



# Frankincense yield is related to tree size and resin-canal characteristics



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## ARTICLE INFO

### Article history:

Received 5 March 2015

Received in revised form 8 May 2015

Accepted 9 May 2015

Available online 29 May 2015

### Keywords:

*Boswellia papyrifera*

Frankincense

Path analysis

Resin canals

Tree characteristics

Tapping

## ABSTRACT

*Boswellia papyrifera* Hochst. is the most important global source of frankincense. Tree numbers are rapidly decreasing in many populations of *B. papyrifera* in Ethiopia, where most of the internationally traded frankincense comes from. Improper tapping is among the frequently mentioned reasons for this decrease within populations. We still lack sustainable techniques for frankincense tapping, and these techniques are not yet tuned to individual trees since we are unaware how tree characteristics influence frankincense yield. This study investigates the relationships between different tree characteristics and their relation to frankincense yield. We selected 53 trees and measured frankincense yield and their DBH, tree age, number of leaf apices, radial growth, bark thickness, total resin-canal area, and total number of resin canals in a cross-section. Regression and path analysis were used to unravel cause-effect relationships between tree characteristics and frankincense yield. Frankincense yield was independent of the actual radial growth rate, but increased with increasing total resin-canal area in the bark, stem diameter, tree age, and the number of leaf apices. We show that frankincense yield by trees is not only a simple function of tree size. Remarkably, trees that grew slower over their whole life history produced more frankincense, suggesting an intra-specific trade-off in growth rate and frankincense production. Overall, this study thus shows that frankincense production is the result of complex plant trait networks and long term tree life properties. The results contribute to management regimes that minimize the damage to trees, while maximizing benefits in terms of frankincense yield and can also be used for selection and propagation of trees which are well suited for frankincense production.

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## 1. Introduction

The tree *Boswellia papyrifera* Hochst. is the major source of frankincense. Frankincense is an important export item and source of income for rural households in Ethiopia (Tilahun et al., 2007; Woldeamanuel, 2011; Dejene et al., 2013), as well as in other countries (Langenheim, 2003). Tree numbers and frankincense production are rapidly decreasing in many populations of this species, in Ethiopia (Negussie et al., 2008; Groenendijk et al., 2012) as well as in Eritrea (Ogbazghi et al., 2006) and Sudan (Abteu et al., 2012). Causes of these decreases include the conversion of woodlands to agricultural land (Gebrehiwot et al., 2003; Lemenih and Kassa, 2011), frequent fires, overgrazing and insect infestation (Abiyu et al., 2006, 2010). In addition, improper tapping is frequently mentioned as one of the reasons for the decline of tree numbers within the extant populations (Abiyu et al., 2010; Eshete et al.,

2012a). From earlier studies, it is evident that tapping for frankincense reduces reproductive effort (Rijkers et al., 2006; Mengistu et al., 2012) and exposes the trees to insect attack (Abiyu et al., 2010). Seeds from tapped *B. papyrifera* trees also showed lower germination success as compared to seeds from untapped trees (Rijkers et al., 2006; Eshete et al., 2012b). Similar effects of tapping were reported for other tree species (Silpi et al., 2006, 2007; Varghese and Ticktin, 2008; Chantuma et al., 2009). Developing more sustainable tapping strategies that reduce the risk of over-tapping is important for planning sustainable management of the remaining frankincense resources of species such as *B. papyrifera*. This requires more knowledge on the relation between frankincense yield and various tree characteristics (Tadesse et al., 2001).

Trees produce resins such as frankincense as a defence against potential damage (Krokene et al., 2000; Baier et al., 2002; Pickard, 2008). Upon damage, the released resin may repel and flush or entrap and kill the invading organism (Franceschi et al., 2005; Eyles et al., 2010). Some tree species have resin canals filled with (constitutive) resin, which is transported to and released at

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wounded spots upon wounding, other species start producing (induced) resin after wounding and may require more time for defence against invaders (Lewinsohn et al., 1991; Trapp and Croteau, 2001) and some species can produce both constitutive and induced resin (Raffa and Berryman, 1982; Lombardero et al., 2000; Franceschi et al., 2005). Overall, the resin secretory structures and the type of resin (constitutive or induced) used for defence is largely species specific (Moreira et al., 2014). Recent evidence show that *Boswellia* trees have constitutive resin, but probably also produce induced resin upon wounding trees for frankincense harvest (Tolera et al., 2013a; Eshete et al., 2012a).

