The distribution and regeneration of *Boswellia papyrifera* (Del.) Hochst. in Eritrea

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The distribution and regeneration of *Boswellia papyrifera* (Del.) Hochst. in Eritrea

Woldeselassie Ogbazghi

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Propositions

1. Before effective measures can be taken to prevent *Boswellia papyrifera* from disappearing, information is needed on its distribution, ecological requirements, population structure and natural regeneration, and on the factors and processes leading to the decline of the natural Boswellia population.
   (This thesis)

2. As long as farmers have no rights to tap Boswellia trees and have no title on their land, efforts to counter-act the decline of the Boswellia woodlands should be directed towards solving the prevailing regeneration problem.
   (This thesis)

3. The absence of recruitment in natural Boswellia stands is largely due to low production of viable seed by tapped mother trees.
   (This thesis)

4. By delivering both products and services, and by spreading the risk of crop failure, agroforestry has the potential to strengthen the economic and ecological basis of agricultural production systems.
   (M. Wessel and K.F. Wiersum 1999)

5. Great civilizations have risen where water supply was plentiful and fallen when supplies failed. Therefore, water is both slave and master. Treat the slave well and the master will be served better.
   (I.H. Zahid)

6. A time of crisis is also a time of opportunity, for changes do not occur in time of stability and prosperity.
   (Tewolde B.G. Egziangher).

7. The sandwich of a Dutch PhD fellowship is filled with chocolate rain and peanut butter.

Woldeselassie Ogbazghi
The distribution and regeneration of *Boswellia papyrifera* (Del.) Hochst. In Eritrea.
January 23, 2001

Dedicated to the memory of my father Ogbazghi Temnewo,
my mother Dikan Abraham and my brother Solomon Ogbazghi

Dedicated to my beloved wife Tsegeweini Woldemichael
and my children Biniam, Lidia, Hanna and Nahom.

"When they saw the star, they were overjoyed. On coming to the house, they saw the child with his mother Mary and they bowed down and worshiped him. Then, they opened their treasures and presented him with gifts of gold, and frankincense, and of myrrh" (Matthew 2: 11)

Abstract

Title: Woldeselassie Ogbazghi, The distribution and regeneration of *Boswellia papyrifera* (Del.) Hochst. in Eritrea. Ph.D. thesis, Department of Environmental Sciences, Silviculture and Forest Ecology Group, Wageningen University.

Boswellia papyrifera (Del.) Hochst. is a deciduous gum-producing multipurpose perennial tree species growing in Sudanian and Sahelian regions. The tree is tapped on the stem for oleo-gum called olibanum (true frankincense). Land clearing for agriculture and unregulated grazing are threatening the future of the natural Boswellia woodlands in Eritrea. Against this background, a study was carried out to investigate the distribution of the species and the factors determining its distribution in Eritrea, to study the structure and dynamics of Boswellia populations, including the natural regeneration, and to identify the factors causing the decline of Boswellia woodlands and measures which can reverse this situation. At macro-level, the distribution of the species was found to be limited to the southwestern and southern parts of the country between 800-1850 m altitude receiving a mean annual rainfall of 375-700 mm with a dependable length of growing period of 45-100 days. At micro-level, the abundance and distribution of the species was found to be affected in order of importance by altitude, land use intensity, soil organic matter, and to a lesser extent by silt and pH. Tree development studies showed that trees in the lowlands were twice as high as those in the highlands. The most important outcome of the population structure study is the lack of regeneration. Out of five areas investigated regeneration was only found at two sites where trees were not tapped and which were not accessible to livestock. Further research showed that the present system of intensive annual tapping throughout the dry season leads to low production of non-viable seeds and that where viable seeds are produced, seedlings and saplings are usually destroyed by livestock. Establishment of enclosures in which tapping and grazing is not allowed were found to be an effective measure to promote natural regeneration. Further research is needed to refine this system and to investigate the feasibility of replanting former Boswellia areas.

Keywords: gum, frankincense, distribution, altitude, rainfall, temperature, land use intensity, topography, soil characteristics, tree development and morphology, population structure, seed production, regeneration, tapping, grazing.

Preface

Many indigenous tree species including *Boswellia papyrifera* have become endangered. Some useful tree species have disappeared completely as the result of human and environmental factors. So far, not much has been done to identify the factors affecting the distribution of these endangered species, also the factors affecting their regeneration process. All afforestation activities so far carried out in Eritrea, heavily depended on scientific results generated elsewhere. Nonetheless, commendable reforestation activities and area closures have been under taken to rehabilitate degraded lands. Further steps are necessary to identify the ecological requirements of the indigenous species and to promote the regeneration. The distribution and regeneration study of *Boswellia papyrifera* was carried out against these backgrounds and it is anticipated that, the results of this study will contribute positively to the restoration of *Boswellia papyrifera* in Eritrea. During the inception of this research proposal many individuals have stimulated my ideas and I would like to thank them all.

I would like to express my sincere gratitude to Prof. Dr. M. Wessel and Dr. Frans Bongers for their endurance and much-needed support. Their invaluable scientific guidance and stimulating discussions made my education fruitful both at Wageningen University and Research Centre and in Eritrea. In addition to their scientific guidance, their advice and comments in the structuring of this thesis has been extremely helpful. Without their vivacious support, the work could not have the quality it has now. I highly appreciate the encouragement and support provided by Prof. M. Wessel during his visits of the research site. In addition to this, I really enjoyed the warm friendliness and hospitality of both the Wessel and Bongers families, especially of Mrs. P.C. Wessel-Riemens and Yvonne Geraedts.

This thesis was supported by a MHO-NUFFIC co-operation project between the Wageningen University and Research Centre, the Netherlands and University of Asmara, Eritrea. I wish to express my special thanks to both institutions. During my research period in Eritrea, I was exempted from the normal teaching load and could fully focus on my research. I would like to thank the University of Asmara for its overall support, and specifically the College of Agriculture and Aquatic Sciences.

A rewarding aspect of my study at Wageningen University and Research Centre has been the warm welcome and friendship I have had with a number of academic and administrative staff at the Sub-Department of Forestry. I would like to thank them all. My special thanks go to Dr. Lourens Poorter and Mr. Toon Rijkers who read some of the Chapters of the thesis and provided many constructive comments, and to Mrs. Joke Jansen, Miss. Kathinca Huisman and Mr. Ruud Plas, who greatly facilitated my work. I also would like to thank Mr. Willem Scholten and his colleagues of Unifarm for their continuous support and their work in raising seedlings under controlled conditions at Wageningen. I would like to extend my gratitude to Mr. Piet Kostense, graphic designer, for the preparation of the various maps.

Many individuals and institutions facilitated my field data collection and the experiments in Eritrea. My special thanks go to Mr. Semere Amlesom (Director of the Institute of Agricultural Research and Training, Ministry of Agriculture), and Mr. Tecleab Mesghina (Director of the Department of Environment, Ministry of Land, Water and Environment). Mr Iyassu Gebre-Tatios and Mrs Ghidey Gebreselassie (both staff of the soil laboratory) took care of the chemical soil analyses. The Ministry of Agriculture and Local government staff was extremely helpful in the execution of the fieldwork and I would like to thank them all. In Debub region, Mr Yemane Kibrom (Adi-Quala sub-region) and Mr. Zeray Mesghina (Mai-Mine sub-region) kindly provided land to carry out establishment trials and to raise seedlings in the nurseries of Sheka-Iyammo, Mai-Tsebri and Mai-Mine. They also gave permission to carry out tapping experiments and regeneration studies in permanent plots at Atawen and Adi-Ketina. In North Red Sea region, the late Mr. Amaneul Kidane (Ghinda, Ministry of Agriculture) and the late Dr. Jaeffer Abubaker and Habtom Gudum (Management Institute, Embatkalla) allowed access to land for establishment trials at Ghinda and Embatkalla respectively. In the Anseba region Mr Yohannes Asfeha (local government, Elabered) facilitated the inventory studies and the experiments on the effect of tapping on regeneration in Ferhen.

A good balance between my Ph.D. research and teaching task in a sandwich model could be maintained thanks to the generous co-operation and encouragement of the colleagues at the College of Agriculture and Aquatic Science. In this respect, Dr. Berhane Kifle-Wahid and Dr. Bessrat Ghebru (Deans of the College) did all they could to facilitate the research. My special thanks go to Mr. Mehari Zewde, of the Department of Soil and Water Conservation, who took part in the collection of soil samples.

While undertaking the fieldwork, I had the support of many individuals, too numerous to mention here. Thank you all. A special thanks go to Mr. Naizghi Haile (Gash-Barka, Ministry of Agriculture), Mr. Tekle Berhane (Gash-Barka local government) and the local government staff in Molki and Laelay-Gash sub-regions. They are acknowledged for their support in facilitating the fieldwork and for providing field guides. Among the various areas included in the study, the following sub-zones and village administrations are particularly acknowledged for their participation in the inventory studies in: (1) Anseba (Yegar, Azefa, Ferhen, and Fredareb) (2) Gash-Barka (Molki, Mai-Lam and Dembe-Doran) (3) Laelay Gash (Shilalo, Sheshebit, Mai-Kokah, Dersenay and Deda-laelay) (4) Debub region (Mai-Mine, Adi-Ketina, Meker-Tsablla and Berakit), (5) Adi-Quala sub-region (Adi-Abraham and Bete-Tsion). I can not conclude this note without thanking the communities residing in vicinities of the *Boswellia papyrifera* woodland for providing valuable information on the distribution and the state of the species in their neighbourhood. I warmly appreciate their friendship and hospitality and will remain indebted to them for the years to come. Without their co-operation this thesis would not have been written.

My most dearest gratitude goes to my beloved wife Tsegeweini Woldemichael, my dear children Biniam, Lidia, Hanna and Nahom, and all my family members for their encouragement and their support. They had to endure my absence for long periods, not only when I was in the Netherlands, but also during fieldwork back home in Eritrea. I hope to be more at home in the future.

Woldeselassie Ogbazghi, September 2000.

Contents

CHAPTER 1

1 General introduction

1.1 *Boswellia papyrifera* in Eritrea: its importance and decline

Boswellia papyrifera (Del.) Hochst. belongs to the family Burseraceae. It is a deciduous tree species reaching a height of up to 12 m with thick branches tipped with clusters of leaves. Its bark is smooth, pale yellow-brown, pealing off in large papery pieces. A cut in the bark looks red-brown and a fragrant milky gum comes out of it. The leaves are large pinnately compound on a stalk about 45 cm long consisting of 6-8 pairs of leaflets and one at the tip. Each leaflet is oval in shape, 4-8 cm in size and densely haired below, the edge sharp or rounded–toothed, some times double toothed. Flowers are sweet smelling developing on pubescent panicles at the ends of thick branchlets, appearing when the leaves have fallen off. The red flower stalk is to 35 cm long and bears the white-pink flowers with 5 petals and 10 yellow stamens. The fruit is a red capsule about 2 cm long, three-sided, consisting of three hard seeds with apical horn (Weiss 1987, Vollesen 1989, Bein et al. 1996).

Boswellia papyrifera is an indigenous gum producing multipurpose perennial tree species that grows in drier parts of Africa from Nigeria in the west to Eritrea and Ethiopia in the east. *Boswellia papyrifera* produces an oleo-gum called olibanum (true frankincense) by tapping the stem. This frankincense has been in use since 1700 BC (Howes 1950), and it is still widely used in churches all over the world. It is also the main source of frankincense used in the orthodox churches in Eritrea and Ethiopia (Demissew 1993, 1996). The gum is also a source of essential oils, which are used in the perfume industry, in the fabrication of varnishes and paints and as a laxative ingredient in the pharmaceutical industry (Ahmed 1982, Stiles 1988, Ammon et al. 1993, Kuchar 1995).

Boswellia wood is used for poles and timber by rural communities and to a lesser extent also for industrial manufacturing of wooden products such as match boxes, boards and ply wood (Mueller-Eckhardt 1967, James 1968). The leaves provide dry-season fodder for livestock, while the flowers are a good source of nectar for bees. Leaves, bark, and roots are also used as traditional medicines for various diseases and gums are sometimes used to quench thirst (Bekele et al. 1993, Bein et al. 1996, Gebremedhin and Negash 1999). The species is one of the tree species recommended for economic development and desertification control in arid and semi-arid areas (Stiles 1988, Michele 1993).

Large-scale exploitation of Boswellia trees for gum did not start until 1932, when the Italians introduced a concession system to stimulate the frankincense export (Maugini 1932).

As *Boswellia papyrifera* is not yet domesticated, gum collection takes place from naturally growing trees in the woodlands. Since the introduction of the concession system in Eritrea, gum collection and commercialisation is still an exclusive right of concessionaires.

The ecological functions of *Boswellia papyrifera* have not been systematically studied, but they are thought to play a significant role in soil and water conservation and greening of the landscape. For instance, in some parts of the lowlands, the species constitutes a major plant cover. It could be used in other, ecologically similar, areas as well. Today the species is found mainly on land that is unsuitable for agricultural purposes.

At present, *Boswellia papyrifera* is threatened as the result of several interrelated factors. Increasing population pressure has resulted in the conversion of woodlands to agricultural land while unregulated grazing by which young seedlings are either eaten or trampled by livestock, is hindering the natural regeneration. In part, all this happens because the local community has no interest to protect trees, which they are not allowed to exploit and thus regard as an obstacle on their land.

Another factor causing the decline of *Boswellia papyrifera* is the exploitation system. Trees are tapped every year in the dry season. The frankincense tappers are contracted by the concessionaires and are paid based on the amount of gum collected. This easily can lead to over-tapping. Intensive tapping is thought to have resulted in the death of many trees, especially during periods of drought. Furthermore, there are indications that over-tapping may lead to poor seed production and hence poor regeneration. The decrease in the number of gum-yielding trees is reflected in the decline in gum export which dropped from 2000 tons in 1974 to 400 tons in 1998 (Asmara Chamber of Commerce 1974, Ministry of Agriculture 1999). Long-term export statistics are found in Appendix 1.

1.2 The need for research

Despite the actual and potential uses of *Boswellia papyrifera,* no attempts have been made to improve its utilisation. Nor have attempts been made to understand the reasons for the decline of the population in the country. The occurrence of the species in Eritrea is well documented but detailed information on its distribution, abundance, and stand structure is not available. It goes without saying that before effective measures can be taken to prevent the species from total disappearance, information will be needed on its present distribution and ecological requirements, population structure and natural regeneration, and on the factors and processes leading to the decline of the Boswellia population.

1.3 Research objectives and hypotheses

The general objectives of the research presented in this thesis are:

- to investigate the distribution of *Boswellia papyrifera* (Del.) Hochst. in Eritrea and the factors determining the distribution limits.
- to study the population structure and population dynamics of remnant Boswellia populations, including the natural regeneration.
- to identify the factors causing the decline of the Boswellia woodlands and measures which can reverse this situation.

The main hypotheses are:
Boswellia papyrifera occurs in southwestern parts of Eritrea within an altitude range between 850-1800 m above sea level. Its absence from the central highlands and eastern escarpment suggests that low temperature limits its spread eastwards and that low rainfall prevents its spread to the north and northwest. Within the present distribution limits, intensive land use and unregulated grazing affect the abundance and stand development of the Boswellia woodlands. Tapping of the trees for gum has a negative effect on the reproduction of the species.

