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1 **Title page**

2 1. *Title*

3 Seedling mortality causes recruitment limitation of *Boswellia papyrifera* in
4 northern Ethiopia

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Abstract

The Frankincense tree *Boswellia papyrifera* is an important resource in the semiarid lower highlands of eastern Africa but its populations are declining due to human pressure and environmental degradation. To assess the perspectives of (assisted) natural regeneration for *Boswellia* woodland restoration, we examined *Boswellia* stand structure and seedling densities in a grazed woodland and in a livestock grazing enclosure. We also tested topsoil scarification as a means to increase seedling survival.

Boswellia populations lacked small diameters, indicating recruitment limitation. During the rainy season, seedling densities were 8 331 ha⁻¹ in the enclosure and 3 325 ha⁻¹ in the grazed woodland. Respectively, 19 and 11% of these seedlings survived the first dry season. However, the lack of saplings suggests a lack of surviving seedlings over successive dry seasons and thus, a cumulative seedling mortality approximating 100% within each generation. Topsoil scarification had an adverse effect on seedling survival.

Dry season seedling mortality seriously limits the potential of natural *Boswellia* woodland recovery. To restore a healthy population structure in enclosures, additional management interventions such as shading to support early seedling survival or planting of large rooted cuttings, need to be tested.

Keywords: Desertification; Enclosure; Frankincense; Grazing; Restoration; Savanna woodland

1. Introduction

Frankincense or olibanum is an internationally valued resin obtained from the multi-purpose tree *Boswellia papyrifera* (Del.) Hochst. It is an important resource for rural communities in the semiarid lower highlands of eastern Africa (Ogbazghi, 2001; Gebrehiwot et al., 2003). Throughout its range *Boswellia* populations are declining due to human-induced fire, improper forest use and agricultural land expansion (Gebrehiwot, 2003; Ogbazghi et al., 2006; Lemenih et al., 2007).

In northern Ethiopia, *Boswellia* woodland conservation efforts largely depend on reducing these impacts in livestock grazing exclosures, where free range grazing by domestic animals and cutting of woody vegetation are prohibited. In the cooler highlands, exclosures enable ecosystem recovery, as witnessed by the regeneration of both woody pioneer and secondary climax tree species (Aerts et al., 2004; Mengistu et al., 2005; Abebe et al., 2006; Mekuria et al., 2007). Similar results have been obtained in other browsed woodlands including *Polylepis* woodlands in the Andes (Teich et al., 2005) and *Quercus* forest in the Mediterranean region (Debussche et al., 2001; Plieninger, 2007). Therefore, excluding livestock is expected to have a positive effect on *B. papyrifera* populations.

Tree regeneration problems could also arise during sexual reproduction (flowering, pollination, fruiting and seed setting) and establishment due to stress factors other than fire and grazing. In Eritrea, reduced fertility of mature *B. papyrifera* trees has been linked to overtapping, yielding seed limitation and low seed vitality (Rijkers et al., 2006). Biotic and abiotic factors such as competition and drought may also limit the establishment of new individuals. In these

1 cases, site preparation techniques may assist natural regeneration by
2 increasing germination, seedling development and seedling survival. Soil
3 scarification is such a site preparation technique that has been successfully
4 demonstrated in tropical (Santacruz et al., 2006) and temperate forests (Karlson
5 and Orlander, 2000). By reducing competition and increasing soil moisture
6 accessibility, soil scarification is expected to have a positive effect on *B.*
7 *papyrifera* seedling survival.

8 This study was designed to assess the perspectives of (assisted)
9 natural regeneration for *Boswellia* woodland restoration. More specifically, we
10 examined *Boswellia* stand structure, seedling densities and the effect of
11 topsoil scarification on seedling survival in a livestock grazing exclosure and
12 compared it with the situation in grazed woodland.

13

14 **2. Materials and methods**

15 **2.1. Study site**

16 The study was carried out near Jijike between 13°14' and 13°42'N and
17 38°38' and 39°02'E, 160 km east of the regional capital Mekelle in the lower
18 Geba river catchment in northern Ethiopia. The altitude varies from 1 400 to
19 1 650 m a.s.l. Along the natural drainage lines of the landscape, Chromic
20 Cambisols and Arenosols are formed over an intimate mixture of Mesozoic
21 limestone and Precambrian schist with local veins of quartzite, but elsewhere
22 Leptosols are dominant and are an unambiguous indication of active erosion
23 processes. The soils are shallow and have a high degree of stoniness, which
24 limits the water holding capacity and the root space significantly (Goris, 2002).
25 The study area has a mean annual rainfall of 657 mm, most of which occurs

1 between mid-June and August, and a mean annual temperature of 22.3 °C. It
2 has a long dry season of 9 months. The dry forests are dominated by
3 *Boswellia papyrifera*, *Acacia etbaica* Schweinf., *Terminalia brownii* Fresen.
4 and *Lannea fruticosa* Engl. They have been heavily impacted by subsistence
5 cultivation, grazing, soil erosion and over-harvesting for fuel wood.

