assess growth and carbon sequestration potential of *V. paradoxa*. These results also suggest that climate change could affect the growth and carbon sequestration potential of *V. paradoxa*. Given the limited size of our sample, figures on the amount of carbon are indicative calling for applying the tested approaches to larger samples and also to other tree species in West Africa.

1. Introduction

In the Sahel, most of the people practice subsistence agriculture as a main livelihood activity. Fallowing was a common practice in the region to restore soil fertility and sustain land productivity. However, rapid population growth forced the community to shorten the fallowing period and even stop its practice. Such trend in land-use results from anthropogenic pressures such as conversion of forest areas to agricultural lands for cash crops like cotton and over exploitation of forest resources for energy and construction materials leading to forest degradation in the region. Besides anthropogenic pressures, climate variability and change may also have been playing a role in the observed decline of trees in agro-ecosystems. Indeed, there are reports indicating tree density and species decline in the African Sahel which is attributed to climate change (Maranz, 2009; Gonzalez et al., 2012). However, the way trees respond to climate variability remains an important challenge in the global environmental research (Gebrekirstos et al., 2009; Mokria et al., 2015). Such investigation is even more challenging in tropical Africa due to lack of long-term instrumental climate records and tree growth experiments (Gebrekirstos et al.,

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http://dx.doi.org/10.1016/j.dendro.2016.05.004
1125-7865/

2011) but also due to lack of validated approaches. In such situation, tree-rings are valuable proxies to study climate variations and can provide a long-term perspective on how past droughts have affected the growth of trees (Gebrekirstos et al., 2008, 2014; Bräuning et al., 2010; Zuidema et al., 2013; Brienen et al., 2016). Additionally, tree-ring growth and climate reconstructions provide insights of ecosystems response to increasing anthropogenic warming and therefore will help implement mitigation strategies. However, in Africa only few studies have proven the applicability of dendrochronology to assess the impacts of climate variability on tree growth. Available data is from semi-arid savannas (Fichtler et al., 2004; Gebrekirstos et al., 2008; Worbes and Raschke, 2012), the miombo woodlands in Southern Africa (Trouet et al., 2006, 2010), Central Highlands of Ethiopia (Wils et al., 2011) and central Africa (Groenendijk et al., 2014). Such dearth of references reveals that the potential of dendrochronology remains largely untested for most of West African species (Couralet et al., 2010; Groenendijk et al., 2014). Consequently, the impact of climate change on these species remains unknown for the region in general, and in Mali in particular. Mali, as other Sahelian countries, is characterized by recurrent drought events (Butt et al., 2005) but their impact on the seasonal growth characteristics of most of the species including the most dominant tree species of parklands, *Vitellaria paradoxa* C.F.Gaertn, are still unknown. *V. paradoxa* (Shea tree) has huge socio-economic importance (oil, food, wood, fodder, medicine, skin ointment, etc.) for the rural population as well as ecological functions providing a range of ecosystem services including the mitigative services through the carbon stocked, shade, habitats for biodiversity, etc. (Bayala et al., 2014). Such importance explains the various studies which were carried out in southern Mali on this species like its spatial distribution (Maranz et al., 2004), the impact of human practices on its ecology (Kelly et al., 2004) and its flowering phenology (Kelly et al., 2007). None of the above mentioned studies had investigated *V. paradoxa* tree growth responses to changing climate, total aboveground carbon fixed and its carbon accumulation potential. However, empirical data on these aspects are required for effective conservation and management of this species. Thus, the objectives of the current study were (1) to investigate the formation of rings in *V. paradoxa* using dendrochronological approaches, (2) to assess growth dynamics and climate-growth relationships, and (3) to determine total carbon stock and the sequestration potential of *V. paradoxa* under different land-use types and climatic zones. Based on these investigations, we have discussed the applicability of dendrochronology on *V. paradoxa* and the implications of the growth dynamics of this species on its carbon sequestration in the context of land-use and climate changes.

2. Materials and methods

2.1. Study area and species

The study was carried out in two districts (Koutiala and Yanfolila) in southern Mali (Fig. 1). Koutiala is located at 12°38′N and 5°66′W in the Sudano-Sahelian zone and Yanfolila is located at 11°10′N and 8°09′W in the Sudano-Guinea zone. These areas are characterized by poor soil fertility and low agricultural crop productivity (Voortman et al., 2004). The distance between the two study sites is about 445 km and they were selected to represent two different climatic zones of *V. paradoxa* distribution area. The rainfall pattern at both sites is uni-modal with similar mean temperatures, but rainy season lengths and annual rainfall amounts are different. In Koutiala district, the length of the rainy season is 3–4 months (Fig. 2) with a mean annual rainfall of 889 ± 173.16 mm and mean annual temperature of 27.98 ± 0.42 °C. In Yanfolila district, the rainy season lasts for 4–5 months (Fig. 2) with a mean annual rainfall of 1126 ± 173.96 mm and mean annual temperature of 27.79 ± 0.48 °C.

Vitellaria paradoxa C.F Gaertn. (formerly *Butyrospermum parkia* G. Don) belong to the Sapotaceae family. *V. paradoxa* is endemic to the African Savannas, north of the equator (Maranz et al., 2004) and extends from Senegal to Sudan and to western Ethiopia and Uganda, in a 500–700 km wide belt (Hall et al., 1996; Bouvet et al., 2004). It is the only species in the genus *Vitellaria*, and is a characteristic species of the savanna woodlands (Byakagaba et al., 2011). According to Nouvellet et al. (2006), *V. paradoxa* is the most dominant deciduous tree species in the parklands reaching up to 15 m high (and 100 cm diameter) and covers more than 20 million hectares in Mali. The leaf shedding behaviour of *V. paradoxa* is described in Hall et al. (1996).

2.2. Field sampling

Stem disks of *V. paradoxa* were collected at breast height (1.3 m) from trees of different diameter class, ranging from 9.03–38.23 cm, at both sites (Table 4). As no protected area was found in Koutiala, only parklands and fallows were considered whereas in Yanfolila samples were collected from three land-use types (parklands, fallows and protected areas). Parklands constitute a land-use type, which is formed of scattered trees and shrubs from the natural woodland after clearing the bush for agricultural cropping (Boffa, 1999). These are dominated by *V. paradoxa* in southern Mali. In turn a fallow is cultivated land which has been left uncropped for few years as a way of restoring its soil fertility. The protected areas are delimited areas of forest reserves consisting of mixed species (plants and animals) mainly for biodiversity conservation. The ecosystems under these two latter land-use types are more exposed to nutrients competition because of their denser tree populations compared to the parklands. In total, 20 stem disks, four from each land-use type, were collected. The following information was recorded: tree morphological characteristics (diameter and height) and management practices.