Frankincense yield considerably varies between trees (Gebrehiwot et al., 2003; Tadesse et al., 2004). In two different studies the annual frankincense yield per tree has found to be ranging between 0.4 and 1.8 kg y<sup>-1</sup> (Eshete et al., 2012a), and between 0.1 and 1.7 kg y<sup>-1</sup> (Tilahun et al., 2011). This large difference in annual frankincense yield per tree can potentially be attributed to many factors, including both tree characteristics (size, physiology) and external factors (e.g. tapping regimes and micro-site conditions). It was shown that frankincense yield is not related to soil fertility and soil-moisture holding capacity (Eshete et al., 2012a). Similarly, Lombardero et al. (2000), reported that resin yield of *Pinus taeda* is not related to drought and fertilization. On the other hand, Wekesa et al. (2009), reported a strong correlation between yield of Gum arabic and soil moisture and soil temperature and, similarly, resin yield increases with better soil properties for *Pinus pinaster* (Rodríguez-García et al., 2014; Moreira et al., 2015). In addition, the intra-annual variation in resin yield of this latter species is strongly correlated with temperature, solar radiation, potential evapotranspiration and water deficit (Rodríguez-García et al., 2015). The intensity of tapping has a strong effect as variation in the number of incisions per tree and/or the number of tapping rounds per season leads to high yield variation (Tilahun et al., 2011; Eshete et al., 2012a). Also tree characteristics, such as diameter, basal area, tree height and crown size (McDowell et al., 2007; Tilahun et al., 2011; Eshete et al., 2012a; Rodríguez-García et al., 2014) have a large effect. Similar relationships between tree characteristics (e.g. diameter and height) and resin yield were reported for *Pinus elliotti* (Zheng and Xu, 1992; Wang and Zhu, 1994), *P. taeda* (induced resin; Lombardero et al., 2000) and *Pinus halepensis* (Spanos et al., 2010). Auñón et al. (2001), also found a positive relationship between dendrometric variables and resin yield of *P. pinaster*. In contrast, *P. pinaster* (Tadesse et al., 2001) and *Picea abies* (Baier et al., 2002) did not show such trends, suggesting that such trends are species or context specific.

In addition to tree size, resin yield can also be directly related to characteristics of the resin-secretory structures that are responsible for the synthesis, storage and transport of resin (DeAngelis et al., 1986; Baier et al., 2002). Diameter of internal lumen of resin canals (hereafter diameter of resin canals), density of resin canals and number of epithelial cells are among the commonly mentioned characteristics of resin-secretory structures that determine resin yield (Blanche et al., 1992; Tolera et al., 2013a). These features are closely related to tree size and ontogeny (Levanic, 1999; Wainhouse et al., 2005; Wang et al., 2006; Fabisiak and Czajka, 2011). Moreover, both tree morphology and resin-secretory structures may be affected by climate and soil conditions (Reid and Watson, 1966; Wimmer and Grabner, 1997). In addition to tree and resin-canal characteristics, genetic variation related to physiological production capacity can also account for inter-tree variation in resin yield (e. g. Roberds et al., 2003; Spanos et al., 2010). However, it remains a major challenge to show how these networks of correlated tree and resin canal characteristics interact and ultimately drive the variation in frankincense yield of a tree.

In a previous study, we described and quantified resin-secretory structures of *B. papyrifera*, and showed differences in resin-canal characteristics among trees (Tolera et al., 2013a). We reported that resin canals of *B. papyrifera* are predominantly found in the bark and the density and diameter of axial resin canals are 0.8 mm<sup>-2</sup> and 113 µm respectively. As resin canals form the source of frankincense, their size and density are assumed to be related with frankincense yield. Mengistu (2011) speculated that bark thickness and total area of resin canals could be strongly related to frankincense yield. In addition, resin-canal features are most likely related to tree size characteristics, such as stem diameter, tree height, bark thickness, as well as total leaf area, and possibly also recent radial stem growth. More sustainable management strategies need to aim at selecting specific tapping procedures for individual trees. These should be based on a better understanding of the combined effects of resin canals and different other tree characteristics on frankincense yield, but yet such studies have never been done for *B. papyrifera*. This study aims at unravelling the relationships between resin-canal characteristics, tree morphological and ontogenetic characteristics and frankincense yield, in order to understand what drives frankincense yield.

We hypothesize that total resin-canal area (labelled as “Resin area”, Fig. 3) increases with stem diameter, because the bark cross-sectional area increases with stem diameter (Sonmez et al., 2007; Wainhouse et al., 2005). In addition, we expect that a high resource acquisition rate (Mengistu et al., 2011), expressed by a large number of leaf apices and high radial growth rate (labelled as Growth, Fig. 3), positively impacts the frankincense yield of trees. We added tree age as a potential additional factor of influence on total resin canal area and expect that age has a negative impact on frankincense yield particularly at senescence.

## 2. Materials and methods

### 2.1. Study species

*B. papyrifera* produces the widely traded white incense and occurs in Ethiopia, Eritrea, Nigeria, Cameroon, Central African Republic, Sudan, Chad, and North East Uganda (Vollesen, 1989). In Ethiopia, *B. papyrifera* grows in dry *Combretum* – *Terminalia* woodlands and wooded grasslands in the northern and north-western parts (Gebrehiwot et al., 2003; Eshete et al., 2011). It is a deciduous tree that usually dominates on steep and rocky slopes and shallow soil (Ogbazghi et al., 2006; Abteu et al., 2012). In north-western Ethiopia, it grows on a relatively flat terrain and deeper soil depth (Eshete et al., 2011). It grows to a height of about 12 m (Ogbazghi et al., 2006).

### 2.2. Study site

The study area is located near the village of Lemlem Terara, Metema district, North-Western Ethiopia (12°39' to 12°45'N, 36°17' to 36°23'E). The data for this study was collected from trees growing in open woodland located at 870 m a.s.l. Based on data from National Meteorological Agency of Ethiopia, for the period of 1971–2009, annual rainfall in Metema ranges from 665 to 1380 mm, with a mean annual rainfall of 960 mm. The study area receives an average monthly rainfall of above 50 mm from May to October. The mean annual minimum and maximum temperatures are 19 °C and 36 °C respectively. The study site is dominated by clay soil and its average soil depth is 27.7 cm (Eshete et al., 2011).

### 2.3. Data collection

In October 2011, study trees were selected from tapped *B. papyrifera* populations (Eshete et al., 2011). Frankincense was

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