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Frankincense tree recruitment failed over the past half century

Motuma Tolera[a,b,*], Ute Sass-Klaassen[a], Abeje Eshete[c], Frans Bongers[a], Frank J. Sterck[a]

[a] Forest Ecology and Forest Management Group, Centre for Ecosystem Studies, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[b] Hawassa University, Wondo Genet College of Forestry and Natural Resources, P.O. Box 128, Shashemene, Ethiopia
[c] Forestry Research Centre, Ethiopian Institute of Agricultural Research, P.O. Box 30708, Addis Ababa, Ethiopia

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ABSTRACT

Boswellia papyrifera (Burseraceae) trees grow in dry woodlands south of the Sahara and produce frankincense, the economically important olio-gum resin used for cultural and religious ceremonies throughout the world and as raw material in several industries. Across its distribution area, this species is threatened by farmland expansion, fire, improper tapping and overgrazing. Most of its populations lack saplings and small-sized trees (e.g. <10 cm). It is unknown whether the older, adult trees represent a single or several cohorts, representing single or plural regeneration and survival waves. To understand such long-term population dynamics, it is imperative to evaluate the age structure of the current populations. We used tree ring analysis to determine the age-diameter relationship. This study, (1) determines radial growth dynamics and age-diameter relationship of *B. papyrifera*, including verification of annual growth-ring formation, and (2) constructs the population age structure and discusses consequences thereof for population maintenance and long-term frankincense production. We could prove that *B. papyrifera* forms annual growth rings. The average radial annual growth rate of *B. papyrifera* is 1.15 mm (s.d. = 0.22) and varies significantly among the sampled trees. Age and diameter of *B. papyrifera* trees are significantly correlated. From the population-age structure, it becomes obvious that the current *B. papyrifera* populations lack successful recruitment since 1955, which we attribute to intensive grazing and fire associated with the escalating increase of human settlement in the area. Lack of recruitment leads to rapidly declining populations resulting in strongly reduced frankincense production. Management aimed at seedling survival and sustainable use of relic trees is urgent.

1. Introduction

Boswellia papyrifera (Burseraceae) is a co-dominant tree species in many dry deciduous woodland areas south of the Sahara (Vollesen, 1989). It occurs on steep rocky slopes, lava flows or sandy valleys (Bekele et al., 1993). The species produces frankincense, an olio-gum resin which is extracted from the bark (Tolera et al., 2013) and used as raw material in several industries (Lemenih and Teketay, 2003; Lemenih et al., 2007). Modern uses of frankincense include coffee and church ceremonies, perfume and medicine production (Farah, 2008; Gebrehiwot et al., 2003; Lemenih and Teketay, 2003). Ethiopia is the main producer and exporter of frankincense (Coppen, 2005). Annual local use of frankincense in Ethiopia has been estimated to be about 10,000 tons (Lemenih and Kassa, 2011). A total of 29,340 tons of natural gum and resins was exported from the year 1998 to 2008 (Lemenih and Kassa, 2011; Woldeamanuel, 2011). Ninety percent of the exported gum and resin comes from *B. papyrifera* (Lemenih and Kassa, 2011). Moreover, this species has local uses as source of wood products, and it is one of the few tree species that grows in harsh environments (Abiyu et al., 2010; Ogbazghi et al., 2006a).

B. papyrifera is one of the abundant species in the *Combretum–Terminalia* woodlands of Northern and North Western Ethiopia (Eshete et al., 2011). It is currently facing severe degradation from farmland expansion, fire, improper tapping and overgrazing (Abiyu et al., 2010; Groenendijk et al., 2012; Lemenih et al., 2007; Ogbazghi et al., 2006a; Rijkers et al., 2006). Most populations of this species are characterised by high adult mortality and lack of saplings. Interestingly, many seedlings can be observed during the rainy season, however, these seedlings die-back during dry season (Birhane, 2011; Negussie et al., 2008). The assumption is that these seedlings may survive below ground during the dry season, and produce a new aboveground shoot in the next wet season. It has been argued that such die-back over successive dry seasons may contribute to root development and storage of energy, which in turn may lead to rapid and successful development of saplings

* Corresponding author at: Forest Ecology and Forest Management Group, Centre for Ecosystem Studies, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands. Tel.: +31 686226830, +251 911797142.
E-mail address: motuma.feyissa@wur.nl (M. Tolera).

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once the plant starts permanent aboveground growth probably during years with a favourable climate (Birhane, 2011; Boaler, 1966; Stahle et al., 1999). This leads to the idea that populations might consist of cohorts reflecting waves of establishment (Moloney, 1986; Sato and Iwasa, 1993). Currently, saplings are virtually absent in most *B. papyrifera* populations, and the high mortality of the remaining adult size trees might suggest that those larger trees have not been refreshed by younger vital trees for a considerable period. Consequently, these populations are predicted to decline in density by 90–95% over the coming 50 years and will result in a reduction of frankincense production by 50% in the coming 15 years (Groenendijk et al., 2012).