2.3. Tree-ring analyses

The stem disks were dried in an open area under shade before being transported to the Dendrochronology Laboratory at ICRAF (World Agroforestry Centre) in Nairobi, Kenya. Standard dendrochronological methods were used to prepare the samples for measurement (Cook et al., 1990). To improve the visibility of the growth ring boundaries, the samples were polished gradually using sand paper of grit size 400–1200 and then the dust was removed with compressed air. To study the features that characterize the growth ring boundaries, transversal micro-thin sections (20–30 μm) were prepared from disks of different sites using a microtome. Tree-ring boundaries were marked under a microscope connected with a LINTAB 6.0 measuring systems (Rinntech Inc., Germany). Tree-ring widths were measured from two to four radii (from pith to bark) to the nearest 0.01 mm using a LINTAB 6.0 supported by the software TSAP-Win (Times Series Analysis and Presentation, version 4.6× for Microsoft windows; Rinn et al., 1996). Individual tree series were obtained by combining ring-width curves of 2–4 radii after cross-dating. Cross-dating was done both visually and statistically. The visual cross-dating was conducted using pointer years (extreme wide or narrow rings). The pointer years allowed to detect and correct errors due to possible missing or false rings (Gebrekirstos et al., 2008). Cross-dating was further verified statistically by using the TSAP which allowed to measure the '*Gleichläufigkeitkoeffizient*' (coefficient of parallel variation between tree-ring series) or GLK and T-value that verifies the degree of similarity of two curves (Baillie and Pilcher, 1973). The

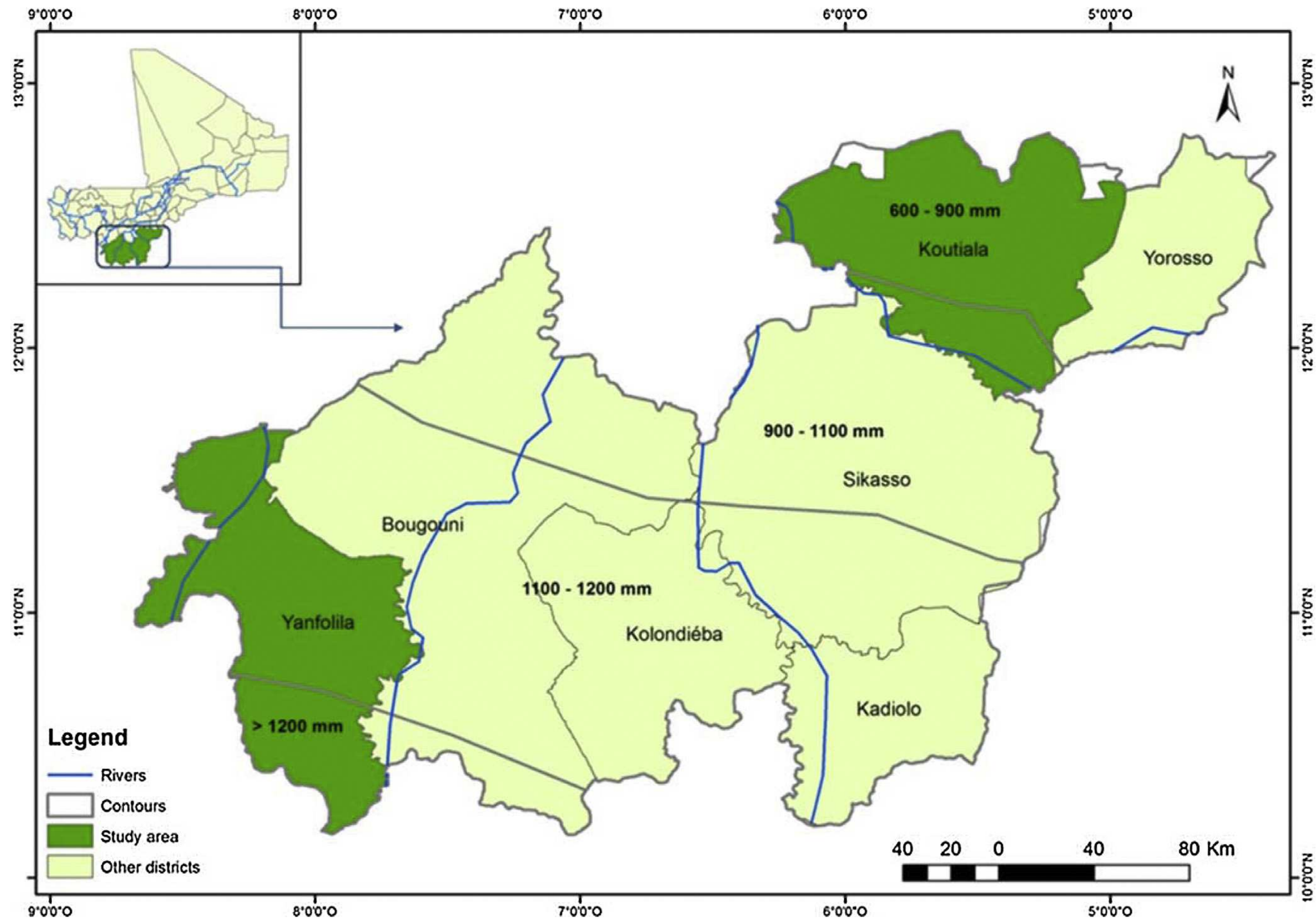

Fig. 1. Location of the study sites in southern Mali, West Africa.