1.4 Theoretical framework of the thesis

Boswellia papyrifera is a sexually reproducing tree species. Generally, a tree's life cycle consists of four major developmental stages, namely seed, seedling, sapling, and adult reproductive tree. Plants maintain and expand their populations over time by the process of regeneration (Alder and Synnott 1992, Barnes et al. 1998). Regeneration includes seed production and maturation of seeds so that they are ready for dispersal. In sexually reproducing plants, seed production is followed by dispersal of fruits and seeds, germination, and finally, the establishment of the seedlings in the area. The establishment of seedlings is followed by vegetative development of saplings and later to an adult reproductive tree. The growth and development of each life stage of plants is affected by internal and external factors (Harper 1977, Larcher 1995, Richards 1996). In this research, the focus is on the external factors affecting the distribution and regeneration of *Boswellia papyrifera*.

Based on this model, the life cycle of *Boswellia papyrifera* is divided into four major stages: seed, seedling, sapling, and tree (Figure 1.1). The transition from one developmental stage to the next is affected by two major factors: environmental and human induced factors. The environmental factors are sub-divided into biotic (e.g. local flora and fauna) and abiotic factors (e.g. topography, soil, climate). These factors in general affect the whole life cycle. The main human-induced factors are land clearing, grazing and tapping of trees. Land clearing affects the whole life cycle. Grazing and tapping affect a specific stage of development: grazing affects both seedlings and saplings while tapping affects the adult tree (Figure 1.1). Both environmental and human factors are also linked in that the modification of the physical environment by man has an effect on the overall environmental setting which in turn influences the life cycle of the species and hence its distribution and regeneration.

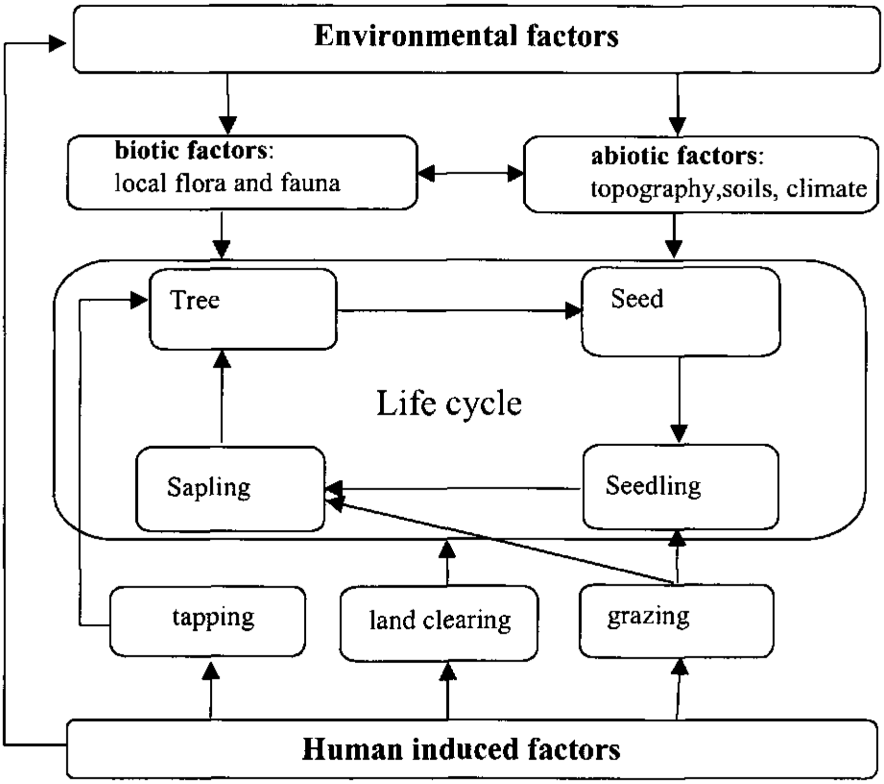

Figure 1.1 A conceptual framework used to analyse the distribution and regeneration of *Boswellia papyrifera* (Del.) Hochst.

1.5 Outline of the thesis

The thesis consists of eight Chapters. Following the introduction Chapter 2 provides general information on the environment, vegetation and forest resources, and the population of

Eritrea. Furthermore, it pays attention to the land use and land tenure and its impact on tree planting and forest conservation.

In Chapter 3, the macro-distribution of *Boswellia papyrifera* is presented. The geographical locations where the species occurs and areas from where it has disappeared are identified. Its occurrence is described and analysed in relation to three factors: altitude, rainfall, and length of growing period.

After identifying the major *Boswellia papyrifera* growing areas in Eritrea, the distribution of the species is studied at micro-level in five representative sites in Chapter 4. Its distribution and abundance are quantified and described in relation to the major site conditions (landforms, soils, and land use).

In Chapter 5, the tree development and morphological characteristics of Boswellia are described. The variations in tree size are determined and analysed in relation to site conditions and altitude.

Chapter 6 deals with the population structure of *Boswellia papyrifera* stands in five representative sites. The size class distribution is described and the regeneration status of the species in those areas is analysed in relation to the land use.

Possible reasons for lack of regeneration of *Boswellia papyrifera* stands in Eritrea are analysed in Chapter 7. The effects of two major factors, e.g. land use and exploitation of the trees for gum, on recruitment and establishment are studied in detail.

Finally, in Chapter 8 a general discussion and synthesis of the research results is presented. Practical measures and research priorities are proposed, to counteract the decline and degradation in Boswellia woodlands.

CHAPTER 2

2 General background: environment, natural resources and population of Eritrea

2.1 Geographic location

Eritrea is situated in the northeastern part of Africa between latitudes 12°40' and 18°02' and longitudes 36°30' and 43°23'. It borders on Sudan in the north and west, on Ethiopia in the south, on Djibouti in the southeast and on the Red Sea in the east and northeast (Figure 2.1). The land surface area of the country is 125,700 km^2 (Department of Environment 1998).

2.2 Geology, topography and soils

The geology of Eritrea is variable due to continuous uplifting and faulting. Geologically Eritrea is divided into two distinct regions: the central and northern highlands, and the coastal areas. The central and northern highlands consist of the Pre-Cambrian Basement complex of the oldest formations found in Africa. The western highlands with their typical flat-topped mountains are mostly covered by tertiary basaltic flows. In western Eritrea, the basement complex was later covered by young quaternary sediments but locally rocky outcrops of the basement complex occur (Mohr 1970, Drury et al. 1994). The formations along the Red Sea coasts and the southern Danakil plains are younger and consist of tertiary and quaternary sediments and volcanic rocks. The latter are associated with the Red Sea and the Afar rift system, which cuts through the area from south to north, accompanied by many fault lines. During the Tertiary, sandstone and limestone were formed along the eastern coast, where at present lagoons and salt plains are found (Mohr 1961, 1987).

Eritrea can be divided into three topographic regions: eastern coastal zone, the highlands, and the western lowlands (Jones 1991). The highlands stretch from south to north dividing the country into the eastern and western lowlands. In the south, the highland is predominantly a plateau while in the north dissected hills, mountains, and escarpments dominate. The western and eastern lowlands are predominantly flat areas with dome-shaped hills (Haggag 1961). The highland is an extension of the high land of East Africa. The descent to the west and the east are different in that the land slopes gradually to Sudan in the west and abruptly towards the Red Sea, where over a distance of 50 km the altitude changes from 3030 m above to 100 m below sea level. These variations in the topography greatly influence the temperature and rainfall regimes of the country.

Information on the Eritrean soils is scarce. Some local studies on surface soils are reported by Murphy (1968), Maskey (1985), and Haile et al. (1998). In view of this constraint, the soils can only be considered in a general way referring to some of the soil groups described by FAO (1994). According to an updated version of their classification (FAO 1997a), nine major soil types distributed over six agroecological zones are identified (see section 2.4, Agroecological zones).

2.3 Climate

The climate of Eritrea ranges from hot and arid adjacent to the Red Sea to temperate in the highlands and sub-humid in isolated micro-catchment area in the sub-humid on the eastern escarpment. It can be described in general terms as follows. Most parts of the country (70%) is classified as hot to very hot with mean annual temperature of more than 27°C; about (25%) as warm to mild with a mean temperature of about 22 °C, and the remaining parts (5%) as cool with a mean annual temperature of less than 19 °C. The total annual rainfall increases from the north to south and varies from less than 200 mm in the northwest lowlands to more than 700 mm in the southwestern lowlands. Besides, the amount of rainfall also increases with altitude. While the coastal lowlands are very dry, some areas on the eastern escarpment get more than 1000 mm. As to areas covered by the different rainfall regimes, about 50% of the country receives less than 300 mm, 40% between 300 and 600 mm and about 10% more than 600 mm of rain per annum (FAO 1994, Haile et al. 1998). Representative data of the major agroecological zones are given in Appendix 2.

2.4 Agroecological zones

As shown in the previous sections, Eritrea has a large variation in landscape and climatic features (Haggag 1961). The agroecological map (FAO 1997a) has six major agroecological zones: moist lowland, moist highland, arid lowland, arid highland, semi-desert and sub-humid (Figure 2.1). The general characteristics of the agroecological zones in terms of area, topography, altitude and climate are specified in Table 2.1.

The major soil types of these zones are given in Table 2.2. The Cambisols and Lithosols are found in all six agroecological zones, while the Regosols Fluvisols are found in four of them. Soils with the highest agricultural potential e.g. the Luvisols, Fluvisols, and Vertic Cambisols are found in the moist highland and moist lowland of Eritrea. Limited soil depth and steep slopes limit their potential in many places.

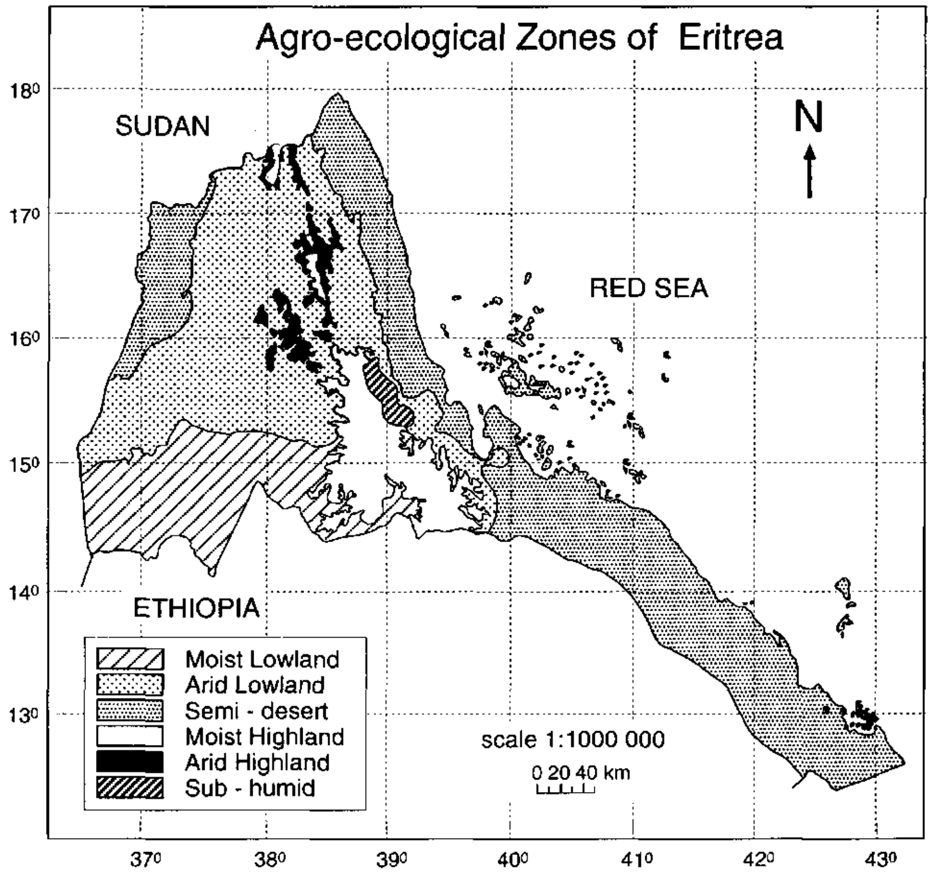

Figure 2.1 Agroecological zones of Eritrea (FAO 1997a)

Table 2.1 Description of the six agroecological zones of Eritrea.

	agroecological zone					
	sub-humid	arid highland	moist highland	moist lowland	arid lowland	semi-desert
area (km^2)	1,006	3,143	9,302	20,363	43,115	48,772
total area (%)	1	3	7	16	34	39
slope (%)	8-100	2-100	2-30	2-30	0-30	0-30
altitude (m a.s.l.)	600-2600	1600-2600	1600-3018	500-1600	400-1600	<100-1355
rainfall (mm)	700-1100	200-500	500-700	500-800	200-500	<200
temperature (°C)	16-27	15-21	15-21	21-28	21-29	24-32
PET (mm) [(1)]	1600-2000	1600-1800	1600-1800	1800-2000	1800-200	1800-2100
DLGP (days) [(1)]	60-210	0-30	60-110	50-90	0-30	0
MLGP (days) [(1)]	90-240	30-60	90-120	60-120	30-60	<30

Source: FAO (1997a).

[(1)] PET is Potential Evapotranspiration, DLGP is Dependable Length of Growing Period, MLGP is Median Length of Growing Period.

Table 2.2 The occurrence of the major soil types in the different agroecological zones of Eritrea. The + sign represents the occurrence and the – sign is absence of the soil type.

soil type	agroecological zone					
	moist highland	arid highland	moist lowland	arid lowland	sub-humid	semi-desert
Cambisols	+	+	+	+	+	+
Lithosls	+	+	+	+	+	+
Fluvisols	-	-	+	+	+	+
Regosols	+	+	+	-	-	+
Xerosols	-	+	-	+	-	+
Vertisols	+	-	+	-	-	-
Andisols	-	-	-	-	-	+
Luvisols	+	-	-	-	-	-
Solonchaks	-	-	-	-	-	+

Source: FAO (1997a).

2.5 Vegetation of Eritrea

The vegetation map of Africa by White (1983) was originally made to document regions of the continent from which groups of associated unique species evolved, the so-called the regional centres of endemism. This map gave 20 major regional centres of endemism of which 4 (Sudanian, Somali-Masai, Afromontane, and Sahel region) are well represented in Eritrea (White 1983, Thulin 1983, Friis 1992). The Sahara regional transitional zone is limited to an isolated area along the Red Sea coast. Within these regions, similar vegetation types are grouped into mapping units. In Eritrea, there are nine mapping units, which represent nine vegetation types. The relation between White's (1983) regional centres of endemism and the distinguished vegetation types in Eritrea is given in Table 2.3. The geographical distribution of these nine types is shown in Figure 2.2.

Boswellia papyrifera is found mainly in the Sudanian and Sahelian regional centres of endemism. In the Sudanian region, it is found in the undifferentiated woodland, Ethiopian type. In the Sahelian region, it occurs in wooded grassland and deciduous bushland. The species also extends to higher altitude in the East African evergreen and semi-evergreen bushland and thicket (Keay 1959, White 1983).

