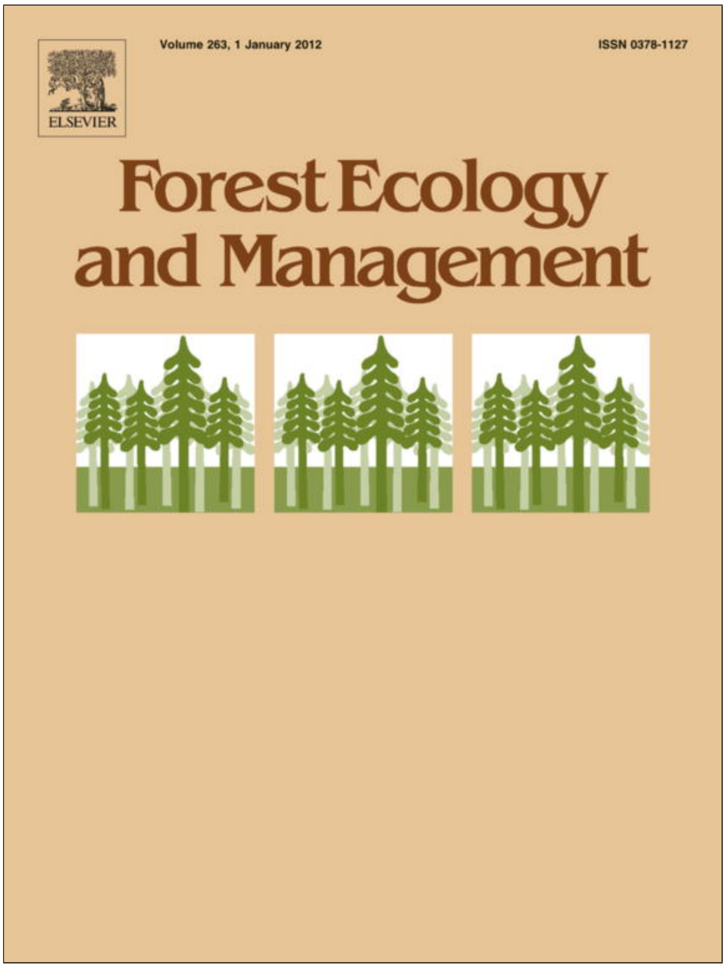
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Frankincense production is determined by tree size and tapping frequency and intensity

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ABSTRACT

Resin production in trees probably depends on trade-offs within the tree, its environment and on tapping activities. Frankincense, the highly esteemed resin from dry woodland frankincense trees of *Boswellia papyrifera* is exploited in traditional ways for millennia. New exploitation practices lead to weak trees and non-sustainable resin production. For 500 trees from four populations of *B. papyrifera* we evaluated how frankincense yield is affected by different tapping intensities (number of incision spots) and frequencies (number of resin collection rounds during the dry season), since both of them have been intensified recently. These effects are considered for trees of different size, since larger trees probably provide more resources for resin production. We predicted that frankincense production would initially increase with tapping intensity and tapping frequency, but later level-off because of resin depletion. Frankincense production varied highly: yield per tree per year of all 500 monitored trees averaged 261 g (±231, but largely varied and ranged from 41 to 1829 g. We indeed found that resin yield increased with tapping intensity, but not anymore beyond an intensity of 6–9 incision spots. Yield peaked around the seventh collection round, and declined thereafter. Yield increased with trunk diameter, but leveled-off beyond trees with a stem diameter of >20 cm. These patterns were similar across populations, and between contrasting areas. Our results suggest that high tapping intensity risks short-term resource depletion, warranting tuning down the intensity of the current collection practices. Less intense tapping rounds per season will reduce damage, increase the health of tree populations, and contribute to long term frankincense production. This study thus allows for developing less damaging and more sustainable management for frankincense trees.