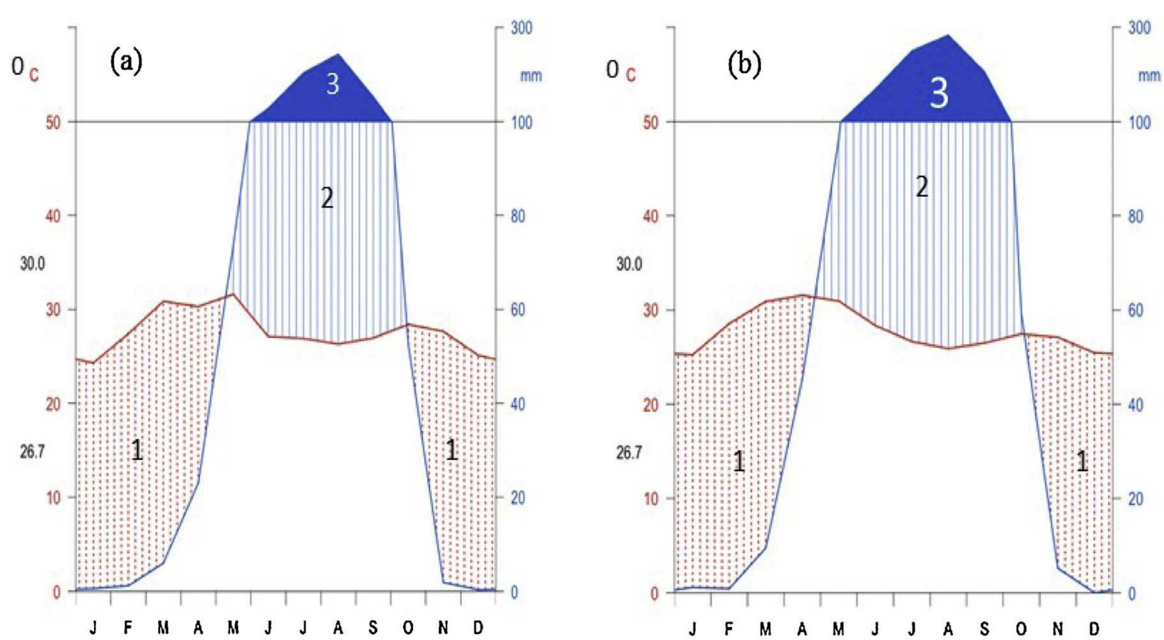

Fig. 2. Climatic diagram drawn according to Walter and Leith (1960) for Koutiala (a) and Yanfolila (b) in southern Mali, West Africa. Rainfall (mm) data from 1968 to 2012 in Koutiala (a) and temperature (°C) from 1982 to 2012 in Koutiala. Rainfall (mm) data and temperature (°C) from 1982 to 2012 in Yanfolila (b). 1 = dry season, 2 = rainy season and 3 = major seasonal precipitation.

COFECHA program was also used to check the accuracy of cross-dating (Cook and Holmes, 1999). Those series with GLK higher than 65% (Eckstein and Bauch, 1969) and T-value greater than 2 were selected for further analysis. Using the same procedure, successfully cross-dated mean ring width series of different sample trees were averaged to build land-use specific mean chronologies. A master sites chronology, with a length of 78 years and 68 years, was further constructed by building the mean of the different land-use types in Koutiala and Yanfolila, respectively.

The average series were detrended by fitting a cubic spline with a 50% frequency response cut-off at 32 years to minimize non-climatic signals (age-related growth trends and competition effects, etc.) using the ARSTAN software (Holmes, 1994). Finally, standard and residual chronology were obtained for each site. The standard chronology, was processed as above without autoregressive modeling. The residual chronology was additionally processed using autoregressive modeling to remove autocorrelation, making it more suitable for regression analysis. The chronology quality was evaluated in each site by using the value of EPS (expressed population signal) with a threshold of 0.85, which determines at which degree the chronology is reliable (Wigley et al., 1984).

2.4. Wood density measurement

Accurate estimates of aboveground biomass and carbon require measurements of wood density. Because of the variability of wood density between and within tree species, wood specific density for individual sample trees was determined (Table 4). To do so, a subsample was taken from each stem disk and saturated with water for 30 min. The wood specific density (ρ) of each individual sample tree was calculated as dry weight to fresh volume ratio after drying the samples for 72 h at 105 °C (Nogueira et al., 2005).

2.5. Estimation of carbon stocks in aboveground biomass

The aboveground biomass (AGB) estimation requires the use of many predictors in order to reduce error. However, Chave et al. (2014) argued that two parameters namely, diameter at breast height (DBH) and wood density (ρ), are enough as the main predictors of AGB. Species-specific allometric equation for *V. paradoxa* has been developed for a site located in Cameroon (Peltier et al., 2007) but it presents about 60% of error risk probably due to the fact that only six individuals were used for its development. As a result, we selected the improved pantropical allometric model because of the similarity of the conditions in which it was developed (dry tropical forests) with our study sites: distinct dry season and rainfall below 1500 mm per year, more than 5 months dry season (Chave et al., 2014). Moreover, this equation was developed from 4004 tree species originating from 58 sites and 1429 (36%) from Africa (Chave et al., 2014).

$$AGB = exp\left[-1.803 - 0.976E + 0.976\ln(\rho) + 2.673\ln(D) - 0.0299[\ln(D)]^2\right] \quad (1)$$

Where:For the units of the parameters used in Eq. (1): AGB is in kilograms, ρ is in grams per cubic centimeter and D is in centimeters.

E is a measure of environmental stress and is defined as:

$$E = (0.178xTS - 0.938xCWD - 6.61xPS)\,10^{-3} \quad (2)$$

Where:The parameters used in Eq. (2) were defined as following: TS is the standard deviation (SD) of the mean temperature over a year, expressed in degrees Celsius multiplied by 100; CWD (maximum climatological water deficit) is computed by summing the difference between monthly rainfall and monthly evapotranspiration (ET), only when the difference is negative and PS (precipitation seasonalty) is the coefficient of variation in monthly rainfall values, or the SD expressed in percent of the mean value.

2.6. Estimation of C-sequestration from tree-ring analysis

The age and diameter increment rates of each sample were determined from tree-ring analyses. Hence, the relationships between age and biomass, age and diameter, and age and height of *V. paradoxa* were established using a non-linear regression.

The AGB of each individual tree was estimated by replacing D in Eq. (1) by its corresponding diameter derived from the tree-rings. Then the AGB of each individual tree over its life span was divided by the corresponding age derived from tree-ring analyses to obtain the annual biomass production (Worbes and Raschke, 2012). Carbon stock and carbon sequestration were derived as representing 50% of the AGB.

The estimates of both biomass and carbon stock for the stand were obtained by multiplying the average values for a given land-use of the sample trees by the density recorded in that same land-use type.