The undifferentiated woodland, Ethiopian type, is found in the southwestern lowlands of Eritrea. As the amount of rainfall decreases from south to north, there is gradual transition to the Sahel region. Whereas the boundary between the Sudanian vegetation and the East African evergreen vegetation type is determined by altitude, the amount of rainfall determines the boundary between the Sudanian and the Sahelian vegetation (White 1983).

Table 2.3 Vegetation mapping units and the main vegetation types present in Eritrea (cf. White 1983).

major centre of endemism	vegetation type represented in Eritrea
Afromontane region	Undifferentiated montane vegetation
Sudanian region	Undifferentiated woodland Ethiopian type
Somalia-Masai region and Sahel region	East African evergreen and semi-evergreen bushland and ticket
	Somalia-Masai deciduous bushland and ticket
	Somalia-Masai semi-desert grassland and bushland
Sahel region	Sahel Acacia wooded grassland and deciduous bushland
	Semi-desert grassland and bushland
Sahara regional transition	Red Sea coastal desert
	Wadis and open desert

In the Sudanian and Sahelian region the major woody plants associated with *Boswellia papyrifera* are (White 1983): *Acacia tortilis, Acacia laeta, Acacia mellifear, Anogeissus leiocarpus, Balanites aegyptiaca, Boscia salicifolia, Boscia senegalensis, Combretum collinum, Combretum hartmannianum, Combretum molle Commiphora africana, Dalbergia melanoxylon, Dichrostachys cinerea, Erythrina abyssinica, Gardenia ternifoli, Lannea shimperi, Leptadenia pyrotechnica, Lonchocarpus laxiflorus, Maerua crassifolia, Piliosigma thonningii, Steriospermum kunthianum* and *Terminalia brownii.*

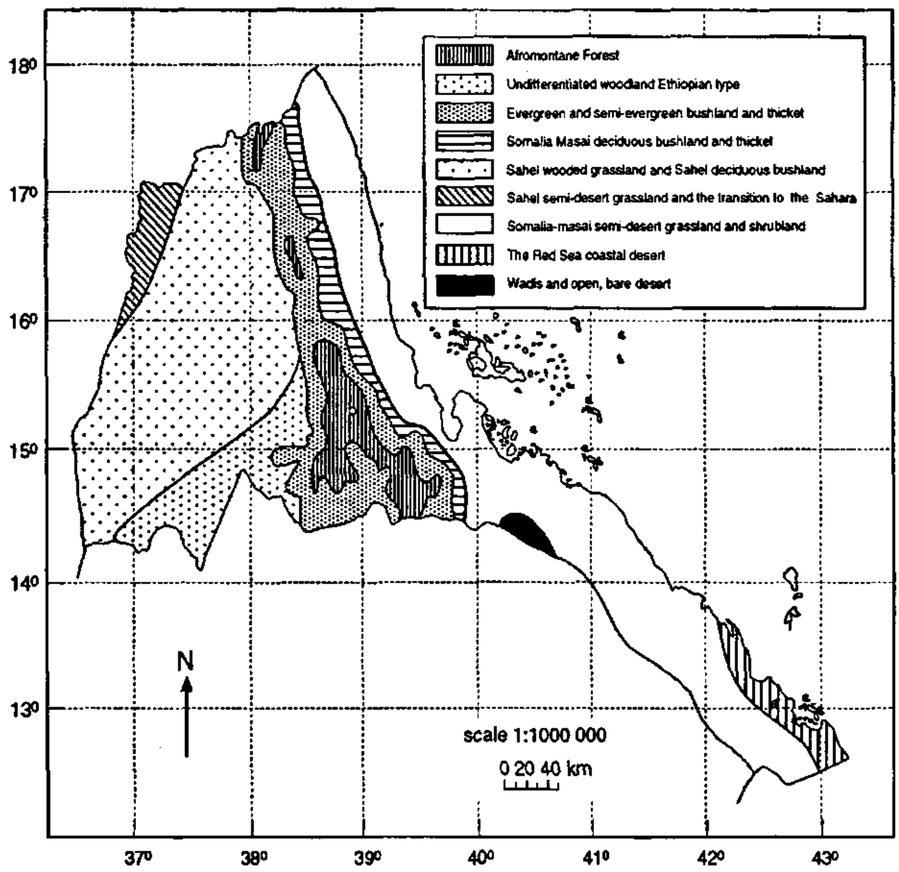

Figure 2.2 The vegetation map of Eritrea, based on the vegetation map of Africa (White 1983).

At the upper limits of the Sudanian and Sahelian region other, more evergreen species, are found in association with Boswellia: *Acokanthera schimperi, Carissa edulis,* *Commiphora africana, Dodonea ungustifolia, Euclea schimperi, Euphorbia candelabrum, Olea africana, Rhus natalensis,* and *Teclea spp.* A comprehensive list of all woody plants found in association with *Boswellia papyrifera* along its entire altitude range is given in Appendix 7.

2.6 Forest cover and its decline

A century ago, about 30% of the total land area of Eritrea was covered by forest. This figure dwindled to 11% in 1952 (NEMP-E 1995, Bein et al. 1996) and in 1960, it was estimated to be 5% (Ministry of Agriculture 1994). Today the closed and open forest covers less 1%, while about 60% of the country is covered by bush land (Table 2.4).

Table 2.4 Vegetation types and area covered in Eritrea.

vegetation type	area covered (km^2)	percentage of total land area
closed-medium forest	591	0.5
open forest	410	0.3
riverine forest	1,865	1.5
mangrove	64	0.1
closed-medium closed woodland	4,533	3.6
open woodland	9,541	7.6
wooded grassland	25,577	20.3
bush land	53,824	42.7
agricultural land	8,712	6.8
barren land	18,265	14.4
others	234	0.2
not classified	2,172	1.7

Source: FAO (1997b).

Recent studies on the causes of the decline of forest resources of Eritrea show that several interrelated factors have contributed to it. The main reasons are land clearing for commercial and subsistence agriculture, overgrazing, consumption of wood for fuel, construction of traditional houses, drought and land clearing for military purposes (World Bank 1994, NEMP-E 1995, Haile et al. 1996, Bein 1998).

During the long history of subsistence agriculture and especially after the introduction of commercial agriculture many forests were converted into agricultural land. The seriousness of the problem was noted already during the Italian colonial period (Fiori 1912). With the increase in population, land clearing was extended to steep areas unsuitable for cultivation. Furthermore, increased demands for firewood and the use of wood for the construction of traditional houses had adversely effected the forest cover (Haile et al. 1996). Licensed commercial exploitation of timber, fuel-wood, and charcoal has further aggravated the problem (Jones 1991, Bein 1998). This is likely to remain as it is because the main source of domestic energy in the country is still wood (Habtesion 1997, FAO 1997b).

Grazing pressure has intensified during the last century. As a result of improved veterinary services the livestock population has increased substantially. For instance, from 1946 to 1976, the number of goats, sheep and cattle increased by 46% (Bein 1998). Recent estimates gave 1.65 million Tropical Livestock Units (FAO 1994, Haile et al. 1996). Grazing pressure is widespread throughout the country and is particularly severe during the dry season. There are no systematic data on the effect of the size of the livestock population on the forest cover but widespread degradation and lack of regeneration of many tree species due to overgrazing is evident everywhere.

Land tenure, particularly the 'Dessa' system involving the periodic redistribution of arable land among villagers, provides no incentive for farmers to carry out permanent improvement to the land. Lack of tree tenure is the cause for neglect by the local communities to protect and plant new trees (Kebreab 1996, Bein et al. 1996).

During the past decades a persistent fluctuation of rainfall has been recorded. Rainfall records in Asmara (1903-1932) show that out of the 30 years only in 13 years the rainfall exceeded the mean annual rainfall of 518 mm and that in the remaining 17 years, it was much less (Civil Aviation Authority, Asmara unpublished data). Later rainfall records (1933-1962) of the same area and other meteorological stations in the country show a similar pattern. The effects of drought on the vegetation are unknown but many people living in areas affected by drought observed that a period of drought is usually followed by tree mortality. Many tree species have been severely affected following the drought of 1968-1973 in the Sahel region. The effect of drought in this area was exacerbated by increased population pressure (White 1983, Workineh 1987).

The negative effects of the 30 years liberation war (1961-1991) on forest resources have been emphasised in the Environmental Management and Action Plan of Eritrea (NEMP-E 1995, Bein 1996). It is, however, difficult to give precise figures on the extent of deforestation caused by three decades of war. Frequent bombardment and fire killed trees and many were cut to provide firewood and to construct trenches and military sheds. As the forest and woodlands were regarded as hiding place for guerrilla fighters they were regarded a nuisance and recklessly cleared (Haile et al. 1998).

In Eritrea, there are opportunities to rehabilitate and restore the degraded forests and woodlands. There are still remnant stands of secondary forest and woodlands that can be used for spontaneous regeneration and to raise seedlings. In the highlands, many forest tree species have been preserved in sacred sanctuaries and areas inaccessible to livestock grazing. These places are important sources of information on the environmental requirements for conservation and rehabilitation activities (Lamprecht 1989). So far, no clear plan has been developed on the conservation of endangered species and on the introduction of new ones. In many areas, various large-scale replanting schemes have been launched but their success has been limited so far.

2.7 Population and livelihood

To date, there is no complete census of the population of Eritrea. Various estimates indicated that the population has increased four fold during the past five decades. In the early 1940's, the population size was 757,000 of which 565,000 were sedentary farmers and the remaining 192,000 nomads (Longridge 1974). In 1952 the population size increased to 1,031,000 (Trevaskis 1975). Tedla (1964) estimated the population to be 1,500,000. The latest estimate by the World Bank (1994) puts this figure to 3 million.

Agriculture is the largest sector of the economy in Eritrea. It occupies 80 % of the labour force, and contributes 26% of the gross domestic product (World Bank 1994). The rural communities live on subsistence agriculture comprising mainly cereal crop and livestock production (Cliffe 1988). Some coastal communities depend on fisheries as their means of livelihood. Agricultural production ranges from nomadic systems to small-scale irrigated horticultural production. Cliffe (1988) recognises three major agricultural systems, namely nomadic, semi-nomadic and sedentary agriculture, which are practised by 11, 22, and 67% of the population, respectively. Because crop cultivation entirely depends on animal traction, Haile et al. (1995) and Haile et al. (1996) classify the rural population as predominantly agro-pastoral.

Because of its ecological diversity, Eritrea produces a wide range of cereals, vegetables, pulses, and fibre crops (Mesghina and Ghebru 1997, Araia et al. 1994). In the highlands, farmers grow taff, barley, wheat, oil seeds including niger seed, and various legumes such as lentils, chickpeas, and faba beans. In the lowlands, the main crops are pearl millet, sorghum, finger millet, sesame, groundnuts, cotton, fruits, and vegetable crops. In the lowlands, sorghum is the most important crop and accounts for about 46% of annual yield in the country (Cliffe 1988, World Bank 1994) followed by pearl millet (16%) and barley (15%) (Araia et al. 1994).

In spite of the wealth of crop diversity in Eritrea, historical records show a chronic crop production deficit due to recurrent droughts and pest out-breaks. Cliffe (1988) estimated a normal harvest under non-disastrous situations to be between 220-250 thousand metric tons of cereals covering about 55-65% of annual national demand. During the liberation struggle and immediately after it, most of the rural communities in the country were dependent on food aid. In the early 1990's about 72% of the population was food-aid dependent (Appleton et al. 1992). Since then, the situation has improved because of increased food production, which resulted from a change in policy of food-aid dependence to food security programmes.

2.8 Land tenure and consequences for the vegetation

In Eritrea, three major land tenure systems have coexisted for many years. These are the 'Rsti' (family ownership), 'Dessa' (village or collective ownership), and 'Demaniale' (state ownership (Nadel 1946, Zekarias 1966, Jordan 1989, Menghisteab 1992). The land tenure system varies from place to place. A new land law issued in 1994 has officially replaced the three traditional land tenure systems, but in practice, the situation has not changed (Government of Eritrea 1994).

Individual family land ownership (Rsti)

The individual family ownership of land refers to a system in which land could be acquired by settlement in a vacant area, purchase, or granting land by rulers (Zekarias 1966). A Rsti owner could be an individual, an institution such as a church, or an extended family. In many cases the extended family has lived in the area for several generations and considers itself as the founder of a settlement. In the Rsti system, in fact the individual ownership is always belonging to the extended family. An individual holder of Rsti land can cultivate or lease it or arrange share cropping, but can not sell it, nor give it away to an outsider without the consent of family members. Thus, individual Rsti holders do not have absolute right over their lands. Haile et al. (1998) mentioned that, although individual families have legitimate rights over their agricultural lands, grazing areas and fallow lands are communally used. Trees within a holding belong to the landholder who has the right to use them when needed. This, however, is not the case for tapping Boswellia trees for frankincense: here concessionaires have the complete right of tapping. Streams, wells, and land around settlements are communally owned and managed by a council elected by the villagers (Zekarias 1966).

Village land ownership (Dessa)

Dessa is a traditional land tenure system of village-wide communal ownership of land. How the Dessa land tenure system came into being in Eritrea is not clearly known. Some sources (e.g. Nadel 1946, Trevaskis 1975, Jordan 1989) report that the Italians introduced it as a means of settling land disputes in the Rsti systems. Within the Dessa system, the village elders form a committee that establishes criteria for eligibility to a full share or a half share of a crop field. An adult member who permanently establishes a household in a village is entitled to a full or to a half share depending on criteria such as marritial status and the number of children in the household. The Dessa system involves land re-distribution every five to seven years by which each eligible household receives, often scattered, fields of different fertility classes. This situation discourages the landholders to make long-term investment such as planting of trees or the construction of soil and water conservation structures. After each land redistribution farmers have often to build new houses, and this puts extra pressure on the remaining forest resources.

State ownership (Demaniale)

During the Italian colonisation and later the British administration (1890-1940), traditional individual lands were confiscated in favour of Italian commercial agriculture (Longridge 1974, Trevaskis 1975,). In the highlands, Demaniale lands were limited to the fertile lands used for irrigated agriculture and dairy farms. In the lowlands, however, all areas below 850 m a.s.l. were declared state lands (Mesghina 1988). The latter status allowed open access to lands resulting in massive clearing of land and extensive unsustainable land use.

Both Dessa and Demaniale systems and the rapid population growth have led to land degradation and unscrupulous cutting of the natural vegetation similar to what Hardin (1968) described it as " the tragedy of commons". The consequence can easily be seen in the highlands where more than 60% of the population lives in about 8% of the total area of Eritrea.

CHAPTER 3

3 Macro-distribution of *Boswellia papyrifera*

3.1 Introduction

Boswellia is one of the 17 genera in the family Burseraceae that is widespread in all tropical regions and extending to the sub-tropics often as a dominant constituent of the vegetation in dry lowland areas (Heywood et al. 1993). The centre of geographic distribution of the genus Boswellia is located in the northeastern parts of Africa where more than 75% of its species are endemic to the area (Vollesen 1989). The species *Boswellia papyrifera*, one of the 20 species in the genus, is widely distributed in the savanna areas of Africa (Breitenbach Von 1963, White 1983, Keay 1989, Vollesen 1989, Menaut et al. 1996).