1. Introduction

Many trees produce gum and resin in response to wounding (Langenheim, 2003) and thus seal the wounds and protect themselves against water loss, insect damage and pathogen invasion (Wink, 1988). Some gum and resins are exploited since a long time and used for traditional or industrial purposes (Nussinovitch, 2010). Sophisticated, commercialized, and sustainable harvest systems have been developed, for example, for rubber in rain forest areas (Cecil and Mitchell, 2003), for different resins in dry Mediterranean or temperate forest areas (Coppen and Hone, 1995), and for Arabic gum in the dry Sahel zone (Fagg and Allison, 2004). In the Horn of Africa, trees of dry tropical forests that produce resin that is used as frankincense lack sophisticated, commercialized, sustainable harvest systems. People carve the bark along the trunk and collect the resin with a traditional knife by making incisions at different locations along the trunk, and at regular time intervals during the dry season. In this way, frankincense trees of different sizes are harvested for resin, despite alarming reports that the current harvest practices dramatically reduce the vitality, reproduction and seedling performance (Ogbazghi, 2001; Rijkers et al., 2006). There is a dire need to develop sustainable harvest systems by searching for a compromise of achieving a high resin yield and low damage levels.

Aiming at sustainable resin harvest, forest managers may select trees of different size and use different amounts of incisions and collection rounds to achieve a high resin yield at a relatively low damage level. Since trees of larger size have higher resource acquisition rates (Lambers et al., 1998) and larger storage pools for secondary metabolites (Goralka et al., 1996), larger trees are expected to produce more resin than smaller trees, conforming to the growth differentiation balance hypothesis (Herms and Mattson, 1992). Resin yield is also predicted to increase with the amount of incisions made along the trunk and the amount of tapping and resin collection rounds, particularly for the larger trees when they indeed have greater resin production capacity. Under limited resource availability, resin production may level-off beyond a thresh-

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old for the number of incisions, tapping/collection rounds, or a combination of these two resin harvest practices. We expect that the larger trees will start slowing down resin production at higher threshold values for number of incisions or tapping/collection rounds.

Here we evaluate what determines the frankincense production of *Boswellia papyrifera* trees of different size, and exposed to different tapping regimes. We address the following questions: (1) Does resin production increase with tree size? (2) Does resin production increase with the tapping intensity and frequency, but also level off beyond a threshold value for the number of incisions and number of tapping rounds? (3) Are more intensive tapping regimes, in number of incisions and number of tapping rounds, only beneficial for larger trees? We tested these predictions for four populations growing in two sites that differ in macro-climate and soil conditions. The outputs of this study will be discussed from an eco-physiological perspective, but also to discuss possible steps towards more sustainable management and utilization of the frankincense populations and resin production in the Horn of Africa.

2. Methods

2.1. Study species

Frankincense trees of the species *B. papyrifera* (family: Burceraceae, Fichtl and Admasu, 1994) are encountered in the *Combretum–Terminalia* (broad-leaved) deciduous woodlands of Ethiopia, where they can dominate on steep rocky slopes, lava flows or sandy valleys within the altitudinal range of 950–1800 m (Eshete et al., 2005). Beyond Ethiopia, frankincense trees are found in Nigeria, Cameroon, the Central African Republic, Chad, Eritrea, Sudan, Somalia and Uganda (Vollesen, 1989; Bekele et al., 1993). Trees are easily identifiable by its bark that looks whitish to pale brown, peeling off in large flakes; slash red-brown and exuding a fragrant resin. They grow to a height of 16–18 m and to a stem diameter of ~50 cm at adult stage (Eshete et al., 2011). The species is deciduous since trees only carry leaves for ~4 months (June–September), and are without leaves for the remaining 8 months per year. Flowering occurs in October and fruiting in December at Metema, whereas flowering occurs in February and fruiting in March at Abergelle (Eshete et al., unpublished data). Despite such variation in fruiting phenology, trees of both sites are tapped from October until the first week of June, thus spanning the period when trees are without leaves during the dry season in both sites. *B. papyrifera* trees are economically and culturally important for their frankincense production, which dates back to more than 2000 years (Groom, 1981), but also for a multitude of other products including wood for household furniture and doors, leaves for fodder, nectars for honey bees (Eshete et al., 2005). The main economic importance is however the frankincense that comes after tapping the stem/bark of the tree. Ethiopia is the major producer and exporter of frankincense.