2.7. Climate data

Mean monthly rainfall and temperature were provided by the meteorological station of Koutiala; and the Yanfolila climate data was obtained from the Bougouni meteorological station located at 80 km. The recorded meteorological data of rainfall covered a period of 45 years (1968–2012) for Koutiala, and 31 years (1982–2012) for Yanfolila. Temperature data for both sites was recorded for the last 31 years (1982–2012). Evapotranspiration (ET) data covering a 12-year period (2000–2012) were collected from the above mentioned meteorological stations for the two sites, respectively.

2.8. Statistical analyses

The climate-growth relationships were investigated through multiple regression analysis between tree-ring index and climatic factors (rainfall and temperature). Pearson's correlation analysis was applied to investigate the existence of similarities in *V. paradoxa* growth patterns of the two climatic zones. Annual and major seasonal precipitation (defined as the amount of rain recorded between June to September) and mean annual temperature of each site were considered. The ring widths of the two sites were compared with a *t*-test. Data of carbon accumulated per year and over the life span of trees were subjected to a one-way ANOVA for both land-use types within the sites and between the sites using the statistical software SPSS (version 20.0). When the analysis proved to be significant at 5% level, means separation was done using the least significant difference test.

3. Results

3.1. Tree-ring structure and ring width analysis

Wood anatomical analyses showed that *V. paradoxa* forms distinct growth rings on the samples of all land-use types and sites (Fig. 3). However, we found few false, partially indistinct and locally missing rings near the bark in most samples from Yanfolila parklands. The growth ring boundary of *V. paradoxa* is characterized by smaller size vessels and thick cell walls at its end (Fig. 3). The transition between early to late wood is gradual with more distinct transition in wider rings. Tree-ring analyses revealed that the tree age ranges from 16 to 78 years. The sample size is small to make statistically sound comparisons among the land-use types. Nevertheless, between land-use types, there was not a significant difference in annual radial growth for the same site whereas the mean annual radial growth of the parklands in Yanfolila was statistically different ($p < 0.05$) from that of the fallow in Koutiala

Table 1
Annual radial growth of *Vitellaria paradoxa* in different land-use types in southern Mali, West Africa.

Sites	Land-use types	N	Annual radial growth ring width (mm) Mean ± SE
Koutiala	Parklands	4	2.60 ± 0.13ab
	Fallow	4	2.10 ± 0.12b
Yanfolila	Parklands	4	3.25 ± 0.33a
	Fallow	4	2.50 ± 0.07ab
	Protected area	4	2.57 ± 0.14ab

NB: N = number of stem disks collected per land use types. Values followed by the same letter are not statistically different at 95%.

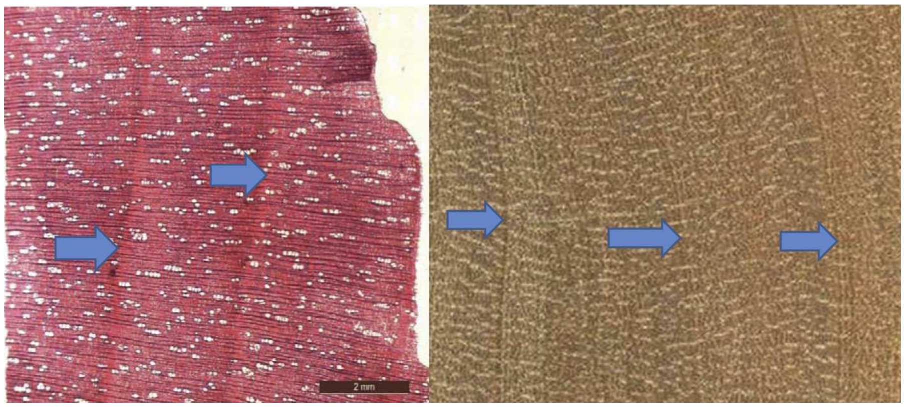

Fig. 3. Image of the cross-sectional surface of wood sample of *Vitellaria paradoxa* from southern Mali, West Africa. The arrows indicate growth ring boundaries.

Table 2
Descriptive statistics of tree-ring width chronologies (average of Person's correlation, T-value ($p < 0.05$) and GLK or coefficient of parallel variation for *Vitellaria paradoxa* from southern Mali, West Africa.

Statistical parameters	Sites	
	Koutiala	Yanfolila
Number of samples	7	8
Mean length of series (year)	46	40
Time span (year)	(78)1936–2013	(68)1946–2013
Common interval time span (year)	(34)1980–2013	(44)1970–2013
Mean sensitivity (MS)	0.30	0.33
Standard deviation (SD)	0.73	0.77
Correlation among all radii	0.35	0.40
Correlation between-tree	0.23	0.30
Autocorrelation	0.20	0.01
Expressed Population Signal (EPS)	0.93	0.94
Radii vs mean	0.55	0.64
Mean T-value	2.00	2.00
Mean GLK (%)	66.00	76.00

(Table 1). Thus, there is a significant difference in ring width growth between the sites (df = 134, t-value = −3.9, *p*-value = 0.00007) with Koutiala displaying the lowest values.

3.2. Tree-ring chronologies

Cross-dating between radii of the same disk was successful for most of the disks from all land-use types, in both sites, except for all disks from the parklands in Yanfolila and one disk from the fallows in Koutiala. This corresponds to successful cross-dating of 7 out of 8 trees in Koutiala and 8 out of 12 trees in Yanfolila, i.e., a total of 15 out of 20 or 75% success for both sites. Cross-dating of different samples was successful with GLK of 66% in Koutiala and 76% in Yanfolila (Table 2). The length of chronology varied between 68 years in Yanfolila and 78 years in Koutiala. The mean sensitivity (MS) and standard deviation (SD) provide information on inter-annual variability on ring width. The high values of mean sensitivity and standard deviation in both sites indicate that *V. paradoxa* growth is sensitive to changes in environmental conditions and that external factors affected tree growth at both sites. The correlation coefficients values between all radii and between trees (Table 2) indicate similarity in annual growth patterns among sampled trees. The results revealed that *V. paradoxa* annual growth patterns were more similar among sample trees from Yanfolila as compared to the samples of Koutiala. Expressed population signal (EPS) value of our studied trees (0.93 in Koutiala and 0.94 in Yanfolila) is higher than the threshold standard (0.85) indicating strong coherency among the different time series included in the final tree-ring chronologies. Our findings showed a weak non-significant correlation ($r = 0.20$; $p > 0.05$) between the chronologies at both sites (Koutiala and Yanfolila).