Boswellia papyrifera is reported from several countries mainly in the Sudanian and Sahelian regions: Nigeria, Cameroon, Central African Republic, Chad, Sudan, Northeastern Uganda, Ethiopia, and Eritrea (Vollesen 1989, Demissew 1993) (Figure 3.1). In northern Nigeria, *Boswellia papyrifera* is found in the Zamfara forest reserve, and the Yola region from where it extends eastwards to Sudan (Keay 1959, 1989) and to the savanna area of northern Cameroon and the Central African Republic (White 1983). In Sudan, it is found in three major areas: the Roseires in the vicinity of the Ingessana hills, at the foot of Nuba mountains, and in the southern and western parts of the Jebel Mara massifs (James 1968, Wickens 1977, White 1983). In the Jebel Mara massifs, the species is found in pure or mixed stands on gently to steeply sloping land but mostly on steep slopes. The underlying rock in this area is the basement complex rock (White 1983), Nubian sandstone, and volcanic ashes (James 1968).

In Ethiopia, *Boswellia papyrifera* is reported from different provinces namely in Tigray, Gondar, Gojam, and Showa (Vollesen 1989, Bekele et al. 1993, Demissew 1993). In these provinces, it occurs in dry regions, dominated by Acacia-Commiphora woodland and wooded grassland between 950 and 1800 m a.s.l, mainly on steep rocky slopes and on lava flows. In the semi-arid lowland agroecological zone between 500 and 1300 m, it is also found in sandy river valleys, on sandy terraces and plains associated with scrub and savanna vegetation (Breitenbach 1963).

In Eritrea, the occurrence of *Boswellia papyrifera* has been documented in various studies listing trees used for timber, gum production and medicinal purposes (Fiori 1912, Baldrati 1946, Negri 1948, Pichi-Sermolli 1957). White (1983) distinguishes nine vegetation associations in Eritrea. On his map, the occurrence of the species is indicated in two plant associations: in the undifferentiated woodland, Ethiopian type and in the Sahel Acacia wooded grassland and deciduous bushland. The flora of Ethiopia (Vollesen 1989) briefly mentioned its occurrence in different parts of Ethiopia and Eritrea. Two more recently published monographs on useful trees and shrubs in Ethiopia and Eritrea (Bekele et al. 1993, Bein et al. 1996) also mention the occurrence of *Boswellia papyrifera* in western Eritrea.

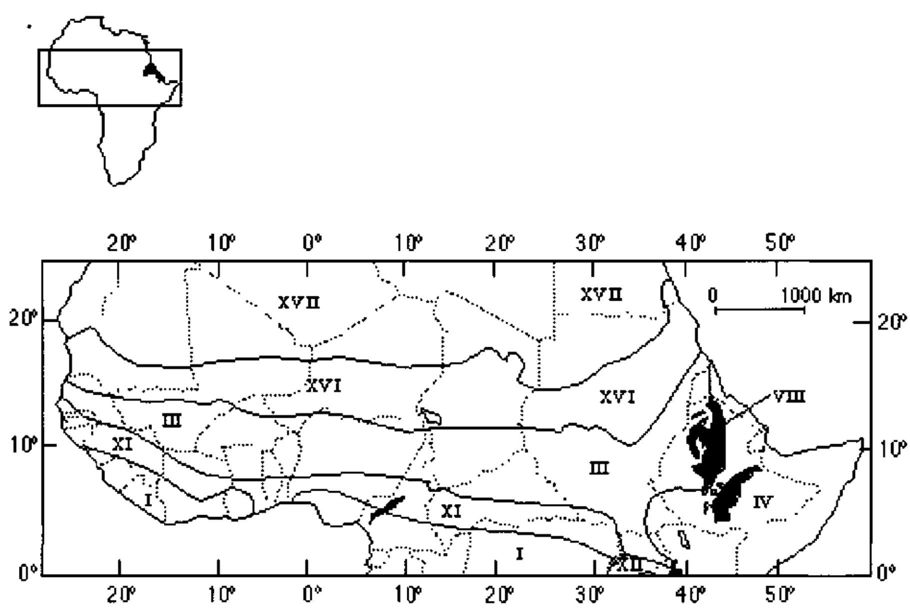

Figure 3.1 The vegetation map of a part of Africa showing the main regions defined by White (1983). The main regions where *Boswellia papyrifera* occurs are III (the Sudanian regional centre of endemism) and XVI (the Sahel regional transition zone). The other roman numbers represent: IV, the Somalia-Masai regional centre of endemism, VIII, Afromontane region, XI, Guinea-Congolia/Sudanian regional transition zone, and XVII, Sahara regional transition zone.

So far, however, the occurrence and geographical distribution of the species in Eritrea has never been investigated in relation to the environment in the different regions. The study presented in this Chapter was undertaken to provide this information and had the following main objectives:

- to relate the occurrence of the species to environmental factors and describe its ecological niche. The underlying research hypothesis is that low temperature in the highlands and low and short duration of rainfall in the lowlands limit the *Boswellia papyrifera* distribution to southwestern Eritrea.
- to identify *Boswellia papyrifera* woodlands for detailed studies on the abundance and population structure in Eritrea.

3.2 Methodology

3.2.1 Selection of survey areas

The major frankincense collection areas in the country were located on the basis of the information provided by the Ministry of Agriculture head office, which controls frankincense production, and by the concessionaires involved in the collection and commercialisation of frankincense in Eritrea. Both sources provided a preliminary list of gum collection areas in the different regions of the country and this information was used as a starting point to select the regions and sub-regions for the study. Because there were no indications about the past and present occurrence of *Boswellia papyrifera* in the North Red Sea and South Red Sea administrative regions these were not included in this study. In the remaining regions (Centre, Debub, Anseba and Gash-Barka) the occurrence of *Boswellia papyrifera* was investigated in all 39 sub-regions. To cover the complete altitude range all accessible villages (113 in total) were visited (see Table 3.1). In addition, observations were made along roads linking various villages.

Table 3.1 The administrative regions, the number of sub-regions, observation villages and altitude ranges included in the macro-distribution study of *Boswellia papyrifera* in Eritrea.

administrative regions	nr of sub-regions	nr of village areas	altitude range (m a.s.l.)	agroecological zones covered
Anseba	10	30	600-2400	SD, AL, MH, AH [1]
Gash-Barka	14	34	500-2200	SD, AL, ML, MH [1]
Debub	12	38	1400-3000	ML, MH [1]
Centre	3	11	2000-2400	MH [1]
total	39	113	600-3000	

[1] SD: semi-desert, AL: arid lowland, MH: moist highland, AH: arid highland, ML: moist lowland

3.2.2 Data collection

In all 113 village areas, field observations were made to see whether Boswellia was present or absent. If no Boswellia trees were found in the vicinity of the villages, the villagers were asked if the species was present in the area or had grown there in the past. The local resource persons included people who were directly involved in the tapping and gum collection activities. Their information was very useful to obtain a general impression of the abundance of the species and to describe its present and past geographical distribution. The location of each village area was mapped and its altitude recorded with an altimeter.

Rainfall data were collected from the sub-region meteorological stations of the Ministry of Agriculture and from the regional offices of the National Civil Aviation Service. The minimum, maximum and mean temperatures for each village area were calculated on the basis of altitude using temperature-altitude regression equations (Appendix 3). These equations are based on long-term records from 12 meteorological stations in Eritrea and two from northern Ethiopia (FAO 1997a). The mean annual potential evapotranspiration (PET) was calculated with the PET-altitude regression equation (FAO 1997).

The dependable length of growing period (DLGP) in days was compiled for each village from the FAO (1997a) agroecological map. The length of growing period (LGP) is defined as the time of the year when moisture and temperature are suitable for plant growth and development. In Eritrea, LGP is mainly determined by moisture availability and hence it is defined as a continuous period of the year when precipitation exceeds 50% of the potential evapotranspiration plus the time required for the evapotranspiration of stored soil moisture. The length of growing periods used by FAO are based on ten days rainfall and potential evapotranspiration totals as recorded at the various meteorological stations in Eritrea.

3.2.3 Data analysis

The occurrence of *Boswellia papyrifera* in relation to altitude, rainfall and the length of growing period were analysed using a logistic regression analysis (Huisman et al. 1993, Bongers et al. 1999). The binary data on the presence (+) or absence (-) were converted to numerical values of 1 and 0 respectively (Ter Braak and Gremmen 1987). Regression methods are useful in the analysis of the relationship between a response variable and one or more explanatory variables and it is preferred as a practical method for summarising species distribution along environmental gradients (Ter Braak and Looman 1986, Peeters and Gardeniers 1998). The analyses were carried out at two-levels. First, using a forward stepwise analysis the likelihood ratio was determined to identify the main factor influencing the occurrence of the species by including all the 113 village areas covered in the study.

Second, each of the independent variables was analysed to investigate how each of them affects the occurrence of the species. For the occurrence of the species in relation to altitude, the very low rainfall areas (annual rainfall smaller than 350 mm) were excluded. For the relationship with rainfall and length of growing season, the areas at high altitudes (above 1900 m a.s.l.) were excluded. The single logistic regression provides a good description of the optimum habitat requirement and the multiple regression gives insight into the relative importance of each environmental variable (Peeters and Gardeniers 1998). For the relationship between a single independent variable such as altitude, rainfall, or length of growing period and the occurrence of *Boswellia papyrifera* the logistic regression curves were estimated using the following equation:

$$p(x) = \frac{1}{1 + e^{-(B_0 + B_1 X)}} \qquad \text{(Eq. 3.1)}$$

in which:

$p_{(x)}$	:	probability of an event;
e	:	base of natural logarithm, approximately 2.718;
B_0 and B_1	:	coefficients estimated from the data;
X	:	independent variable (altitude, rainfall or length of growing period).

All statistical analysis was carried out using SPSS for Microsoft 1998.

3.3 Results

3.3.1 Geographical distribution

Boswellia papyrifera was found in three administrative regions of Eritrea, Anseba, Gash-Barka and Debub and not in the Centre region. Out of the 30 villages visited in Anseba, *Boswellia papyrifera* was present in 8, had disappeared in 5 and was absent in 17 villages. In the 34 villages in the Gash-Barka region these figures were 13, 10 and 11 respectively, meaning that the species is still present or was present in about two third of the villages. In the Debub where 38 villages were visited the situation was the reverse: *Boswellia papyrifera* was and is present in about one third of the villages. This information is given in Table 3.2 and Figure 3.2b. The latter shows that Boswellia was and still is mainly found in the moist lowland agroecological zone. In the Anseba region, fragmented and rather sparse stands are mainly found in mountainous areas on sites that are not suitable for agriculture and inaccessible to livestock. This gives a distribution pattern in which the remnant stands are separated by vast plains and riverine areas. In the Gash–Barka region on the other hand, a relatively large area of intact *Boswellia papyrifera* woodlands are found (Figure 3.2b).

Table 3.2 The number of sub-regions and villages in the four administrative regions in Eritrea where *Boswellia papyrifera* occurred in the past and is still present.

region	total nr sub-regions	occurrence in sub-regions			total nr villages	occurrence in villages		
		present	past	absent		present	past	absent
Anseba	10	4	1	5	30	8	5	17
Gash-Barka	14	6	3	5	34	13	10	11
Debub	12	3	2	7	38	7	5	26
Centre	3	0	0	3	11	0	0	11
total	39	13	6	20	113	28	20	65

The data in Table 3.2 clearly show that the occurrence of *Boswellia papyrifera* has decreased over the years. This is in line with the opinion of the farmers living near the *Boswellia papyrifera* woodlands, that the species covered larger areas in the past. Elder farmers have witnessed the disappearance of Boswellia trees during their lifetime especially near the settlements where the vegetation was cleared for crop production. Figure 3.2b shows that Boswellia disappeared at the northern limit of its distribution, e.g. in the transition zone between the moist lowlands and arid lowlands.

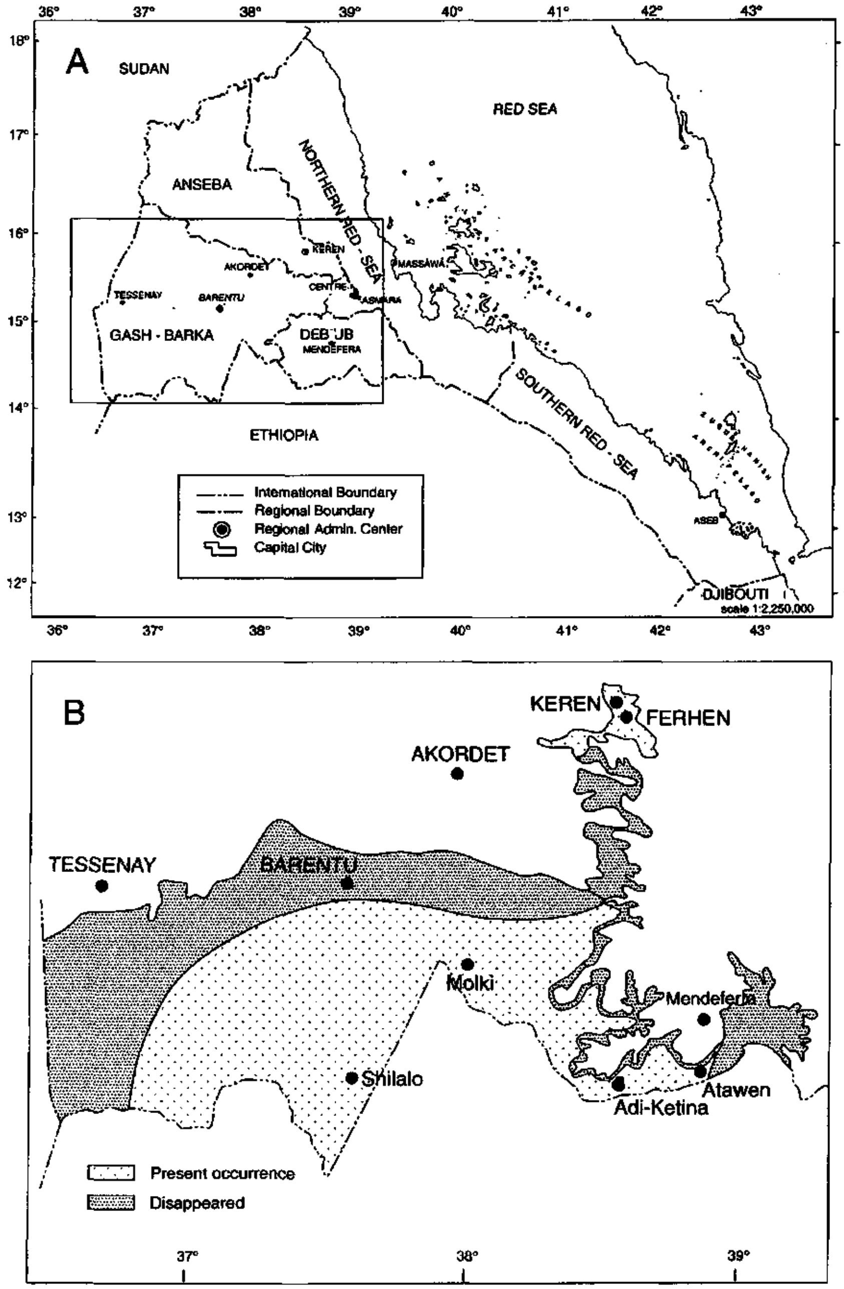

Figure 3.2 A map showing the administrative regions of Eritrea (A) and the present and past occurrence of *Boswellia papyrifera* in the southwestern part of the country (B).