2.2. Study areas

We investigated the frankincense production of natural tree populations of *B. papyrifera* located in northern Ethiopia, but using experimentally controlled tapping techniques. We selected *B. papyrifera* populations at Abergelle in the Tigray region, and populations at Metema in the Amhara region. The two regions are at relative extreme and opposite environmental and climatic conditions, with Abergelle characterized by a higher altitude, drier, colder and more intensively sun-lit site conditions than Metema (Mengistu, 2011). *B. papyrifera* dominated forests cover an area of 330,000 ha in Tigray and 604,000 ha in Amhara, and are mostly found in deciduous woodlands occupying sites with very shallow soils, steep rocky slopes, lava flows or sandy river valleys (Eshete, 2002; Fichtl and Admasu, 1994; Teketay, 2000; see also Ogbazghi et al., 2006a). The four study populations also differ in species composition, diversity and structure (Eshete et al., 2011). The rainfall is seasonal in both areas with a wet season from June to September at Metema and from June to August at Abergelle. Hence, both areas can be classified as dry tropical forests (White, 1983; Friis et al., 2010; Teketay et al., 2010).

Table 1
The site characteristics of the areas where the populations of study were selected.

Variable	Unit	Abergelle	Metema
Environmental conditions			
Mean annual rain fall	mm	800	965
Mean annual maximum temperature	°C	29.3	35.7
Mean annual minimum temperature	°C	14.2	19.6
Vegetation structure			
Tree/shrub abundance (⩾1.5 m height)	No. individuals/ha	629	439
Boswellia papyrifera abundance	No. individuals/ha	281	192

Table 2
The effects of the stem diameter size and tapping intensity and their two-way interactive effects on the mean annual frankincense yield. Population and site were added as random factors to the model. Results are based on a generalized linear model ($n = 500$).

Variable	df	2007/08 (7 collections)			2008/09 (14 collections)		
		MS	F	P	MS	F	P
Corrected model	51	4.14	9.34	0.000	2.45	10.07	0.000
DBH class	4	18.46	41.83	0.000	17.74	72.78	0.000
Tapping level	4	22.16	50.22	0.000	8.26	33.88	0.000
Population	3	5.62	12.74	0.000	1.36	5.57	0.001
Site × tapping level	12	0.27	0.61	0.835	0.47	1.94	0.028
DBH class × tapping level	16	0.47	1.06	0.393	0.44	1.79	0.030
Site × DBH class	12	1.86	4.21	0.000	0.43	1.75	0.054

2.3. Tapping techniques

Tapping of *B. papyrifera* trees involves removal of the bark, leaving the xylem intact, using a special fist knife or tool called mengaff. Mengaff is a wooden-handled tool with a sharp metal blade at the end, which is used to wound the tree by making deep longitudinal incisions (4–8 cm). The opposite end of the mengaff is blunt and used to remove the resin from the tree after it has hardened (Gebrehiwot, 2003). Tapping starts in the first week of October (at the start of the dry season) and ends in the first week of June (just before the start of the rainy season). During this dry period, the tree has no leaves. Traditionally a tree is tapped 8–12 times during tapping and resin collection rounds (tapping frequency) per year (Gebrehiwot, 2003). During the first tapping round, a thin layer of the bark (~1 mm deep and ~2.5 cm^2 in area) is removed. The subsequent tapping's deepen and enlarge the already established wounded spots. At the last tapping round the size of a tapping spot will be ~6 cm in horizontal direction, ~10 cm in vertical direction, and approximately 10–20 mm deep. Using the traditional tapping technique all trees with a diameter of 10–30 cm are tapped at 6–8 spots (tapping levels) while trees with a diameter of >30 cm are tapped at 8–12 spots. During and after each tapping a white resin flows out of the bark, dries and becomes solid