3.3. Climate-growth relationships

The annual radial growth varied according to years (larger ring formed during good rainfall years and narrower rings in low rainfall years) as shown in Figs. 4 and 5. Growth of *V. paradoxa* was positively correlated with moisture availability (Table 3). A significant relationship was found between *V. paradoxa* tree growth and annual rainfall amounts in Koutiala ($r^2 = 0.62$, $n = 45$ years, $p < 0.001$; Fig. 4a) and Yanfolila ($r^2 = 0.66$, $n = 31$ years, $p < 0.001$; Fig. 4b). The relationship between major seasonal precipitation and residual chronology was even stronger in Koutiala ($r^2 = 0.66$, $n = 45$ years, $p < 0.001$; Fig. 5a) and Yanfolila ($r^2 = 0.72$, $n = 31$ years, $p < 0.001$; Fig. 5b). The values of this regression coefficient were slightly higher than those of the standard chronology (Table 3). However, no significant correlation was found for temperature either in Koutiala ($r^2 = -0.06$, $n = 31$ years, $p > 0.05$) or in Yanfolila ($r^2 = 0.05$, $n = 31$ years, $p > 0.05$).

3.4. Estimation of carbon stocks and sequestration in AGB

V. paradoxa density (number of *V. paradoxa* trees per hectare measured in the field) varied according to land-use types and sites. Higher density was observed in the parklands with 16 individu-

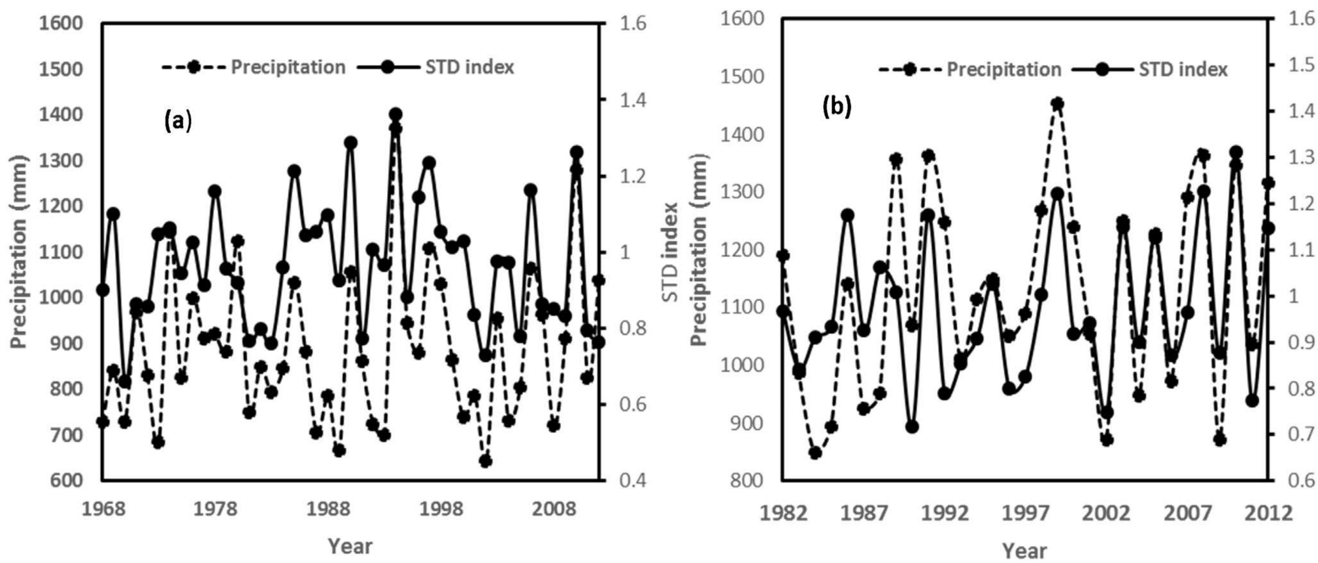

Fig. 4. Relationship between standard index (STD) of *Vitellaria paradoxa* and precipitation in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa.

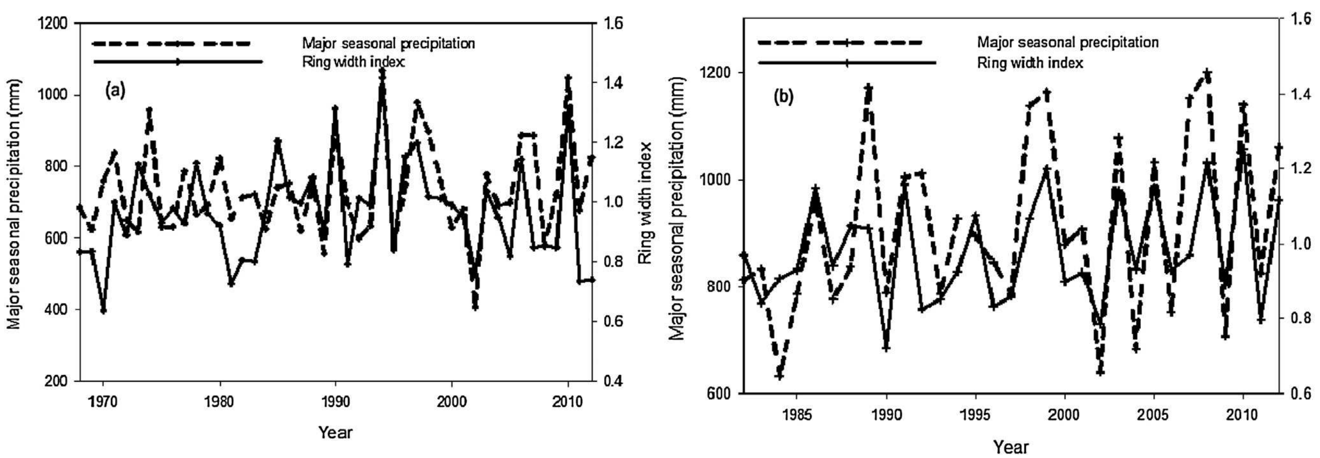

Fig. 5. Relationship between the residual chronology of *Vitellaria paradoxa* and major seasonal precipitation in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa.

Table 3
Multiple regression analysis between *Vitellaria paradoxa* tree growth and selected climatic parameters in southern Mali, West Africa.