Table 3.3 The past and present occurrence of *Boswellia papyrifera* in different regions and sub-regions of Eritrea in relation to altitude and climatic conditions. The + and – signs represent present or absent, respectively.

region	sub-region	AEZ [1]	max. altitude (m a.s.l)	mean rainfall (mm)	max PET [2] (mm)	max. DLGP [3] (days)	occurrence past	occurrence present
Anseba	Adi-Tekelezan	MH	2400	507	1673	75	-	-
	Asmat	AL, AH	1800	299	1792	30	-	-
	Gheleb	MH	2000	507	1673	75	-	-
	Kerkebet	SD	849	140	1986	15	-	-
	Selea	AL	1100	300	1851	15	-	-
	Elabered	AL	2400	509	1778	75	+	+
	Habero	AH	1600	418	1754	45	+	+
	Hagaz	AL, MH	1145	428	1900	45	+	-
	Halhal	AL	2000	416	1752	45	+	+
	Keren	AL, AH	2000	489	1790	75	+	+
Gash -Barka	Forto	SD	800	100	1950	15	-	-
	Logo-Anseba	MH	2200	650	1673	95	-	-
	Mogoraib	SD	700	200	1930	15	-	-
	Tekloy	AL	700	303	1930	15	-	-
	Tesenay	AL	628	309	1950	15	-	-
	Barentu	ML	1127	516	1871	75	+	+
	Gonge	ML	850	600	1901	70	+	-
	Haykota	AL	850	600	1901	70	+	-
	Laelay-Gash	ML	1000	700	1901	70	+	+
	Mensura	ML	1200	425	1925	45	+	-
	Mogolo	AL	1000	475	1911	70	+	+
	Molki	ML	1600	600	1871	75	+	+
	Omhager	ML	900	625	1901	70	+	+
	Shambuco	ML	1000	600	1893	75	+	+
Debub	Adi-Keih	MH	2239	534	1673	75	-	-
	Debarwa	MH	2100	589	1685	95	-	-
	Decemhare	MH	2021	600	1669	75	-	-
	Mendefera	MH	1900	574	1693	100	-	-
	Segeneiti	MH	2221	831	1693	75	-	-
	Senafe	MH	3000	654	1637	75	-	-
	Tsorona	MH	1910	491	1693	75	-	-
	Adi-Quala	MH	2000	612	1792	95	+	+
	Areza	ML, MH	2000	655	1772	95	+	+
	Kudoabur	ML, MH	2100	700	1732	95	+	-
	Mai-Aini	ML, MH	1911	454	1757	75	+	-
	Mai-Mine	ML, MH	2000	694	1792	95	+	+
Centre	Berik	MH	2300	530	1653	80	-	-
	Gala-Nefhi	MH	2300	540	1633	75	-	-
	Seregeka	MH	2600	550	1695	75	-	-

(1) AEZ: agroecological zones, ML: moist lowland, MH: moist highland, AH: Arid highland, AL: arid lowland, SD: semi-desert

(2) PET: Potential evapotranspiration,

(3) DLGP: Dependable length of growing period.

3.3.2 Combined effects of altitude, rainfall and growing period

In Eritrea, *Boswellia papyrifera* occurs in areas that are located between 800 and 1850 m a.s.l. These areas show considerable variation in terms of rainfall and the length of growing period. This is illustrated in Table 3.3 and in Appendix 5 where altitude and climatic data and the occurrence of *Boswellia papyrifera* are given of all sub-regions and all villages covered by the survey. Detailed long term climatic data of natural Boswellia areas, e.g. those of Barentu and Keren, are given in Appendix 2.

The logistic regression analyses between the occurrence of *Boswellia papyrifera* as dependent variable and altitude, rainfall and the length of growing period as independent variables shows that the three factors combined have a significant influence on the occurrence of the species (with a Nagelkerke r^2 value of 0.66). Comparing these factors, altitude has greater influence on the occurrence of the species than both rainfall and the length of the growing period (Table 3.4). The table contains the coefficients and related statistics from the logistic regression model that predicts its occurrence across the entire study area.

Table 3.4 Parameter estimates for the logistic regression model used to relate the occurrence of *Boswellia papyrifera* to environmental factors. B: coefficients calculated from the data. Significance levels: ***, P <0.001 and *, P<0.05. R: the partial correlation between the dependent variable and each of the independent variables.

variables in equation	B	P-value	R
altitude (m a.s.l.)	-0.0046	0.000***	-0.34
rainfall (mm)	0.0076	0.013*	0.16
dependable length of growing period (days)	0.0420	0.042*	0.12
constant	0.1376	0.885	

Table 3.4 shows that the occurrence of *Boswellia papyrifera* decreases with altitude and increases with the mean annual rainfall and the dependable length of growing period. It is also clear that altitude is the most important factor, followed by rainfall and length of the growing period. Rainfall and length of growing period are positively related to rainfall, but the correlations are weak (R=0.46 and R=0.32, respectively),. Rainfall and the length of growing period are strongly linked to each other (R=0.83), as expected.

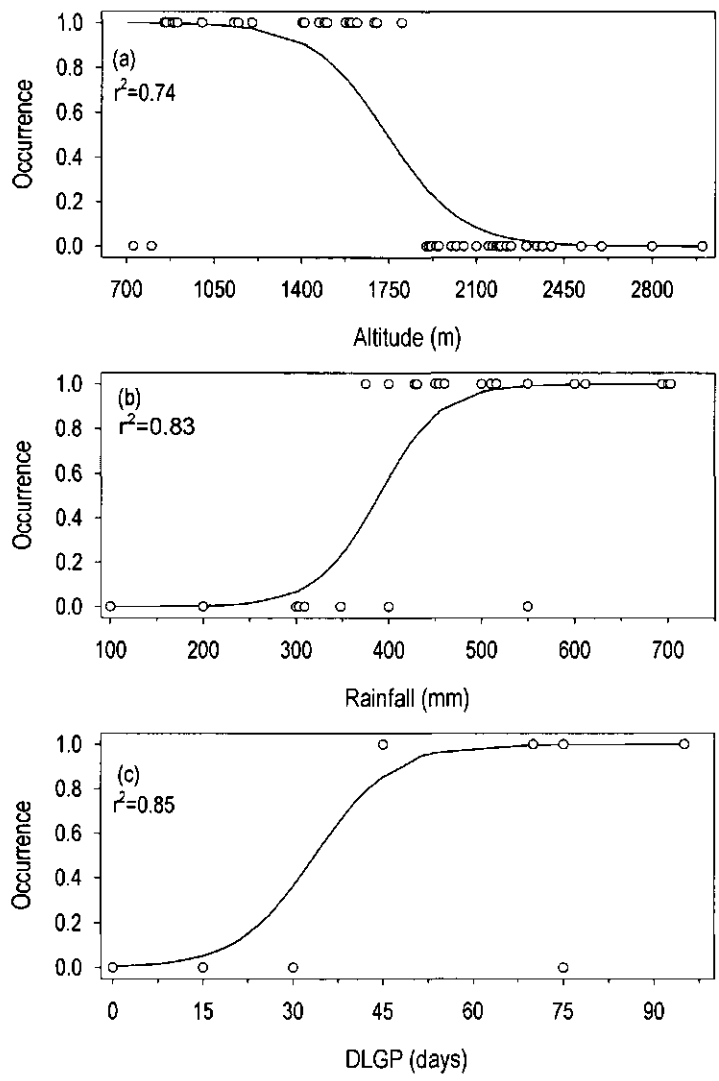

Figure 3.3 The probability of occurrence in relation to (a) altitude (b) rainfall and (c) Dependable length of Growing Period (DLGP) of *Boswellia papyrifera* in Eritrea. Each dot represents a village area. A probability of 1 indicates sites where the species is present and 0 where it is absent. The smooth lines are fitted using logistic regression. r^2 is a Nagelkerke coefficient of determination.

3.3.3 **Occurrence in relation to individual factors**

Altitude

Boswellia papyrifera in its habitat is exposed to the combined action of different environmental factors. Although the altitude covered by the study ranges between 600 and 3000 m a.s.l., Boswellia trees were found only in areas located between 800 and 1850 m. The probability of occurrence of the species decreases with altitude (Figure 3.3a).

Rainfall

Rainfall is an additional important factor affecting the distribution of the species. The amount of rainfall is not uniform throughout the country. Generally, its amount gradually increases from the north to the south and from the lowlands to the highland parts of the country. Within its altitude limits, the probability of finding the species in a given area increases with increase in rainfall (Figure 3.3b).

Throughout the survey, no *Boswellia papyrifera* stands or isolated trees were found in areas receiving an annual rainfall less than 375 mm. The probability of occurrence of the species increases from 0.1 at 300 mm to 1.0 at 550 mm. In the southwestern lowland where the most important Boswellia woodlands are found, the annual rainfall ranges between 500 and 700 mm. In the northwestern lowlands of Eritrea, the species is absent because of the low rainfall (less that 200 mm). Besides shortage of rainfall, these areas are also affected by high evapotranspiration (exceeding 2000 mm per annum) which also increases the soil moisture deficit. This shows that rainfall is an important ecological factor limiting the macro-distribution of *Boswellia papyrifera* in Eritrea.

Growing period

The probability of occurrence of *Boswellia papyrifera* increased with the length of growing period.(Figure 3.3c). The species does not occur in places with a dependable growing period of less than 45 days. Within its appropriate altitude ranges, the species grows in areas with a growing period of 45-100 days. The likelihood of the occurrence of the species increases from 0.1 at 30 days to 1.0 at 60. Areas with DLGP values between 45–100 days are found in the moist lowlands and the lower parts of the moist and arid highlands.

Following the rainfall pattern in the country, the length of growing period increases from north to south. Because of short growing season, the species is absent in northwestern semi-desert lowland and arid lowland agroecological zones.

Temperature

The probability of occurrence of the *Boswellia papyrifera* trees increased with, minimum, maximum and mean temperatures (Figure 3.4).

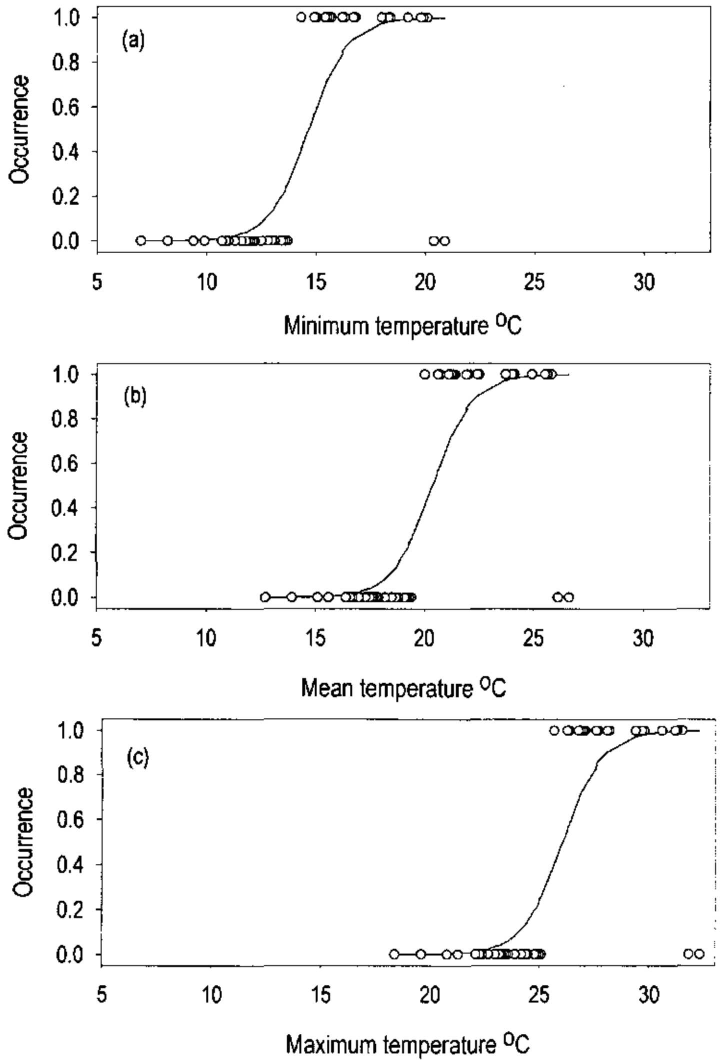

Figure 3.4 The probability of occurrence of *Boswellia papyrifera* in relation to the minimum (a), mean (b) and maximum (c) temperatures of the village areas as defined by altitude. Each dot represents a different village area. A probability of 1 indicates the species is present and 0 is absent.

In view of the fact that the temperature of a location is determined by altitude, it was possible to estimate the temperature ranges within which the species occurs (Appendix 4). The upper and lower altitude limits used to define the upper and lower temperature limits are 800 and 1850 m a.s.l. The temperature at the higher altitude limit is moderate throughout the year with minimum, maximum and mean temperatures of 14.0, 25.4 and 19.7°C, respectively. At the lower altitude limit the minimum, maximum and mean temperatures are 20.4, 31.8 and 26.1°C, respectively.

3.4 Discussion

In Eritrea, the probability of occurrence of *Boswellia papyrifera* is positively affected by rainfall, and length of growing period and negatively by altitude. Along the altitude gradient, there is a marked variation in the occurrences of *Boswellia papyrifera*. At higher altitude, its presence is limited by low temperature while at lower altitude it is restricted by the amount of rainfall. This study suggests that the "the ecological niche" of *Boswellia papyrifera* comprises mainly areas which are located at an altitude range of 800-1850 m receiving a mean annual rainfall of 375-700 mm distributed in such a way that the growing season lasts 45-100 days.

These conditions are found in south-western Eritrea in the Gash-Barka region and in parts of the Debub and Anseba regions. In terms of agroecological zones, this is mainly in the moist lowlands, moist highland and arid highlands, respectively. Suitable conditions for *Boswellia papyrifera* are also found in the sub-humid agroecological zone in the eastern part of the country (Northern Red Sea region). But there, the species has been found absent, apparently because it has not been able to cross the Central Highlands. With an altitude of over 1800 m, associated with mean annual minimum temperatures below 14°C and below 7°C in the coldest month, they form a temperature barrier preventing *Boswellia papyrifera* from spreading eastwards. Inadequate rainfall is the main reason that *Boswellia papyrifera* had not spread from the south-west to the north-west into the semi-desert and arid lowland agroecological zones.

The study indicates that the species needs a growing period of at least 45 days. The upper limit of 100 days reflects the maximum length of growing period in the areas where altitude favours the presence of *Boswellia papyrifera* but it does not mean that a longer length of growing period is not suitable. A prolonged growing season may, however, be unsuitable in view of the fact that *Boswellia papyrifera* requires a very marked and long dry season for flowering and fruit setting (see Chapter 7).

The occurrence of *Boswellia papyrifera* in the Centre Region as suggested by resource persons in the Ministry of Agriculture and in the tapping trade, has not been confirmed in our survey. This is due to the fact that, in the past, the administrative Centre Region was larger and it included parts of the lowlands, which now belong to the Gash-Barka and Anseba regions.