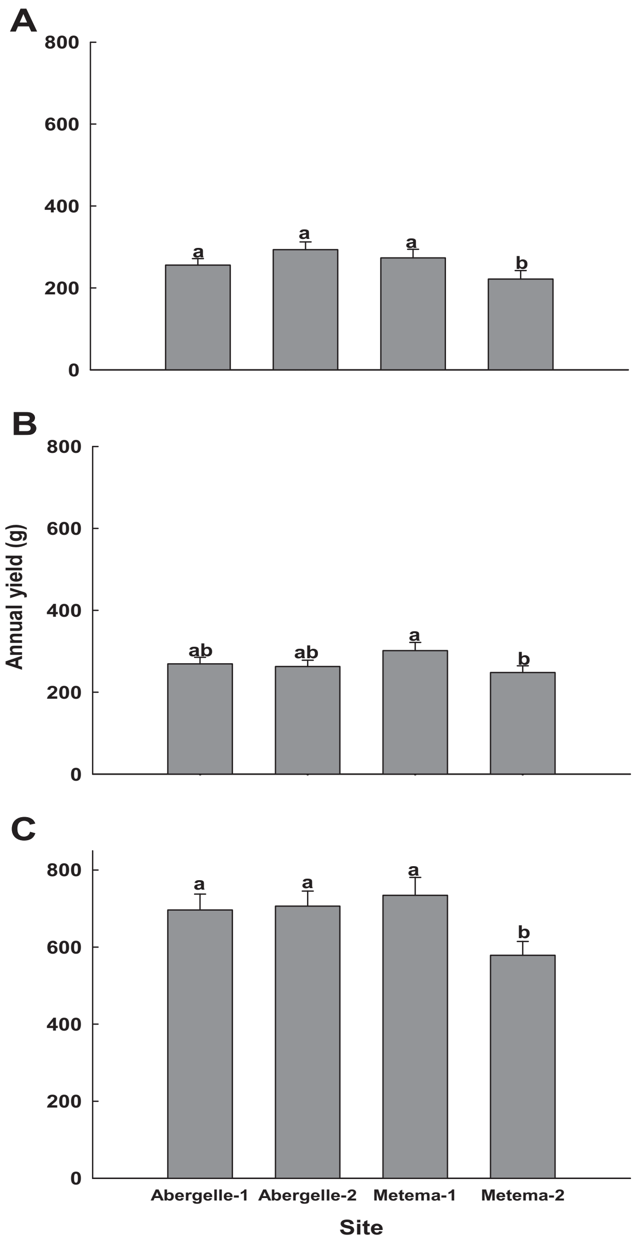

Fig. 1. Mean annual frankincense production of *B. papyrifera* of the four populations during: (A) the first year production season, (B) the second production season, the first seven rounds only, and (C) the second season, all 14 collection rounds included. Yield data from all diameter classes and tapping levels were pooled in each population. Error bars are standard errors. Identical letters indicate means that are not significantly different between sites following Tukey test ($p < 0.05$).

on top of the wound, and is collected by tappers before they start the next tapping round.

2.4. Experimental design

We selected 125 trees in each of two populations within randomly selected 1-ha plots in the Metema in Amhara region (M1 and M2), and in a similar way also in Abergelle in the Tigray region (A1 and A2). As mentioned, these regions represent the climate extremes where *B. papyrifera* populations are found in Ethiopia. While both Abergelle populations and one Metema population (M2) had very similar poor soil conditions, the M1 population was characterized by better soil conditions (Eshete et al., 2011). Trees of each population were experimentally allocated trees to different, controlled, tapping regimes in the same way.

The 125 trees were selected such that they were equally distributed over five size classes ($n = 25$ per size class and population), with stem diameters in the categories 10–15, 15–20, 20–25, 25–30 and >30 cm. Subsequently, groups of five randomly selected individuals per size class were allocated to five different tapping intensity treatments, ranging from 3, 6, 9, 12 to 16 spots incision spots along the trunk. We thus established a fully crossed 5×5 design, with five replications for every tapping intensity – tree size combination.