Sites	Standard chronology index			Residual chronology index		
	Annual precipitation	Seasonal precipitation	Annual temperature	Annual Precipitation	Seasonal precipitation	Annual temperature
Koutiala	0.62***	0.63***	−0.06	0.62***	0.66***	0.02
Yanfolila	0.66***	0.70***	0.05	0.67***	0.72***	0.11

NB: *** P < 0.001.

Table 4
Characteristics of sampled trees and wood parameter of *Vitellaria paradoxa* in different land-use types in southern Mali, West Africa.

Sites	Land-use types	N	Age range	DBH (cm) range	Height (m) range	ρ (g cm^{-3}) Mean ± SE
Koutiala	Parklands	4	21–78	11.39–34.16	4.71–9.22	0.72 ± 0.03a
	Fallow	4	35–72	12.94–33.15	4.12–8.28	0.75 ± 0.02a
Yanfolila	Parklands	4	19–43	11.39–33.64	6.15–10.10	0.76 ± 0.01a
	Fallow	4	22–54	11.72–25.16	4.24–8.40	0.71 ± 0.03a
	Protected area	4	16–68	9.03–38.23	3.31–12.37	0.70 ± 0.04a

NB: N = number of stem disks collected per land use types; Mean values within each site followed with the same latter in the same column are not statistically different at 95%.

als ha^{-1} as compared to the fallows with 13 individuals ha^{-1} in Koutiala. In Yanfolila, the species displayed a density of 27, 23 and 18 individuals ha^{-1} in parklands, fallows and in protected areas, respectively. The higher density of *V. paradoxa* in parklands indicates the impacts of human beings who preserve and nurture it as compared to the fallows and protected areas where such inten-

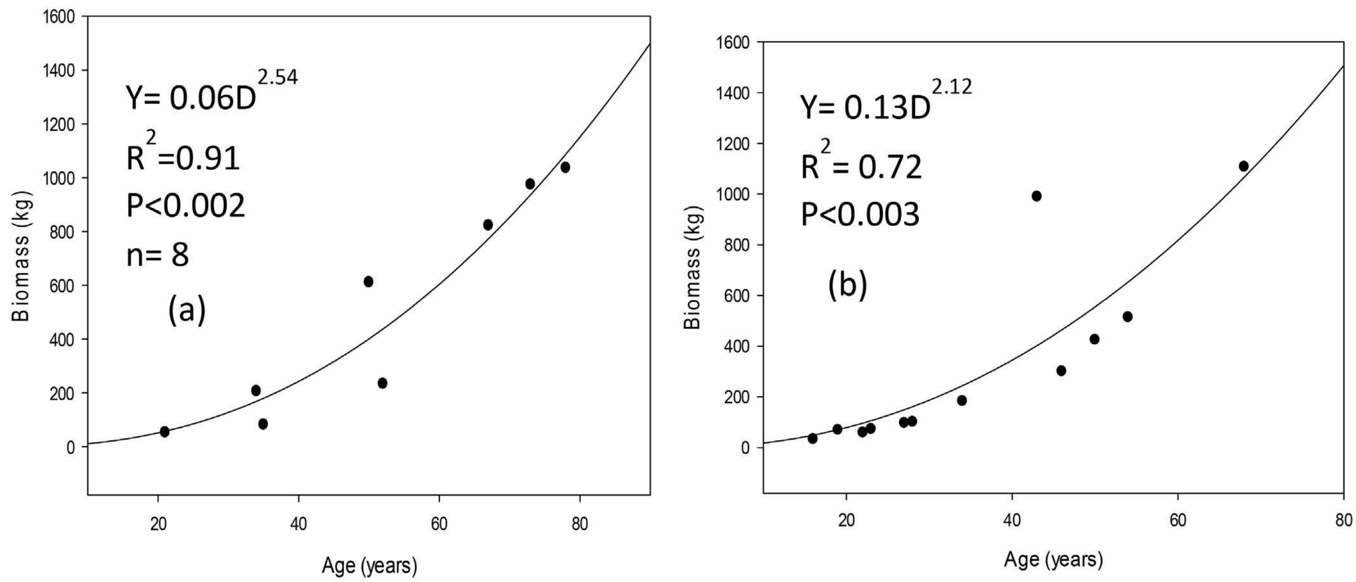

Fig. 6. Relationship between age and biomass of *V. paradoxa* in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa.

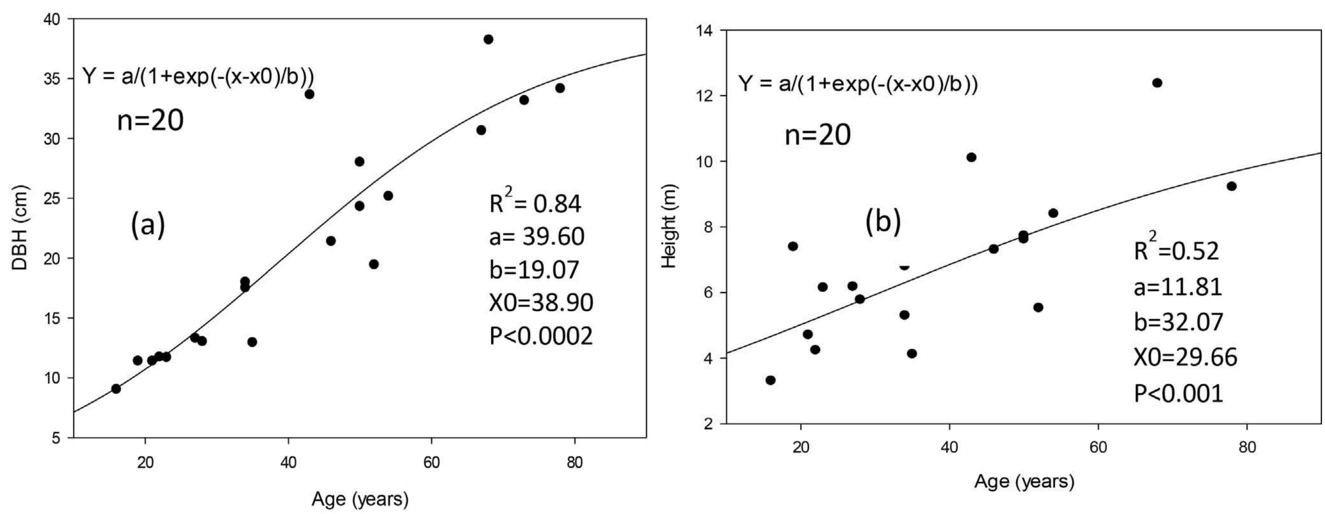

Fig. 7. Relationship between age and diameter (a) and age and height (b) of *V. paradoxa* from southern Mali, West Africa.

tional management action does not exist. Wood specific density of *V. paradoxa* ranged between 0.61 and 0.82 $g\,cm^{-3}$ with an overall mean value of $0.74 \pm 0.07\,g\,cm^{-3}$. Thus, it was not statistically different for both land-use types and study sites (Table 4).