Looking at the distribution of *Boswellia papyrifera* in Africa as a whole, a more or less continuous vegetation belt of the species can be observed stretching from Nigeria eastwards till it reaches the temperature barrier of the highlands of Eritrea and Ethiopia. Northwards, this belt is delineated by low rainfall and southwards most likely by a prolonged rainy season which prevents *Boswellia papyrifera* from flowering and thus from reproduction.

The macro-distribution survey has clearly shown that the species has disappeared in many village areas lying in the transition between the moist lowland in the south and arid lowland further north. Farmers attribute this mainly to land clearing for crop production. Factors causing inadequate regeneration such as overgrazing and poor seed production may play a role as well. These are treated later in Chapters 6 and 7.

3.5 Conclusion

Altitude, amount of rainfall, and the length of growing period determine the macro-distribution of *Boswellia papyrifera*. It mainly occurs in the south-western lowlands (Gash-Barka region) and the south (Debub region) at an altitude range of 800-1850 m a.s.l. The absence of the species from the central highlands and the eastern lowlands with a comparable climate as found in the western lowlands, suggest that low temperature impedes its spread from the western lowlands eastwards across the highlands.

The species occurs in areas with mean annual rainfall range of 375-700 mm per annum distributed over a dependable growing period of 45-100 days. The absence of the species in the northern lowlands and in areas located at higher altitudes clearly suggest that a low rainfall and a short length growing period limit its spread into these areas.

Boswellia papyrifera has disappeared from some areas especially from the drier transition zone between the moist lowlands and arid lowlands. Also, it has declined in the heavily populated areas bordering with the highlands. Its disappearance is mainly due to land clearing for agriculture, grazing and also by intensive tapping of trees for gum as will be discussed later on (Chapter 7).

CHAPTER 4

4 The micro-distribution of *Boswellia papyrifera*

4.1 Introduction

The distribution of a species in an area is influenced by various environmental factors. These factors include climate (Krebs 1994), soil moisture and nutrient content (Veenendaal and Swaine 1996, Swaine 1996), historical events, disturbances, interaction with local fauna, competition with other plant species for space and human influence (Bongers et al. 1999). The fundamental niche of a species is the result of a combination of environmental conditions and resources, which allow the species to maintain a viable population (Begon et al. 1995). The realised niche is much more restricted because of biotic interactions and historic perturbations.

In Eritrea, detailed studies of individual tree species are scarce. Some reviews show that vegetation greatly varies with altitude and moisture regime and that the distribution of plants follows more or less the altitude gradient (Bein et al. 1996). How the abundance and distribution of individual plant species vary in relation to specific environmental factors is not yet well documented. Besides these environmental factors, human induced factors have also modified the composition and distribution of the local flora (Jones 1991). Especially the pressure on the scarce forest and woody vegetation resources has resulted in changes in distribution pattern and decline of abundance of several tree species (Jones 1991). The National Environment and Management Plan for Eritrea (NEMP-E) clearly stipulates that several useful tree species in the highlands and lowlands are listed as endangered and that *Boswellia papyrifera* is one of threatened plant species (NEMP-E 1995, Bein et al. 1996).

The result of the study on the macro-distribution of *Boswellia papyrifera* in Eritrea (Chapter 3) shows that the species occurs in the southwestern and southern parts of the country. Within these regions, it is found in areas at an altitude between 800 and 1850 m with a mean annual rainfall between 375 and 700 mm and a growing season ranging between 45 and 100 days in length. In areas where it occurs its distribution and abundance is not uniform across the entire area. It varies from isolated trees to sizeable stands following certain site conditions such as the topography and the local land use practices. To what extent the observed distribution pattern reflects its ecological preference for specific topographic features, soil properties, or human influence is not yet well understood.

This Chapter reports on a study on the micro-distribution of *Boswellia papyrifera* in five representative sites covering the Boswellia woodlands in the lowlands and the highlands. It includes quantification of land and soil factors and attempts to establish relationships between the distribution and abundance of the species and the environmental conditions. It investigates the actual distribution and abundance at local level and the possible reasons for the difference between the potential and the actual situation.

4.2 Material and methods

4.2.1 **Selection of study areas**

Based on the findings of the reconnaissance survey, on the macro-distribution of *Boswellia papyrifera* in Eritrea (Chapter 3), five study areas were selected. These are Adi-Ketina, Atawen, Ferhen, Molki, and Shilalo (see Figure 3.2b) . For their selection several aspects were taken into account: the occurrence of relatively intact *Boswellia papyrifera* stands in each area, the type of agroecological zone, the altitude range covered, the accessibility, and whether Boswellia exploitation for gum and grazing in the stands was allowed or not. Information on the location and altitude of these sites is given in Table 4.1.

Table 4.1 Background information on the five representative stands used to study the micro-distribution of *Boswellia papyrifera* in Eritrea.

study areas	agroecological zone	administrative region	sub-region	altitude range (m a.s.l.)
Adi-Ketina	moist highland	Debub	Mai-Mine	1600-2000
Atawen	moist highland	Debub	Adi-Quala	1600-1900
Ferhen	arid highland	Anseba	Elabered	1600-2000
Molki	moist lowland	Gash-Barka	Molki	1100-1600
Shilalo	moist lowland	Gash-Barka	Augaro	800-1100

4.2.2 **Placement of sample plots**

To become familiar with the local topography and the variation of the Boswellia population in each study area, an exploratory transect walk was undertaken. With this method, first the upper and lower altitude limit of each study area was determined. Then a hypothetical line was drawn perpendicular to the contour lines delineating the lowest and highest altitude limits where Boswellia stands were found. The whole altitude range covered in each area was then divided into narrower altitude intervals of 100 m. This was done to minimise horizontal climatic and edaphic variations within the altitude range (Mueller-Dombois and Ellenberg 1974, Van der Hammen et al. 1989). Within the defined altitude intervals, sample plots measuring 20 m x 20 m were randomly placed parallel to the contour lines. This resulted in total number of 144 sample plots in the five study areas. The sites, altitudinal range, and the total number of sample plots per altitude interval are shown in Table 4.2.

Table 4.2 The distribution of sample plots over the altitude intervals in the five study areas and the total number of plots per altitude range.

altitude (m a.s.l.)	location					total nr plots/ altitude range
	Shilalo	Molki	Adi-Ketina	Atawen	Ferhen	
800-900	9	- [(1)]	-	-	-	9
900-1000	8	-	-	-	-	8
1000-1100	7	-	-	-	-	7
1100-1200	5	7	-	-	-	12
1200-1300	-	8	-	-	-	8
1300-1400	-	8	-	-	-	8
1400-1500	-	8	-	-	-	8
1600-1700	-	-	8	8	9	25
1700-1800	-	-	10	8	8	26
1800-1900	-	-	8	8	9	25
1900-2000	-	-	8	-		8
total nr of sample plots	29	31	34	24	26	144

[(1)] – represents no sample plots available over the altitude interval

4.2.3 Description of sample plots

The altitude, topographic features, and land use characteristics of each sample plot were recorded. The altitude in m a.s.l., and the inclination of the terrain (slope in degrees) were determined using an altimeter and a Suunto clinometer, respectively. The exposure of each sample plot was described as North, South, East, West, Northeast, Southeast, Southwest and Northwest using a compass (Woldu et al. 1989, Bekele 1994).

The shape of the terrain of the sample plots was described as convex, concave, rolling or flat following the system proposed by Faniran and Areola (1978). The topographic positions of the sample plots on the transect were described as hill summit (6), upper slope (5), mid-slope (4), lower slope (3), terrace (2) and valley (1).

The intensity of land use was classified on a six point scale: agricultural land (1), fallow area (2) grazing area (3) non-grazing area (4), temporarily enclosed area (5), and permanently enclosed area (6). The difference between temporary enclosures and permanent enclosures is that temporary enclosures are open to grazing during the dry season while permanent enclosures are not accessible to livestock at all times. Since the occurrence of land use 5 appeared to be very rare, it was pooled with land use type 6 in the non-linear regression analysis (see section 4.2.6).

4.2.4 **Soil sampling and analysis**

In the centre and in each of the four corners of each sample plot, soil samples were collected from the upper 15-20 cm of the soil layer and combined in one composite sample per plot. The samples were stored in polythene bags and sent to Asmara, the capital city, for physical and chemical soil analyses. These analyses included soil texture, pH, organic matter, available phosphorus, and exchangeable bases (sodium, potassium, calcium and magnesium) and electric conductivity. The analytical methods employed are given in Appendix 6. In addition, core samples were taken from each plot for the determination of soil bulk density. These core samples were sealed and immediately brought to the laboratory for drying (105°C for 24 hours) and weighing. The day-time soil temperature in July was recorded at a depth of 10 cm using a soil thermometer. The soil depth above parent rock was measured with a soil auger. If rocks occurred below 120 cm, the value was set at 120 cm.

4.2.5 **Plant measurements and counts**

In each sample plot, all *Boswellia papyrifera* plants were counted and all plants were grouped into three major classes: trees (dbh [diameter at breast height] >8 cm), saplings (dbh 4-8 cm), seedlings and germinants (dbh <4 cm). The distinction between germinants and young seedlings is based on the presence or absence of cotyledons. After germination, germinants retain their cotyledons during the first growing season. They are shed at the end of rainy season and in the following year replaced by simple leaves. Accordingly, all juveniles with cotyledons were treated as germinants irrespective of their sizes.

4.2.6 **Data analysis**

The relationship between the abundance of *Boswellia papyrifera* and the environmental variables was analysed at (1) study area level and at (2) the level of all five sites combined. (1) In each study area the relation between the abundance of *Boswellia papyrifera* and various environmental factors (all factors are listed in Table 4.5) was analysed using Pearson's correlation coefficients. To evaluate the relative importance of the various factors a forward stepwise multiple linear regression analysis was performed. Because altitude appeared to be the overriding factor, a linear regression analysis was used to describe this relationship between abundance and altitude in more detail. To investigate for significant relationships between the abundance of the species and land use and topographic features an analysis of variance was carried out.

(2) All sites were combined to investigate the relationships between abundance and the environmental factors across the entire range of available conditions. By studying the occurrence of *Boswellia papyrifera* at a single site, only a smaller part of the gradient is considered, and the abundance of the species may simply increase or decrease with the environmental variable under consideration. By pooling all sites, a large part of the gradient is included and in that case, the species may show a bell-shaped species curve to the environment in which it attains its maximal abundance within the gradient considered. As there is no *a priori* a reason to assume that the response of Boswellia should have a certain shape, a set of five hierarchical response models ranked by their increasing complexity, can be used (Huisman et al. 1993, Bongers et al. 1999). These five models (I-V) are:

- I showing no significant trend,
- II increasing or decreasing trend (with a maximum equal to the upper limit of abundance),
- III increasing or decreasing trend (maximum below that upper abundance limit),
- IV symmetrical response curve (increasing and decreasing at same rate) and
- V skewed response curve (increase and decrease at different rate).

In these models it is assumed that the density of species is in equilibrium with the local climate without human influence (Huisman et al. 1993). To account for possible human interference on the abundance of the species and in order to include areas which were not sampled, the upper limit of the species abundance was set to 1.2 times the actual maximum plant density.

For the relation between abundance and altitude the best of these five models was selected following the methods described by Huisman et al. (1993). This was model V (see equation 4.1), a skewed response of abundance on altitude. In order to include other factors into this model first land use was included. To be able to do this dummy variables were created. For this analysis, the sample plots categorised as temporary (5) and permanent enclosure (6) were pooled together as single variable. The resulting new land use types were regrouped as agricultural (1), fallow (2), grazing (3), non-grazing (4), and enclosed area (5). These classes were transformed into dummy variables (Table 4.3). These variables were included into the model (equation 4.2).

Table 4.3 The dummy variables used to codify the five land use types encountered in the *Boswellia papyrifera* stands.

	dummy variables				
land use type	d_1	d_2	d_3	d_4	d_5
agricultural	1	0	0	0	0
fallow area	0	1	0	0	0
grazing area	0	0	1	0	0
non-grazing area	0	0	0	1	0
enclosed area	0	0	0	0	0

To be able to include other environmental factors into the model, the most important (significant) ones were selected using a forward stepwise multiple linear regression. Four factors were significant (organic matter, slope, silt content and pH). These were included into the new model in order of importance, resulting in equations 4.3–4.6, respectively.

The equations for model V:

a) altitude

$$Y = m\,1.2\left(\frac{1}{\left(1+e^{a+b*alt}\right)}\frac{1}{\left(1+e^{c+d*alt}\right)}\right) \quad \text{(Eq. 4.1)}$$

b) altitude and land use

$$Y = m\,1.2\left(\frac{1}{\left(1+e^{a+b*alt}\right)}\frac{1}{\left(1+e^{c+d*alt}\right)}\right) + ed_1 + fd_2 + gd_3 + hd_4 + i \quad \text{(Eq. 4.2)}$$

c) altitude, land use and organic matter

$$Y = m\,1.2\left(\frac{1}{\left(1+e^{a+b*alt}\right)}\frac{1}{\left(1+e^{c+d*alt}\right)}\right) + ed_1 + fd_2 + gd_3 + hd_4 + i + jOM \quad \text{(Eq. 4.3)}$$

d) altitude, land use, organic matter and slope

$$Y = m\,1.2\left(\frac{1}{\left(1+e^{a+b*alt}\right)}\frac{1}{\left(1+e^{c+d*alt}\right)}\right) + ed_1 + fd_2 + gd_3 + hd_4 + i + jOM + kSL \quad \text{(Eq. 4.4)}$$

e) altitude, land use, organic matter, slope and silt content

$$Y = m\,1.2\left(\frac{1}{\left(1+e^{a+b*alt}\right)}\frac{1}{\left(1+e^{c+d*alt}\right)}\right) + ed_1 + fd_2 + gd_3 + hd_4 + i + jOM + kSL + lSi \quad \text{(Eq. 4.5)}$$

f) altitude, land use, organic matter, slope, silt content and pH

$$Y = m\,1.2\left(\left(\frac{1}{1+e^{a+b*alt}}\right)\left(\frac{1}{1+e^{c+d*alt}}\right)\right) + ed_1 + fd_2 + gd_3 + hd_4 + i + jOM + kSL + lSi + mpH \quad \text{(Eq. 4.6)}$$

in which:

Y	:	the abundance of *Boswellia papyrifera* trees
alt	:	altitude;
m	:	a constant equal to the maximal number of trees attained in one of the plots;
a, b, c and d	:	coefficients to be estimated; b and d have opposite signs.
e, f, g, h, and i	:	coefficients for the dummy variables (agricultural (d_1), fallow area (d_2), grazing (d_3) non-grazing (d_4) and enclosed area (i) respectively)
j, k, l, m	:	coefficients for organic matter (OM), slope (SL), silt (Si) and pH.

4.3 Results

4.3.1 Topography and soil conditions

In general, the study areas are predominantly hilly and characterised by slopes with shallow soils with sandy clay loam to sandy loam texture (Table 4.4). The soil reaction is neutral to moderately alkaline (site averages between 7.4 and 7.8). The topsoils are low in organic matter except for some isolated sites at Shilalo. They are low in available phosphorus and moderately high to high in exchangeable cations. There are no indications of salinity (E.C values are low). The ranges in Table 4.4 show that within sites the variation is quite large. The land and soil data of individual plots used in correlation studies are presented below.