For trees with three tapping spots, the spots were separated vertically by 50 cm at either the eastern or western side of the trunk. For trees with six tapping spots, the three spots were at the east side and three at the west side of the trunk. For trees with nine tapping spots, three directions were used (3 E, 3 W and the remaining 3 in either N or S). Trees with 12 tapping spots are tapped in four directions (3 in each of the cardinal directions). Trees with tapping level 16 were tapped in four directions with four tapping spots above each other at each side. The vertical distance between two successive tapping spots was in all cases 50 cm.

The experiment was conducted for two production seasons. The first production season (October 2007–June 2008) involved a tapping frequency with seven frankincense collection rounds, similar to traditional tapping techniques. We implemented 14 frankincense collection rounds for the same trees during the second production season (October 2008–June 2009) to show the possible exhaustion of frankincense production with increasing tapping frequency. The first frankincense collection round started at the second tapping round. Frankincense production was determined by weighing the freshly harvested frankincense (locally called 'greazo') per tree directly after each collection round, using a digital balance (0.01 g precision).

2.5. Data analysis

We used a generalized linear model to test for the predicted tree size and tapping intensity effects on frankincense production, and included the population and region as a random factors in the model. Two-way interactions of the main effects were also included in the model. We performed this analysis for the two seasons separately, because the amount of tapping rounds was doubled during the second season. Annual resin yield differences resulting from each of the main effects were tested using Tukey test. A paired *t*-test was used to evaluate the difference between the resin yield summed over all seven collection rounds during the first year (in that year equal to annual resin yield) with the resin yield summed over the first seven collection rounds during the second year, using two observations per tree as the unit of replication. For all analyses, data were transformed to natural logarithm to meet the assumption of normal distribution. We used PASW Statistics 17.0 for all tests.

3. Results

The average annual frankincense production of all trees was 261 g ± 213 (SD) for the first year with seven collection rounds, and 679 g ± 446 (SD) for the second year with 14 collection rounds. The annual frankincense production was similar for three out of the four populations, and only slightly lower for the M2 site. Because these differences amongst populations were minor compared the effects of tree size and tapping intensity, we pooled all the individuals of the four populations for some of our analysis (e.g. Fig. 2).

The frankincense production largely varied among size classes and tapping intensities, and also between both years (Table 2

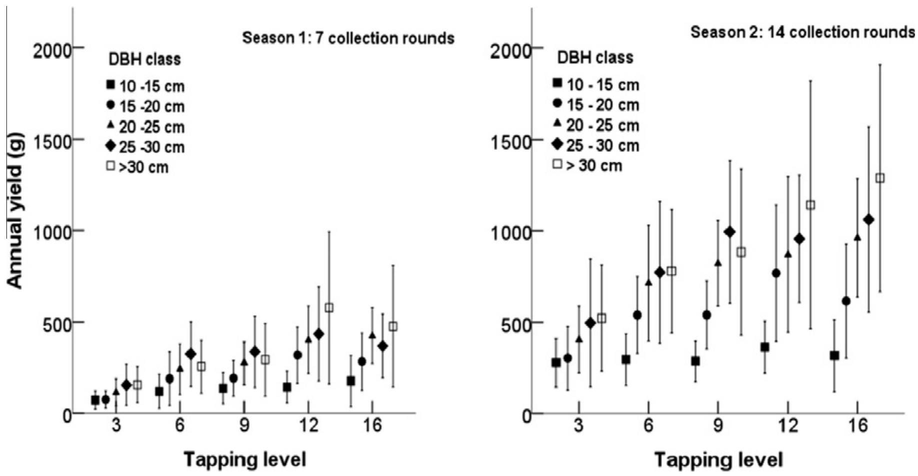

Fig. 2. Effects of tree size (stem diameter) and the number of tapping spots (tapping intensity) on the mean annual frankincense yield of *B. papyrifera*. Five stem diameter classes were used: 1, 10–15 cm; 2, 15–20 cm; 3, 20–25 cm; 4, 25–30 cm; and 5, >30 cm. Yield data of all individual trees from the four sites were pooled. Error bars are standard deviations.