AGB was estimated using allometric Eq. (1) associated with tree-ring analyses. Biomass ($n = 8$, $r^2 = 0.91$, $p < 0.002$ Fig. 6a and $n = 12$, $r^2 = 0.72$, $p < 0.003$ Fig. 6b), diameter ($n = 20$, $r^2 = 0.84$, $p < 0.0002$ Fig. 7a) and height ($n = 20$, $r^2 = 0.52$, $p < 0.001$; Fig. 7b) were significantly correlated with age. There was no significant difference for C-sequestration in AGB ($p > 0.05$) for both land-use types and sites (Table 5). Similar trend was observed for carbon stocks for both land-use types and sites (Table 5).

4. Discussion

V. paradoxa showed distinct ring boundaries at both sites characterized by small size vessels and thick cell walls (Fig. 3). Despite the distinctiveness of the growth ring boundaries some disks could not be successfully cross-dated. Our samples from protected areas presented no missing rings as opposed to those from parklands and fallows, especially, in Yanfolila. Factors that may have caused these differences are the land-use management inducing, in some cases, growth ring anomalies (missing rings). Indeed, most of the non-cross-dated disks were collected from parklands where more active management operations are applied to both land (e.g. manure, tillage, etc.) and to the preserved trees (e.g. pruning). These assertions are in agreement with Gebrekirstos et al. (2008) who reported difficulty of cross-dating stem disks collected from communal grazing and cultivated lands due to possible missing rings. They also corroborate the findings of Schweingruber (1996), who reported that only samples from undisturbed areas provide the best information for dendroclimatological studies.

In the absence of reference chronologies for our studied species, we compared our data to similar studies from tropical Africa. The thresholds of GLK and T-value found in this study were within the range of those reported by previous authors (Schöngart et al., 2006; Gebrekirstos et al., 2008; Trouet et al., 2010; De Ridder et al., 2013).

The distinct growth zones are indication of periodic dormancy induced by the following factors. First, both study sites are characterized by seasonal climate, i.e., there is a distinct seasonality

Table 5
Carbon stocks ($Mg\,C\,ha^{-1}$) and carbon sequestration ($Mg\,C\,ha^{-1}\,yr^{-1}$) in aboveground biomass by *V. paradoxa* in different land-use types and sites in southern Mali, West Africa.

Land use types	Sites			
	Koutiala		Yanfolila	
	Carbon stocks	Carbon sequestration	Carbon stocks	Carbon sequestration
Parklands	3.810 ± 1.760a	0.068 ± 0.020a	4.148 ± 3.071a	0.112 ± 0.065a
Fallow	3.431 ± 1.418a	0.053 ± 0.017a	3.398 ± 1.211a	0.075 ± 0.018a
Protected area			3.473 ± 2.224a	0.064 ± 0.028a

NB: Mean values within each site followed by the same letter in the same column are not statistically different at 95%.

between dry and rainy season (Fig. 2). Second, the species displays a leaf phenology that matches the distinct seasonality of rainfall pattern, shedding its leaves during the dry season, between December and March and new leaf flushing as soon the next rainy season starts (Hall et al., 1996). Hence, the coherent pattern of tree-ring series among the chronologies of land-use types within a site suggests that an external factor, which is the seasonal precipitation, affected the trees in a similar way. Similar findings were reported in other dendrochronological studies on tree species from Africa (Fichtler et al., 2004; Trouet et al., 2006; Gebrekirstos et al., 2008). Considering all the above factors, it can be concluded that tree-rings in *V. paradoxa* formed in the study sites, in southern Mali, are annual. However the weak non-significant correlation ($r = 0.20$, $p > 0.05$) between the sites indicates that *V. paradoxa* growth is not only influenced by the precipitation amount but probably by site specific factors such as soils and management practices. Similar findings were reported by Fichtler et al. (2004) in southern Africa for *Burkea africana*, and Trouet et al. (2010) in Miombo woodland for *Brachystegia spiciformis*.

In both sites, regardless of the type of chronology (standard or residual), significant correlations were established ($r^2 = 0.62$, $r^2 = 0.66$, $p < 0.001$, Table 3; $r^2 = 0.66$, $r^2 = 0.72$, $p < 0.001$, Table 3) with major seasonal precipitation, which is one of the most influential factors determining tree (*V. paradoxa*) ring growth in southern Mali. This finding agrees with Krepkowski et al. (2011), Brienen et al. (2016) and Hiltner et al. (2016) who found that tropical tree growth is sensitive to the amount of rainfall received. The fact that major seasonal precipitation displayed higher regression coefficient values with ring growth compared to annual precipitation (Fig. 4) also agrees with some findings of previous tree dendrochronological studies in Africa (Fichtler et al., 2004; Gebrekirstos et al., 2008; Nicolini et al., 2010; Trouet et al., 2010). In contrast, the studies of De Ridder et al. (2013) on *Terminalia superba* did not find any correlation between precipitation and tree growth in Ivory Coast while the same species showed a positive correlation with the rainfall in the Democratic Republic of Congo (DRC).

Significant positive correlation with major seasonal precipitation suggested that soil moisture, which depends on the amount of rainfall, may be one of the major factor affecting tree growth (Therrell et al., 2006). Non-significant lower growth rates and carbon stocks in the northern site may be due to lower (soil) water availability while correlation with temperature in both sites was also not significant. The lack of significant correlation with temperature corroborates the findings of Gebrekirstos et al. (2008) from Ethiopia but in our case this could also be an artefact of the number of tree samples and sites (only 2). In contrast, Fichtler et al. (2004) and Vlam et al. (2014) reported a negative correlation with temperature indicating a loss of assimilated carbon as a source of energy through respiration.

The diameter and biomass of *V. paradoxa* were significantly correlated (Figs. 6 and 7a) to its age in the study sites corroborating other studies that reported similar trends (Mbow et al., 2013; Beedy et al., 2015; Mokria et al., 2015). In the absence (very limited) of planted stands of known age of *V. paradoxa*, the relationships established between tree age and tree parameters will be very useful for managers and ecologists and for generating data needed for carbon market.