4.3.2 Abundance in relation to altitude

Depending on the study area covered, the number of *Boswellia papyrifera* plants increased or decreased with altitude (Figure 4.1). In Shilalo and Molki, the number of Boswellia plants per sample plot significantly increased with altitude. Both areas are situated in the moist lowland agroecological zone between 800 and 1600 m a.s.l. In the remaining three areas, which are found at higher altitudes (1570-2000 m a.s.l), its abundance decreased significantly with altitude (Figure 4.1). Maximum plant densities per plot vary between a 32 in Adi-Ketina and 9 in Ferhen. The maximum in Adi-Ketina, Atawen and Ferhen were found at their lower altitude limits of 1600 m a.s.l. Those in Molki and Shilalo were found at their highest altitude limits of 1500 and 1200 m a.s.l. respectively. Ferhen, an arid highland area, had only a very low abundance. When all sites were pooled a type V model, a skewed bell shaped model, described the data best. The explained variation by the model is rather low (r^2=0.43), however (see section 4.1).

Table 4.4 Mean values and ranges of selected land and soil characteristics in five chosen areas in Eritrea. For the number of plots per site see Table 4.2.

	study area					
	Adi-Ketina		Atawen		Ferhen	
environmental variables	mean	range	mean	range	mean	range
slope (°)	18	1-35	22	5-35	17	1-30
soil depth (cm)	41	10-120	47	20-100	43	20-120
soil temperature (°C)	29	24-35	29	25-32	27	24-31
bulk density (g cm^{-3})	1.3	1.2-1.6	1.4	1.1-1.7	1.5	1.2-1.7
sand (%)	64	38-83	58	28-90	83	58-93
silt (%)	25	9-38	34	9-52	14	3-41
clay (%)	11	5-25	8.5	1-50	3	1-8
pH	7.7	6.9-8.4	7.6	7.1-8.0	7.8	7.0-8.6
organic matter (%)	1.7	0.1-3.3	2.3	0.5-4.4	1.6	0.5-2.9
available P (ppm)	4.1	1.8-8.2	6.6	0.8-15.7	6	0.2-26.3
Na (m. e. per 100 g soil)	0.3	0.2-0.7	0.2	0.1-0.5	0.2	0.1-0.8
K (m. e. per 100 g soil)	0.3	0.1-1.2	0.6	0.1-2.6	0.2	0.1-1.5
Ca & Mg (m. e. per 100 g soil)	31	14-63	40	11-80	31	12-46
electrical conductivity (µS cm^{-2})	187	132-288	187	159-201	194	148-319

	study area			
	Molki		Shilalo	
environmental variables	mean	range	mean	range
slope (°)	18	1.0-31	20	1-36
soil depth (cm)	47	25-100	66	5-120
soil temperature (°C)	30	25-36	34	30-37
bulk density (g cm^{-3})	1.3	1.2-1.6	1.2	1.1-1.6
sand (%)	63	35-75	76	62-85
silt (%)	28	17-42	18	8-28
clay (%)	9	5-23	6.2	2-14
pH	7.4	6.7-8.3	7.7	6.9-9.8
organic matter (%)	2.4	0.4-6.0	3.6	1.7-6.0
available P (ppm)	7.7	1.6-16.2	9.1	4.0-27
Na (m. e. per 100 g soil)	0.3	0.1-1.9	0.3	0.2-0.9
K (m. e. per 100 g soil)	0.5	0.1-3.0	0.3	0.2-1.1
Ca & Mg (m. e. per 100 g soil)	36	8-66	46	22-88
electrical conductivity (µS cm^{-2})	186	166-198	208	100-348

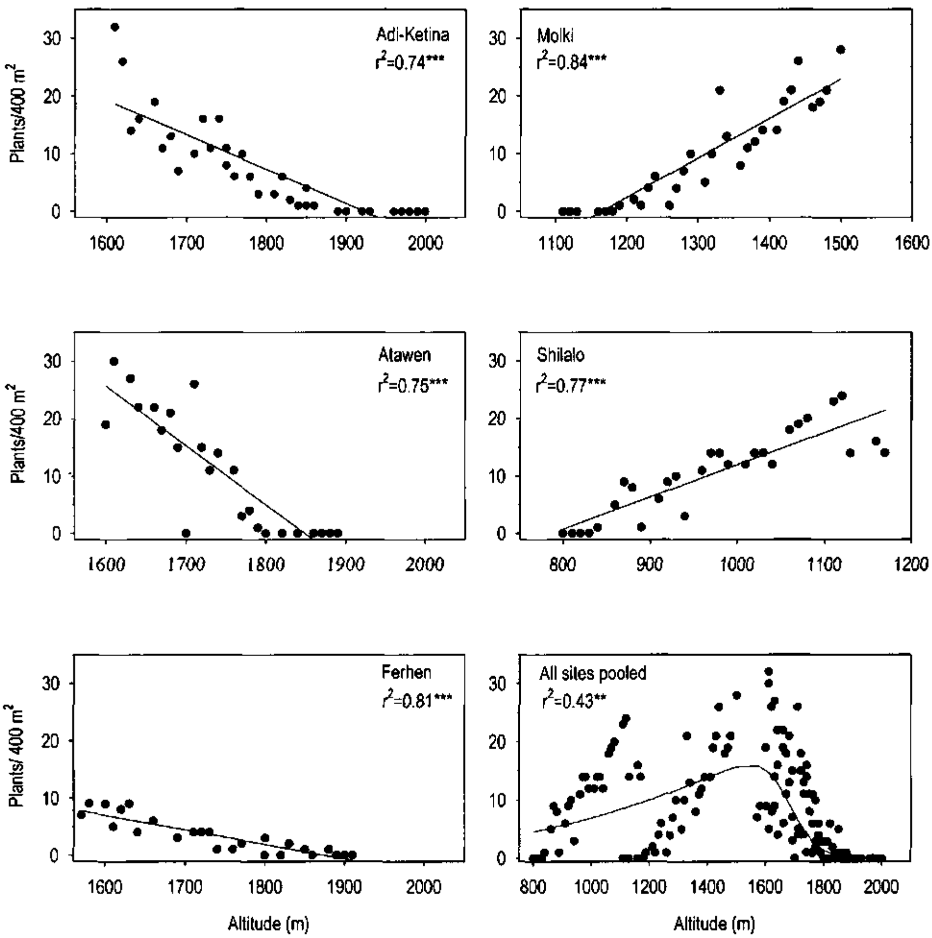

Figure 4.1 The total number of *Boswellia papyrifera* plants per 400 m^2 plotted against altitude in each study area (Adi-Ketina, Atawen, Ferhen, Molki and Shilalo) and in all five areas pooled. The linear regression line for each area and the non-linear one for all areas pooled and their coefficient of determination r^2 are given. Level of significance: ***$P<0.001$,**$P<0.01$.

4.3.3 Abundance in relation to land and soil characteristics

The abundance of *Boswellia papyrifera* is positively related to slope and soil organic matter content, and negatively to pH, in all five areas (Table 4.5). The correlation with altitude varies from positive at Molki and Shilalo, to negative in the three others sites. In some areas, other factors play a significant role. Soil depth is important at three sites. Na has a significant negative effect at two sites, and bulk density a negative and P, Ca and Mg a positive effect at one of the five sites only. When data from all sites were pooled, all factors have a significant effect, except soil temperature, clay content, available P, K and electrical conductivity.

Table 4.5 Pearson correlation coefficients between the total number of *Boswellia papyrifera* trees per 400 m^2 sample plot and selected environmental variables in Adi-Ketina, Atawen, Ferhen, Molki, and Shilalo areas in Eritrea. Significant levels: *P<0.05; **P< 0.01 (two tailed).

	study area					
environmental variable	Adi-Ketina	Atawen	Ferhen	Molki	Shilalo	all sites
altitude (m a.s.l.)	-.84**	-.86**	-.90**	.92**	.88**	-0.18*
slope (°)	.58**	.70**	.74**	.68**	.84**	0.67**
soil depth (cm)	-.20	-.56**	.03	-.36*	-.44*	-0.25**
soil temperature °C	-.07	-.25	.16	-.24	-.28	0.05
bulk density (g/cm^3)	.13	-.15	-.30	-.07	-.36*	-0.24**
sand (%)	-.23	-.38	-.05	.12	.18	-0.24**
silt (%)	.32	.62**	.09	-.03	-.10	0.33**
clay (%)	-.06	-.09	-.15	-.33	-.28	0.04
pH	-.61**	-.77**	-.44*	-.51**	-.60**	-0.53**
organic matter (%)	.65**	.66**	.74**	.82**	.62**	0.68**
available P (ppm)	-.03	.43*	-.26	.02	-.32	0.06
Na (m.e. per 100 g soil)	-.55**	-.35	-.17	.04	-.62**	-0.19*
K (m.e. per 100 g)	.15	-.22	-27	-.35	-.42	-0.11
Ca and Mg (m.e. per 100 g soil)	.11	-.05	.38	.54*	-.03	0.23**
electrical conductivity (μS cm^2)	.15	.19	-.10	.06	-.15	0.01

Since most of the environmental factors co-vary, it was necessary to determine the most important factors influencing its abundance, both for each of the sites separately and for the sites pooled (Table 4.6)

For all sites altitude is the most important factor affecting the abundance of Boswellia stands. At Adi-Ketina altitude was the sole factor, while at Atawen in addition to altitude significant effects were found for (in order of importance) pH, soil depth, bulk density and organic matter. In Ferhen, only slope played an additional significant role. At Molki P is the only additional factor, while at Shilalo pH and slope (in that order) are additional significant factors.

When the data of the five study areas were pooled, altitude was not significant anymore (as expected from Figure 4.1). The most important factor was organic matter, followed by slope, silt content and pH, respectively.

Table 4.6 Results of forward step-wise linear regression analysis of major land and soil factors.

Y= a+b_{1-8} x_{1-8};. Y: number of trees per plot, x_{1-8}: environmental variables: altitude, slope, soil depth, bulk density, silt, pH, organic matter (OM), and available phosphorus (P), respectively; a: intercept; b_1-b_8: regression coefficients for each of the variables x_{1-8}. Significant levels: ns P>0.05; * P<0.05; **, P<0.01; *** P<0.001. r^2 is the coefficient of determination and n: number of sample plots. For units of variables see Table 4.4.

study area	a	altitude (b_1)	slope (b_2)	soil depth (b_3)	bulk density (b_4)	silt (b_5)	pH (b_6)	OM (b_7)	P (b_8)	r^2
Adi-Ketina	114.1	-0.06***	ns	ns	ns	ns	ns	ns	ns	0.71
Atawen	253.1	-0.06***	ns	-0.05*	-11.8**	ns	-15.9***	1.3*	ns	0.95
Ferhen	37.5	-0.02***	.08*	ns	ns	ns	ns	ns	ns	0.84
Molki	-86.1	0.07***	ns	ns	ns	ns	ns	ns	0.4**	0.88
Shilalo	-9.2	0.04***	2.0*	ns	ns	ns	-2.4*	ns	ns	0.86
All sites	21.6	ns	0.3***	ns	ns	0.2***	-3.8***	2.6***	ns	0.70

4.3.4 The abundance of Boswellia across the whole altitude gradient

The positive correlation between the abundance of Boswellia trees and altitude at lower altitudes, and a negative one at higher altitudes clearly demonstrates that the *Boswellia papyrifera* abundance does not change uniformly along the entire altitude range. Based on these facts, the data from the five areas were pooled and further analysed using a non-linear regression model. The results show that the relationship between altitude and the abundance of Boswellia shows a peak in the areas located between 1500-1600 m a.s.l. (Figure 4.1). A line was fitted through the scatter points and this line is slightly skewed to the right with a coefficient of determination of 0.43. The model was improved by adding land use and additional environmental variables: organic matter, slope, silt content and pH. Except for pH all factors gave a significant increase in the r^2 value of the model (Table 4.7).

Table 4.7 A summary of results of the non-linear regression model between the abundance of Boswellia plants in five study areas pooled and the significant environmental variables. r^2 value is the coefficient of determination calculated based on equations. 4.1-4.6.

variables included in the model	r^2
altitude	0.43
altitude + land use	0.66
altitude + land use + organic matter	0.74
altitude + land use + organic matter + slope	0.76
altitude + land use + organic matter + slope +silt	0.80
altitude + land use + organic matter + slope +silt + pH	0.79

Table 4.7 shows that in order of importance the abundance of *Boswellia papyrifera* depends on altitude, land use type, organic matter, slope, and silt. The contribution of slope and silt is very low. The addition of pH did not improve the model.

4.3.5 The abundance of Boswellia in relation to land use and topography

Abundance in relation to land use types

Six-land use types were identified: agricultural land (1), fallow area (2), grazing area (3), non-grazing area, (4) temporary enclosure (5) and permanent enclosure (6). Only in Molki, all six lands use types were found (Figure 4.2).

In both Shilalo and Atawen, no temporary or permanent enclosures were present. Permanently enclosed areas were found only in Adi-Ketina and Ferhen. At all sites, the present land use practices have a profound effect on the abundance and distribution of *Boswellia papyrifera* (Figure 4.2). One way analysis of variance of all sites pooled showed significant differences among the six-land use types ($P<0.001$). The data of the individual sites and of all sites combined show that the abundance of the species decreases with the land use intensity. The tree abundance in inaccessible areas to livestock (4) as well as in enclosed sites (5 and 6) is greater than in the grazing area.

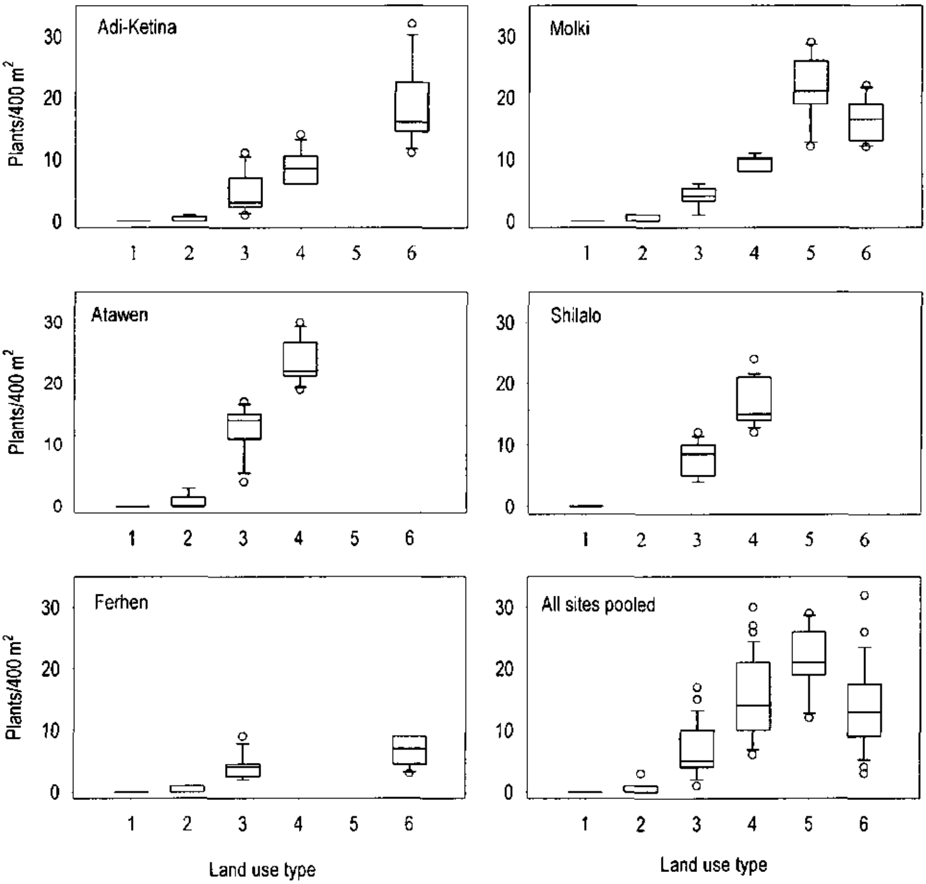

Figure 4.2 Box plots of abundance of *Boswellia papyrifera* under different land use types: agricultural land (1), fallow area (2), grazing area (3), non-grazing area (4), temporary enclosure (5) and permanent enclosure (6). The upper and lower borders of the box are the 75th and 25th percentiles, respectively. The black horizontal line within the box is the median and the error bars represent the 10th and 90th percentiles. The dots represent outliers.