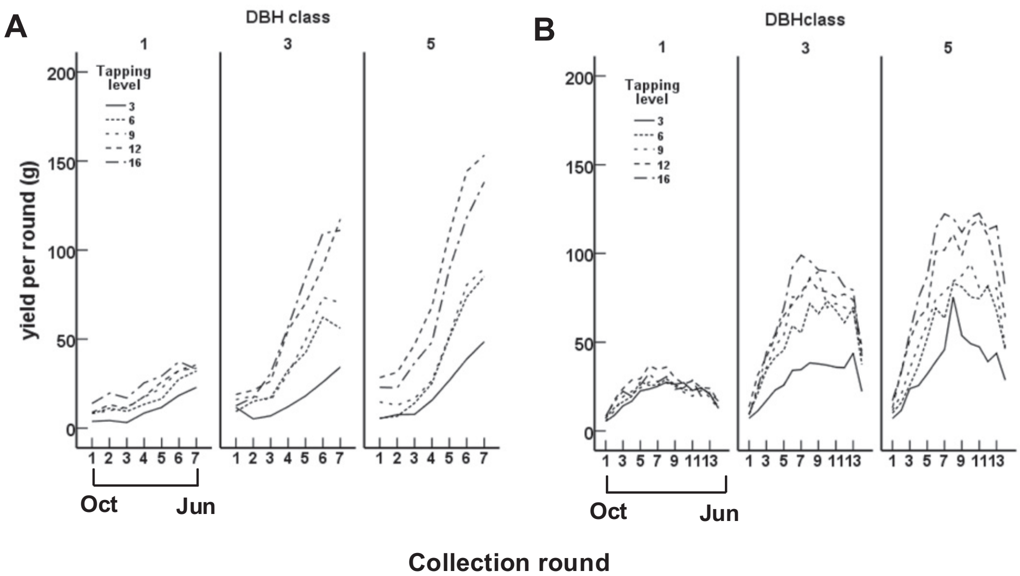

Fig. 3. The frankincense yield per tapping round in relation to the applied tapping level (3, 6, 9, 12, and 16 tapping spots) and tree size, as categorized by stem diameter: 1, 10–15 cm; 3, 20–25 cm; and 5, >30 cm DBH) in 2007/08 (A) and in 2008/09 (B). Note that the seven collection rounds during 2007/08 and the 14 collection during 2008/09 cover the same time span from the first week of October until the first week of June. The comparison of the panels (A) and (B) thus sketches the effect of doubling the tapping frequency.

and Fig. 2). The 10–15 cm stem diameter trees produced 84–181 g resin in the four populations during the year with only seven collection rounds, and 253–341 g resin during the year with 14 collection rounds. The >30 cm stem diameter trees produced 287–489 and 744–1233 g during years with 7 and 14 collection rounds, respectively. Close inspection of the results however shows that the increase in frankincense production with tree size leveled-off gradually after 20 cm stem diameter for both seasons (Table 2 and Fig. 2).

3.1. Effect of tapping intensity and frequency on frankincense production

Frankincense production increased with a higher tapping level, but leveled-off beyond 6–9 spots (Table 2 and Fig. 2). Frankincense production did not differ between the two seasons when only seven collection rounds were considered (paired t-test, df = 470; $t = 4.591$; $p = 0.386$). However, because of more tapping rounds, the total annual frankincense production was much higher over the second production season (Fig. 2). Moreover, our analysis accounts for several interactive effects of population, size class and tapping level, whereby the interactions were much stronger in the second than in the first year (Table 2).

3.2. Frankincense production trends across collection rounds

Frankincense production per collection round increased over the first seven collection rounds, both for the first season and the second season (Fig. 3). This trend was consistent for different size classes, tapping levels and populations. After the 9th and 10th collection round in the second production season the frankincense production stabilized and then declined for different size classes, tapping levels and populations (Fig 3). The small sized trees declined more rapidly in resin yield after the 9th round than the larger sized trees. Remarkably, the trees that were tapped at different intensities showed very similar qualitative trends in initial increase and later decline in resin yield.