The difference between the mean values of C-sequestered in parklands ($0.112 \pm 0.065\,Mg\,C\,ha^{-1}\,yr^{-1}$), fallows ($0.075 \pm 0.018\,Mg\,C\,ha^{-1}\,yr^{-1}$) and protected areas ($0.064 \pm 0.028\,Mg\,C\,ha^{-1}\,yr^{-1}$) was not statically different in Yanfolila. Similarly, the carbon sequestered in parklands ($0.068 \pm 0.020\,Mg\,C\,ha^{-1}\,yr^{-1}$) was not statically different from that of the fallows ($0.053 \pm 0.017\,Mg\,C\,ha^{-1}\,yr^{-1}$) in Koutiala. Parklands are derived from human agricultural activities. Hence, the highest amount in parklands could be due to management practices that increase the density of *V. paradoxa*. Like carbon sequestration, the carbon stock have similar trend according to land-use types at each site. In Koutiala, the estimates of carbon stocks in AGB ranged from 3.431 to $3.810\,Mg\,C\,ha^{-1}$, whereas in Yanfolila the range was 3.398 to $4.148\,Mg\,C\,ha^{-1}$ (Table 5). The lack of significant difference for carbon stocks and sequestered among land-use types could be due to the limited number of samples collected that did not represent the structure of the population sampled. Nevertheless, our results revealed that the amount of carbon stocks as well as carbon sequestration is higher in Yanfolila (with higher rainfall amount) compared to Koutiala.

The carbon estimates of the current study are within the range reported by Peltier et al. (2007) in Cameroon ($5.046\,Mg\,C\,ha^{-1}$ in AGB in the parklands of *V. paradoxa*) and lower than those of Saïdou et al. (2012) in Benin ($20.17\,Mg\,C\,ha^{-1}$ in the parklands of *V. paradoxa*). In turn, they are lower than other reported carbon ranges, which are $22.4–54.0\,Mg\,C\,ha^{-1}$ for parklands of *V. paradoxa* and *Faiderbia albida* in southern Mali (Takimoto et al., 2008), $22.2–70.8\,Mg\,C\,ha^{-1}$ for parklands (Luedeling and Neufeldt, 2012), and within to $3.1–86.5\,Mg\,C\,ha^{-1}$ for the genera of Acacia and Combretum in Mozanbique (Ryan et al., 2011). The range of carbon sequestered found in the literature in areas ecologically close to ours evolves from $0.4\,Mg\,C\,ha^{-1}\,yr^{-1}$ (Luedeling and Neufeldt, 2012) to $1.09\,Mg\,C\,ha^{-1}\,yr^{-1}$ (Takimoto et al., 2008). The difference between our values and the ones reported in the literature may be explained by the difference in allometric equations used, the density of tree species, the difference in tree growth rates and climatic zones and the fact that our study focused on a single species. In addition to the above cited investigations conducted on natural stands, there are emerging data from commercial planted stands. For instance, Bakayoko et al. (2012) estimated the biomass of 12-year old plantation of *Cedrela odorata* in Ivory Coast to be $1.6\,Mg\,C\,ha^{-1}$ and $5.95\,Mg\,C\,ha^{-1}$ for 18-year old planted *Gmelina arborea*. The results of the last study constitute an indication of the relationship between the accumulated amount of biomass (carbon) and tree age agreeing with our findings. Moreover, our figures using ring analysis may be more accurate compared to those of most of the above carbon estimates which used only the diameter as a main predictor of the biomass. As reported by Williams et al. (2008) the allometric model can strongly influence biomass estimate. However, environmental conditions like climate constitutes a key factor affecting carbon sequestration (Nair et al., 2009; Luedeling and Neufeldt, 2012). In our case, lower rainfall amount was associated with narrow rings regardless of the sites and land-use types and this is in agreement with Woomer et al. (2004) who have observed an important reduction of AGB in the Sahel. Our results are also in line with Ahlström et al. (2015), who reported that the semi-arid ecosystems biomass is strongly associated to precipitation and Poulter et al. (2014) whose findings showed that higher precipitation increased soil moisture and plant carbohydrate reserves to the benefit of biomass in semi-arid ecosystems.

Overall, the potential of the most dominant parkland species in carbon stocks in southern Mali is modest as well as that of the whole system under the dryland conditions (Luedeling and Neufeldt, 2012). If this potential is feeble compared to other agro-ecosystems in other climatic conditions, the contribution of the carbon sequestered by *V. paradoxa* and indeed the parkland tree species in general (Bayala et al., 2014) in maintaining the soil conditions (soil carbon) is very critical for the sustainability of the production systems in the drylands.

5. Conclusions

As far as we know, the tree-ring chronology presented in Figs. 4 and 5 is the first for *V. paradoxa* in southern Mali, and probably, so far, the first for this species in West Africa. This pilot study revealed that *V. paradoxa* forms annual rings. The tree-ring chronologies were significantly correlated with precipitation indicating that it is one of the most important climatic factors affecting tree growth patterns in the study sites. Higher values were observed for AGB and C-sequestration rate in the more humid site (Yanfolila) compared to Koutiala. Our study clearly demonstrated the applicability of dendrochronology approaches to *V. paradoxa*, despite some of its weaknesses, which are small tree sample size, limited number of sites, the use of rainfall data far away (80 km) from Yanfolila, and the use of a general equation for biomass estimation. Future studies of the same nature (comparing land-uses) should be based on larger samples that closely mimic the structure of the vegetation. This pilot study may contribute to increase scientific knowledge and will be a reference in the dendrochronology application for this common species in the West African drylands. There is also a need to extend such approach to other species in different ecologies of the whole West Africa.

Acknowledgements

This research was funded by the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) program, CRP 6.4 and 7 (Consortium Research Programme) and the West and Central Africa Regional Office – Sahel Node of the World Agroforestry Centre (ICRAF), which are gratefully acknowledged. Special thanks to Edith Anyango and Mulugate Mokria for their assistance during all the laboratory processing at ICRAF Dendrochronology laboratory in Kenya. We thank the farmers for allowing us to work in their fields. We extend our thanks to all staff of the ICRAF Sahel node, Mali, for their support during the fieldwork and my internship at ICRAF.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dendro.2016.05.004.

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