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

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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 were 1.13 ± 0.63 Mg C ha^{-1} yr^{-1} in parklands, 0.93 ± 0.50 Mg C ha^{-1} yr^{-1} in fallows 0.66 ± 0.43 Mg C ha^{-1} yr^{-1} in the protected areas in Yanfolila. In Koutiala, the values were 0.73 ± 0.40 Mg C ha^{-1} yr^{-1} in the parklands and 0.67 ± 0.52 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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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 39 to 130 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