4. Discussion

In this study we show how the frankincense yield in 500 trees from four *B. papyrifera* dry woodland populations located in two different regions in Ethiopia varied with tree size, tapping intensity and tapping frequency. Remarkably, trees from two populations in the Abergelle area and one population in the Metema area had similar annual frankincense yields, although the Metema population was characterized by a richer soil (Eshete et al., 2011). Possibly, the photosynthetic acclimation to the higher illumination in the Abergelle area (Mengistu, 2011) compensates for resource acquisition for resin production, despite rather poor soil conditions and a short wet season (Table 1). The fourth population occurred on relatively poor soils in the Metema area, but only had a slightly lower annual frankincense yield compared to the other populations (Fig. 1). These overall small differences amongst populations characterized by different environmental conditions suggests that the selection for a sufficient amount of resin is relatively strong.

Bigger trees indeed produced more frankincense than smaller trees, in line with our prediction (Figs. 2 and 3). This phenomenon was consistent over two production seasons, five tapping levels and four populations. Similar results were also reported for a number of Pinus species (Coppen, 1995; Lombardero et al., 2000; Rodrigues et al., 2008) and for Protium (copal) trees (Neels, 1996). Rodrigues et al. (2008), for instance, studying the effects of tree size on oleoresin yield of *Pinus elliottii* in Brazil, found bigger Pinus trees (22–23.5 cm DBH) to give 20–25% higher oleoresin yield than smaller trees (18–19.5 cm DBH). Higher yield in bigger trees may result from larger resin stocks, larger resource acquisition capacities that allow for more resin production, and more resin canals in the trunks of bigger trees (Coppen, 1995; Ella and Tongacan, 1987; Lambers et al., 1998). In rubber trees (*Hevea brasiliensis*), the rate of latex production was related to CO_2 assimilation capacity of the trees (Gomez, 1983), which in turn depends on the crown size and leaf area of trees (Lambers et al., 1998). Gebrehiwot (2003) and Ogbazghi et al. (2006b) reported a linear relationship between stem diameter and crown diameter for *B. papyrifera* in Ethiopia and Eritrea, respectively. Thus, the higher frankincense production from bigger *B. papyrifera* trees in the present study may result from their larger photosynthetic carbon acquisition capacity. This is consistent with the growth differentiation balance hypothesis (GDBH) that production of secondary producing structures and the metabolites produced, such as frankincense, increase with plant size (Goralka and Langenheim, 1996; Goralka et al., 1996; Herms and Mattson, 1992). However, beyond a stem diameter of 20 cm we did not observe any further increase in resin yield. Similar results have been reported for, for example, *Anisoptera thurifera* in Philippines (Ella and Tongacan, 1987). It is unclear how such limits in increasing resin production with size results from physiological or ecological constraints, or a combination of these.

Frankincense production increased with the number of tapping spots on the tree (Fig. 2). In a similar way, gum arabic production by *Acacia senegal* increases with tapping intensity in Sudan (Ballal et al., 2005). The increase in frankincense production with the number of tapping spots is probably due to the fact that more resin canals are opened up (Trapp and Croteau, 2001). A similar result has been reported for grand fir (*Abies grandis*) where the production of plant defense was proportional to the injury applied (Klepzig et al., 2005; Lewinsohn et al., 1991; Lombardero et al., 2000). In commercial production of resin from pine trees chemicals are used to simulate insect or fungal attack for maximizing resin production (Chaudhari et al., 1996; Coppen, 1995; Klepzig et al., 2005; Rodrigues et al., 2008), but this is not yet the case for *B. papyrifera* where people only experimented with different numbers of tapping spots (Abiyu et al., 2010; Kebede, 2010; Ogbazghi, 2001; Rijkers et al., 2006).