Sustainable management of this resource is crucial to ensure the continuity of its economic, social as well as ecological services. However, planning of concerted management activities requires information on past dynamics in the population and that can only be generated when information on tree age is available. The earlier studies (Abiyu et al., 2010; Groenendijk et al., 2012) lack any time perspective since the analysis of population dynamics were based on diameter distributions. Therefore, it remains unclear during what time period recruitment has been hindered, and whether this lack of recruits is synchronised to one particular external factor. For example, Groenendijk et al. (2012), speculated about increase in fire and grazing intensity as potential primary causes for recruitment failure, but no evidence for this has been shown so far. It is also unknown whether the adult trees represent a single or multiple cohorts, which successfully established during years favouring juvenile tree establishment, growth and survival. Alternatively, a wide spread in ages in the remaining tree population would indicate that the current lack of recruitment is driven by a more recent change in factors that limit tree establishment. Age identification of the remaining tree population can indicate how long tree establishment is failing, and whether establishment of the remaining adult trees was linked to distinct periods in the past.

The population age structure of a given species can vary depending on the site conditions; drought, competition for light, fire and browsing by ungulates (Barnes, 2001; Caro et al., 2005; Steenkamp et al., 2008), elevation (Whipple and Dix, 1979), seed predation (Nakagawa et al., 2005) and insect attacks (Crawley, 1989). For *B. papyrifera*, there is evidence that inverted J-shaped population size structures are rare, and continuous size structure of this species is restricted to areas that are not accessed easily by people (Groenendijk et al., 2012). Here, two alternative hypotheses are tested: first, while most populations lack recruits and juveniles, the adults come from multiple years, suggesting that the current lack of recruits results from a recent change in the environment and/or disturbances. Alternatively, the adults come from a few narrow time windows, indicating that successful recruits and juveniles need favourable years. This information is crucial for planning sustainable management of this species and sustainable production of frankincense.

Assessment of age-diameter relationship is crucial to estimate population-age structure and is enabled by the rapid development of dendrochronology to apply it on tropical tree species (Baker, 2003; Rozendaal and Zuidema, 2010; Steenkamp et al., 2008; Trouet et al., 2006, 2010; Worbes, 2002). Dendrochronological application is species dependent (Brienen and Zuidema, 2005; Worbes and Fichtler, 2010) and it has not been assessed yet for *B. papyrifera.* This study (1) determines radial growth dynamics and age-diameter relationship of *B. papyrifera*, including verification of annual growth-ring formation, and (2) constructs the population age structure and discusses consequences thereof for population maintenance and long-term frankincense production.

2. Materials and methods

2.1. Study area

The study was carried out in Lemlem Terara, Metema district, North-west Ethiopia. *B. papyrifera* is the most abundant species (Eshete et al., 2011) of the *Combretum–Terminalia* woodland (Bekele et al., 1993; Demisew, 1996) that dominates the study area. In this woodland, *B. papyrifera* has a median height of 9 m and median diameter of 20 cm and grows to a maximum height of 12 m (Eshete et al., 2011; Vollesen, 1989). The soil in the study area consists of 39% sand, 24% silt and 37% clay (Eshete et al., 2011). Based on data from National Meteorological Agency of Ethiopia, for the period of 1971–2009, annual rainfall recorded at Metema ranges from 665 to 1380 mm, with a mean annual rainfall of 965 mm (Fig. 1). The site is characterised by uni-modal rainfall with a major rainy season from June to September. Annual mean maximum and minimum temperatures are 36 °C and 19 °C respectively.

2.2. Verification of annual growth-ring formation and estimation of tree age

We collected a total of 12 stem discs from eight trees with stem diameters between 15 and 30 cm in January 2010. We had pin-marked four of these trees at 2 m above the ground in October 2007 and sampled one disc at the marked height (= total of 4 discs) for verification of the periodicity of growth ring formation. From the remaining four trees, discs were collected at soil level and 1 m above the ground (= total of 8 discs). These discs served for wood-anatomical investigation and description of growth-ring features and assessment of differences in number of growth rings between soil level and 1 m stem height as indication for initial height growth. This is important for reliable estimates of tree age based on samples that have been taken at same distance from the stem base. Collection of discs was restricted to eight individuals to limit the damage to the already threatened population of *B. papyrifera.*

2.3. Assessment of radial-growth trajectories and diameter-age relationships

Radial growth dynamics and diameter-growth relationships were done based on increment cores taken from a total of 100 trees. The study samples were collected from two sites that are about 5 km apart. The cores were collected from four plots (2 plots in site 1 and 2 plots in site 2) of about 2 ha each. These plots were established in 2007 for monitoring recruitment and growth for population dynamics study by Eshete et al. (2011). During two sampling campaigns, in April and October 2011, we sampled 50 trees from site 1 and site 2 respectively. We randomly selected five trees each from five diameter classes, i.e. 10–15 cm, 16–20 cm, 21–25 cm, 26–30 cm, and >30 cm per plot. Two increment cores were collected per tree from opposite directions at c. 0.4–0.5 m above the ground. In addition, diameter at breast height (DBH) of all sample trees was measured during the sampling.

2.4. Sample preparation

The sample discs and increment cores were air-dried at the wood-science laboratory of Wondo Genet College of Forestry and Natural Resources, Ethiopia. After drying, the transverse section of each disc was sanded using progressively finer textures of sand papers (80–1200 grit). The transversal sections of the increment cores were prepared using a core-microtome (Gärtner and Nievergelt, 2010) and when needed sanded with finer (600–1200 grit) sand paper to improve the visibility of growth-ring boundaries.