7 2.2. Data collection and analysis

8 *Boswellia papyrifera* stand structure and seedling densities were
9 assessed between April 2004 and August 2005. Using a random sampling
10 procedure, 32 20 × 20 m² plots were selected in two land use types: 16 plots
11 in woodland grazed by domestic livestock (principally goats, cattle and
12 camels), and 16 plots in grazing exclosures established in 1994.

13 In each plot woody species were recorded; those with a diameter at
14 breast height ≥ 0.10 m were considered mature trees, and those with a
15 diameter at breast height between 0.10 and 0.05 m juvenile trees or shrubs.
16 Saplings (woody species with 0.025 m ≤ collar diameter ≤ 0.05 m and height ≥
17 0.5 m) were recorded in a random 5 × 5 m² subplot.

18 Each 20 × 20 m² plot was subdivided into four 10 × 10 m² subplots. In
19 two subplots, two topsoil scarification treatments were carried out before
20 seeding, at the start of the rainy season, using a grub hoe – the first one to a
21 depth of 7.5 cm and the second to a depth of 15 cm. The other two subplots
22 were left untreated, one was used as control and the other was not taken into
23 further account. Seedlings (germinants and small individuals with a collar
24 diameter < 0.025 m) were counted five times during the study: at the
25 beginning of the rainy season in July 2004, at the start of the dry season in

November 2004, mid-dry season in April 2005, after a spring rain in May 2005 and in the rainy season in July 2005.

Differences in stand structure between grazed woodland and exclosure were analyzed using one-way ANOVA. The effect of season, grazing and soil scarification on seedling density was analyzed using repeated measures ANOVA, using land use (grazed woodland versus exclosure) and soil scarification as the between-subject factors and the five seedling counts as levels for the within-subject factor. Analysis was carried out using SPSS 12.0 (SPSS Inc., Chicago, IL).

3. Results

3.1. Stand structure

The population density of mature *B. papyrifera* trees was not significantly different between the two land uses. Mean stem numbers and standard errors of means were 452 ± 30 trees ha⁻¹ in the exclosure and 394 ± 26 trees ha⁻¹ in the grazed woodland ($n = 32$; $F_{1,30} = 2.118$; $p = 0.156$). *Acacia etbaica* was the dominant shrub in both land uses, followed by other pioneers including *Senna singueana* (Del.) Lock, *Acacia asak* Willd., *Stereospermum kunthianum* Cham. and *Dichrostachys cinerea* (L.) Wight & Arn. Only four *B. papyrifera* were recorded as juvenile trees and none as sapling.

The diameter frequency distributions of *B. papyrifera* in grazed woodland and in exclosures approximated normal distributions. The highest frequencies were found in the diameter range 16–20 cm; no trees were recorded in the size classes below 8 and above 36 cm (Fig. 1).

[Insert Fig. 1]

3.2. Seedling population

The number of *Boswellia* seedlings varied throughout the year, showing higher values in the rainy season and lower values in the dry season. Land use ($F_{1,90} = 37.039$; $p < 0.001$) and soil scarification treatment ($F_{2,90} = 5.764$; $p = 0.004$) both had significant effect on the number of seedlings, without interaction: there were more seedlings in exclosures than in grazed woodland and the control plots had more seedlings than plots subjected to soil scarification. In the control plots, the mean seedling densities were 8 331 ha^{-1} in the exclosure and 3 325 ha^{-1} in the grazed woodland during the rainy season. In the exclosure 28.2 % and in the grazed woodland 22.4% of these seedlings were still alive at the start of the dry season (November 2004). In April 2005, no seedlings were detected. In March 2005, after a short spring rain, seedlings had reappeared but survival rates had further dropped to 18.5 and 11.0% in the exclosures and the grazed woodland respectively (Fig. 2).