In our study trees, the increase in resin yield leveled off beyond 3–6 tapping spots in the two smallest size classes (DBH 10–20 cm), and beyond the 9th tapping spot in the three larger size classes. We speculate that the leveling-off of the frankincense production beyond a threshold tapping intensity occurs when different spots start to drain resin from the same pool. This result is in line with the results of *B. papyrifera* bark and wood anatomical studies (Menger, 2010), showing that resin canals are interconnected over longer distances than those between tapping spots, and thus allowing for draining frankincense from one spot by the other. Our result suggest that the relatively high resin yield can be achieved in 10–15 cm at a low tapping intensity of ~3 spots, in 15–20 cm trees at an intermediate tapping intensity of ~6 spots, and in larger trees at a tapping intensity of ~9 spots. Given the relatively low production of the smaller tree sizes (<20 cm stem diameter), selection of larger sized trees for resin yield would be another option, since this would save the smaller trees from damage and possible increase their ability to grow to a larger, and more, productive size.

In line with our hypothesis, annual frankincense production increased with a higher tapping frequency (Fig. 3). Frankincense production per tapping round increased over the first seven collection rounds, then leveled-off, and ultimately decreased. The initial increase in frankincense production with tapping round may result from opening-up more resin canals (Trapp and Croteau, 2001) deeper in the bark and closer to the cambium, where the density of productive resin canals is highest (Menger, 2010). We expect that this anatomical mechanism is more important for increasing the resin production with tapping round than a higher temperature (Wekesa et al., 2009) or the production of constitutive resin. Subsequently, the decline in resin production with 14 instead of seven tapping and collection rounds indicates that trees are drained of the resources for frankincense production (Ella and Tongacan, 1987). Similar trends for resin yield per collection round have been obtained for *Pinus roxburghii* in India (Chaudhari et al., 1996) and *Protium copal* in Guatemala (Neels, 1996). Remarkably, the decline was observed for all tapping intensity levels in our study. This latter result suggests that despite an extensively, branched, resin channel network in the bark (Menger, 2010), the resin transport towards incisions is constraint over distances beyond ~50 cm.

4.1. Implications for management

It is clear that smaller trees (10–15 cm DBH) produce much less resin than large trees. We do not know if intensive tapping of small trees will negatively affect the production capacity of these trees when large: longer-term studies are needed to evaluate whether tapping has longer-term effects. However, studies of commercial resin production by Pinus species have led to obligatory minimum tree size limits for tapping (20 cm DBH in China and 20–25 cm DBH in other countries; Coppen and Hone, 1995; Wang et al., 2006). In India a standard minimum diameter for tapping of *Pinus roxburgii* of 30 cm is used (Lohani, 1970): tapping of trees smaller than 25 cm increased annual mortality rate from 1.1% to 29.3%. For *B. papyrifera*, Mengistu (2011) showed that intensive tapping reduced the photosynthetic capacity through a decrease in total leaf area, and thus potentially in carbon gain. Given the low production of resin yield in small trees, the protection of small trees against tapping damage should be considered in management systems for frankincense production. Accordingly, we suggest 20 cm DBH as an appropriate minimum diameter for the tapping trees of *B. papyrifera*.

Our results show how frankincense production varies with tree size, the amount of tapping spots, and the number of tapping and collection rounds. Our study indicates that even the larger trees are limited in resin production, particularly when more than seven tapping rounds are applied over a single season. Moreover, trees do not produce more resin when more than nine tapping spots are applied. From these results, we suggest that the number of tapping spots per tree could be limited at nine, to minimize damage. Less damage and wound sealing may lower attacks by insects, fungi, or other pathogens (Abiyu et al., 2010; Negussie, 2008; Trapp and Croteau, 2001), which agrees with the observation that trees with 12 tapping spots in the Tigray area (Northern Ethiopia) had higher levels of insect attack (Negussie, 2008) and that 65% of the dead trees in the Metema area were infested by the insect (Eshete, 2011). We therefore expect that the high numbers of tapping spots and collection rounds as currently found in some commercial production sites (up to 27 tapping spots – and 16 collection rounds – Kebede, 2010) are therefore likely to result in high adult tree mortality. This effect, together with other the ongoing land use changes causing a decrease of Boswellia populations (Groenendijk et al., 2012), is expected to have devastating effects on the future production of frankincense. Moreover, our results clearly show that limits to the levels of tapping intensity and frequency may hardly affect the frankincense production on the short run, while they reduce the damage to trees on the longer run.

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