[Insert Fig. 2]

4. Discussion and Conclusions

The observed diameter frequency distributions of *Boswellia papyrifera* were equivalent to those of stands in the southwestern lowlands of Eritrea (Ogbazghi, 2001). Medium-sized (16–20 cm) trees are most abundant; large trees (DBH > 36 cm) and small trees (DBH < 8 cm) are generally not found.

1 The diameter frequency distributions of *B. papyrifera* in grazed woodland and
2 in exclosures were Gaussian in shape, whereas in healthy, uneven-aged
3 stands a balanced and reverse J-shaped diameter distribution is expected
4 (Zhang and Liu, 2006). The absence of large diameters can be explained by
5 natural mortality, but the absence of small diameters is a strong indicator of
6 recruitment limitation.

7 Results from this study clearly demonstrate that at present there is no
8 lack in seed production or germination in the studied *Boswellia papyrifera*
9 stands. This is in contrast to the sharp decline in seed production and seed
10 vitality observed in tapped *Boswellia* stands in Eritrea (Rijkers et al., 2006).
11 Even in grazed woodland, seedling numbers were reasonably high during the
12 rainy season. Recruitment limitation of *Boswellia papyrifera* is caused by
13 establishment limitation, and more specifically by seedling mortality.

14 Excluding grazing livestock effectively increases the initial number of
15 seedlings and is essential for woodland restoration, but it is not sufficient as
16 single management technique to solve the regeneration problem; both in
17 exclosures and in grazed woodland dry season seedling mortality was high,
18 and more than ten years after the establishment of exclosures, no
19 improvement in stand structure could be observed (Fig. 1). In semiarid
20 environments, mortality often remains high for seedlings and saplings
21 (Herrera et al., 1994; Ogbazghi, 2001). In our case it approximates 100%
22 over successive dry seasons within each generation, leaving only 1–20
23 saplings ha⁻¹ (Gebrehiwot et al., 2006), which is insufficient as future
24 replacement for the mature standing stock. Since grazing is banned in the
25 exclosures, drought stress may be the main reason.

1 Site preparation did not increase seedling density and survival and
2 probably increased rather than decreased drought stress. The success of soil
3 scarification depends on exposing mineral soil which, for seedlings, often has
4 a more stable moisture regime than the organic topsoil (Hille and den Ouden,
5 2004). In our case, soils were extremely rocky (Goris, 2002); scarification
6 more than often exposed rock and bedrock rather than mineral soil, explaining
7 the negative effect on seedling performance.

8 The absence of (visible) seedlings in the middle of the dry season
9 followed by the sudden emergence of seedlings after short spring rains may
10 be related to drought stress followed by resprouting rather than to new
11 germination, since *B. papyrifera* seeds show little or no dormancy, germinate
12 immediately after dispersal and do not accumulate in the soil seed bank
13 (Gebremedhin and Negash, 1999). In selectively cut savanna-woodland in
14 Burkina Faso, seedling sprouting was the dominant regeneration mechanism,
15 exceeding other mechanisms such as root sucker formation, coppicing, water
16 sprouting and layering by far (Ky-Dembele et al., 2007).

17 Although the creation of grazing exclosures mitigates soil degradation,
18 releases trees and seedlings from browsing pressure and is therefore
19 essential for forest rehabilitation, seedling mortality during the dry season
20 seriously limits the potential of natural regeneration for *Boswellia* woodland
21 recovery. To restore a healthy population structure in exclosures, additional
22 management interventions such as shading to support early seedling survival
23 or planting of large rooted cuttings which are more resistant to drought, need
24 to be tested. Finally, resin overexploitation must be avoided to maintain the

present high seed vitality in the northern Ethiopian frankincense woodlands (Rijkers et al., 2006).

Acknowledgements

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1 **Figure captions**

2 Fig. 1. Diameter (cm) frequency distribution of *Boswellia papyrifera* in grazing
3 exclosures (n = 290 trees) and grazed woodland (n = 254 trees) in northern
4 Ethiopia.

5

6 Fig. 2. Seedling densities (m^{-2}) of *Boswellia papyrifera* in grazing exclosures
7 (n = 16×3 plots) and grazed woodland (n = 16×3 plots) throughout the year in
8 northern Ethiopia in function of soil scarification treatment: T0, control; T75,
9 scarification depth 7.5 cm; T150, scarification depth 15 cm. Error bars were
10 omitted for clarity.

1 **Figures**

2 Fig. 1.

3

1 Fig. 2

2