4.3.6 **Abundance in relation to topographic position**

The present distribution and the population density of *Boswellia papyrifera* also show a marked difference between the topographic positions: valley (1) terrace (2), foot slope (3), middle slope (4), upper slope (5) and summit or ridge (6) (Figure 4.3). The abundance of the species increases from the valley to the summit or the ridge. A one way analysis of variance showed significant differences ($P<0.001$) among the six topographic positions. *Boswellia papyrifera* trees are found abundantly in steep areas mostly on the upper slope and the summit of hills and mountains. Isolated trees occasionally occur on the lower part of hills and on the terraces.

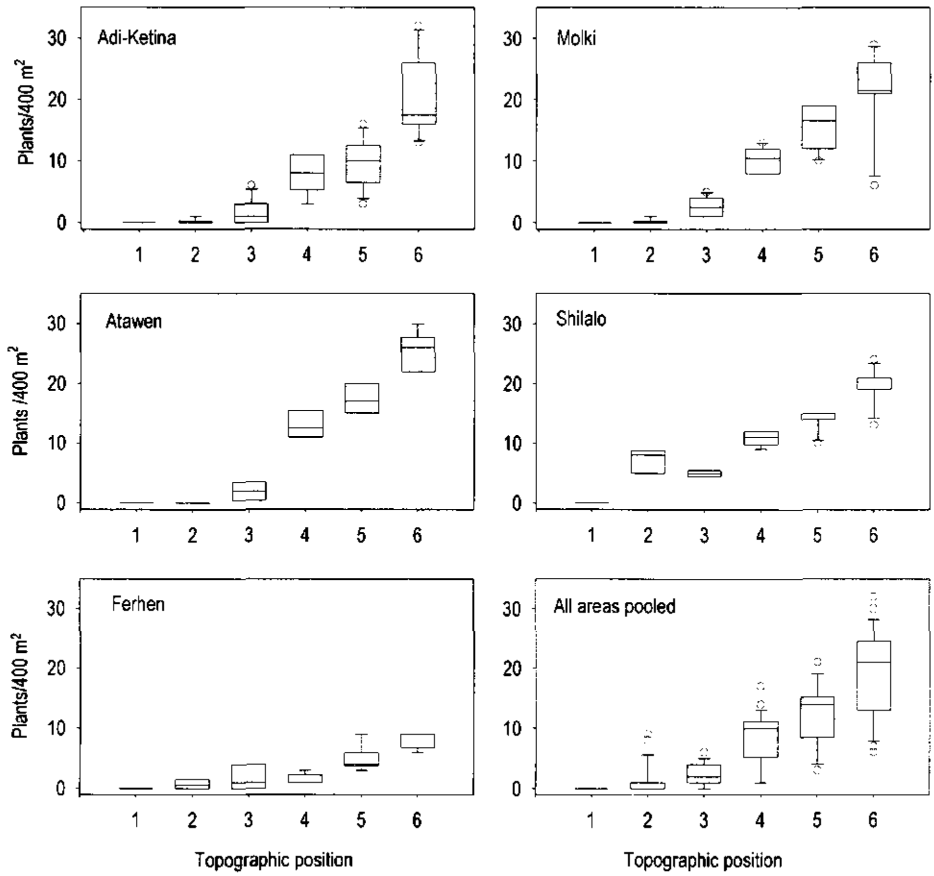

Figure 4.3 Box plots of the abundance of *Boswellia papyrifera* plants along the topographic position: valley (1), terrace (2), foot slope (3), middle slope (4), upper slope (5) and hill summit (6). The upper and lower borders of the box are the 75th and 25th percentiles, respectively. The black horizontal line within the box is the median and the error bars represent the 10th and 90th percentiles. The dots represent outiers.

4.3.7 Abundance in relation to aspect

Only at Atawen and Molki, the orientation of the slope (aspect) had an effect on the abundance of *Boswellia papyrifera*. In Atawen, more plants were found on the southeast and in Molki in the southwest facing slopes. When the data of all sites were pooled, no orientation effect was found (Table 4.8).

Table 4.8 Results of one way analysis of variance between abundance and aspect. F-values and levels of significance (P) are given. ns, P>0.05; *, P<0.05, **, P<0.01.

study area	F-value	P
Adi-Ketina	0.81	ns
Atawen	4.63	**
Ferhen	0.51	ns
Molki	3.16	*
Shilalo	0.65	ns
All sites pooled	1.60	ns

4.4 Discussion

The distribution and abundance of *Boswellia papyrifera* is affected by both environmental and human induced factors. The environmental factors are altitude, local climate (rainfall, temperature), land characteristics (slope and topographic position) and soil properties (texture, organic matter and pH). The human induced factors are land clearing and grazing. At macro level, in terms of occurrence, the most important factors are altitude, rainfall and length of growing period. (Chapter 3). At local level, in terms of occurrence and abundance, the order of importance is altitude, land use, organic matter, slope, silt content and pH. Although rainfall is probably also important at local level, it was not analysed due to lack of data.

The first important factor that affects the distribution and abundance of *Boswellia papyrifera* is altitude. In Chapter 3, it was reported that the occurrence of Boswellia trees decreased with increase in altitude. Furthermore, the species is entirely confined in western Eritrea between 800 and 1850 m a.s.l. to areas receiving between 400 and 700 mm of annual rainfall (Chapter 3). When abundance is taken into account the species shows an maximum between 1500-1600 m a.s.l. Obviously, there are additional factors that give rise to this pattern.

The second factor is land use. Most of the Boswellia stands were cleared from flat and gentle sloping land and replaced by agricultural fields. Absence even of isolated trees on cultivated land shows that it has been completely eradicated from such areas. While land clearing results in the elimination of the species, overgrazing by livestock leads to a decrease in the number of individuals per unit area. The higher number of plant density in non-grazing areas compared to heavily grazed areas demonstrates the negative impact of grazing on tree abundance. Livestock directly eats a whole plant or parts of it and indirectly it tramples seedlings, which results in soil compaction (Vetaas 1993, Breman and Kessler 1995, Teketay 1996, Barnes et al. 1998). In Eritrea, overgrazing is particularly severe at the beginning of the rainy season because this is the critical moment when seedlings and trees resprout after a long dry season of seven to nine months. Moreover, the concentration of livestock in small, especially flat areas results also in soil compaction that hinders recruitment and seedling establishment.

It was expected to find more Boswellia trees in the permanent enclosures as opposed to temporary ones. The reverse, however, was true. This can be explained by studying the time since establishment of these enclosures. The temporary enclosure is a traditional land use practice in which an area is protected from grazing during the rainy season and used under controlled grazing during the dry season. These sites thus existed in this condition for a long time already. The permanent enclosures on the other hand are installed recently by the government with the aim of promoting the natural regeneration of the local flora. Hence, the presence of greater number of trees under the temporary enclosures is probably due to differences in time that allow trees to grow without a strong grazing constraint.

Third, landform (slope and topographic position) affects the distribution and abundance. The largest population density of *Boswellia papyrifera* was found in areas with steep terrain on the upper slopes and ridges of hills and mountains. Two major reasons might account for this distribution pattern. First, there is a direct link between slope and the land use (intensive land use on flat and gently sloping areas). Secondly, the topographic characteristics also affect directly or indirectly the site conditions that in turn influence the development of the species (Faniran and Areola 1978, Barnes et al. 1998, Walsh 1996). On flat areas, the vertical movement of water is fast in sandy and very slow in heavy clay soils. While the former results in excessive drainage, the latter may result in water logging situations. In addition, flat areas, surrounded by highlands are natural sinks for the accumulation of cold air, which may restrict growth and development of plants (Walsh 1996, Barnes, 1998).

Fourth, the abundance of *Boswellia papyrifera* is significantly affected by the soil properties organic matter, silt content and pH (in this order of importance). The soils of the investigated areas generally are poor in organic matter. The abundance of Boswellia trees increases with slight increases in organic matter content. The soil organic matter influences the physical, chemical and biological properties of the soil, which has, direct or indirect consequences for plants (Shahar-Ben 1991, Archibold 1995, Brady 1990, Barnes et al. 1998). It may contribute in the soil aggregate formation, which in turn affects the soil moisture holding capacity of the soils. It stores plant nutrient mainly nitrogen and enhances nutrient recycling. These effects may greatly favour the recruitment, growth and development of *Boswellia papyrifera* which results in higher abundance of the species in areas having higher organic matter. In West Africa, Swaine (1996) also found that the distribution of forest plant species was affected by soil fertility.

The abundance of the species increased with silt and decreased with clay and with sand content. Soil texture affects the amount of surface area exposed by the soil and the amount and size of the pores, and thus the amount of surface area available for the adsorption of water and nutrients and the rate at which air and water flow in the soil (Brady 1990, Landon 1991). The increase in number of Boswellia plants in sites with higher silt content suggests that the species regenerates and grows better on soils with a loamy texture. This may be mainly because silty soils have a higher water holding capacity than sandy soils and provide better drainage conditions for plants than clayey soils (Barnes et al. 1998). In establishment trials on vertisols not far from Atawen, it was clearly shown that impeded drainage during the wet season resulted in the death of Boswellia seedlings (Ogbazghi unpublished data).

The pH of the soil where Boswellia stands are found, is mostly neutral, with slight variations. With a slight increase in soil pH, however, the abundance of the species decreased, probably because of impeded availability of the essential elements (Walsh 1996).

The negative effect of soil depth (although not always significant) is unexpected, because generally trees grow well on deep soils. The fact that *Boswellia papyrifera* trees are especially found on shallow soils reflects that these occur on rocky slopes not suitable for crop production and not accessible to livestock.

4.5 Conclusion

Within its altitude range (800-1850 m a.s.l.), the abundance of *Boswellia papyrifera* peaks in areas between 1500 and 1600 m. As to soil properties, the abundance of Boswellia was positively related with organic matter content and negatively with soil pH.

The abundance of the species decreased with land use intensity. The highest abundance was found in sites not suitable for agricultural production and inaccessible to livestock, e.g. on rocky slopes and enclosed areas. As land use and slope position are closely linked, no distinction between their effects could be made. When the data of five study areas were pooled the most important variables affecting the abundance of *Boswellia papyrifera* were altitude and land use. Apart from these also organic matter, slope, silt and pH had an effect. Because of the large effect of land use, the actual distribution is much smaller than was expected based on environmental factors only.

CHAPTER 5

5 Tree development and morphology of *Boswellia papyrifera*

5.1 Introduction

In Eritrea, the distribution of *Boswellia papyrifera* at macro-level is determined by altitude and climate (Chapter 3). Its occurrence decreases with altitude and increases with the amount and the duration of rainfall. At local level, however, the distribution and abundance of the species is mainly influenced by factors such as altitude, the intensity of land use, the texture of the soil and organic matter content and pH (Chapter 4). The abundance of exploitable Boswellia trees has decreased mainly owing to land clearing for agriculture, overgrazing, and the extraction of gum (see Chapter 7). Because of these human factors, the remaining Boswellia trees are found frequently on steep terrain unsuitable for agricultural use. The decline in annual gum export from more than 2000 tons in 1974 to about 400 in 1998 (Asmara Chamber of Commerce 1974, Ministry of Agriculture 1999) is an evidence for the decrease in abundance of trees in Eritrea

To sustain and possibly increase, the existing gum exploitation levels, there is a need for maintaining the existing Boswellia stands. Moreover, it is important to explore additional locations for expanding its population. In order to achieve these goals, it is essential to understand how the various environmental factors and the current land use practices affect Boswellia tree development and morphology. The study presented below intends to provide this understanding. It describes tree growth and development in terms of diameter, height and crown size and the effects of environment and land use on these characteristics.

5.2 Methodology

5.2.1 The study areas

The study was conducted in the following five areas in Eritrea: Adi-Ketina, Atawen, Ferhen, Molki, and Shilalo. These represent the altitude ranges and the various agroecological zones of the major *Boswellia papyrifera* stands in the country (Chapter 4, Table 4.1). In each area, study plots of 20 m x 20 m were selected at 100 m altitude intervals. At each interval, several plots were used (see Chapter 4 for details on choice and number of plots).

5.2.2 Plant size measurements

In each plot, all *Boswellia papyrifera* plants were measured. Plants were divided into two groups based on the diameter of their stem. Of the plants with a dbh ≥4cm (i.e. saplings and trees), height (H), crown depth (CD) and crown diameter (CW), and dbh were measured. The dbh and height were measured respectively using a diameter tape and a telescopic pole (Philip 1994, Martin 1995). The crown depth was calculated as total tree height minus the distance between the ground and the point at which a tree produces its major branches. The mean crown diameter was measured as the average measurement of the longest and shortest crown diameter with both axes passing across the bole. For plants with dbh<4 cm (seedlings) collar diameter and height were measured using callipers and a measuring stick, respectively. From each sample plot, composite soil samples were collected for physical and chemical analyses. The description of the topographic and soil properties is given in Chapter 4.

5.2.3 Data analysis

Box plots were used to illustrate the variation in morphological characteristics (dbh, height, crown depth, and crown diameter) of Boswellia plants in the five study areas and in relation to land use types encountered. The changes in tree height, crown depth, and crown diameter with increasing dbh were described using the following non-linear asymptotic regression model (Thomas 1996).

$$Y = X_{max}\left(1 - e^{\left(-\alpha D^{\beta}\right)}\right) \qquad \text{Eq. 5.1}$$

in which:

Y	:	plant height (H), crown depth (CD) and crown diameter (CW) in m
e	:	the exponential function
D	:	dbh (cm)
X_{max}	:	asymptotic maximal for H, CD, and CW in m
α and β	:	constants used to describe static allometry.

In the regression analysis diameter was taken as an independent and height, crown depth, and crown diameter as dependent variables. This model was suitable for this type of analysis because of the following reasons. First, it uses static data from an uneven aged tree population and provides an estimate of the maximum value for a given tree morphological trait. Second, trees show an asymptotic growth relationship with increasing diameter. Finally, it assumes no differences among the cohorts in allometry (Thomas 1996).

In order to understand how the various morphological characteristics of Boswellia trees are related among themselves, Pearson correlation coefficients were calculated. In addition, the tree characteristics were correlated with selected soil properties and the slope. Linear regression analysis was used to describe how the various morphological characteristics of the species vary with altitude. In this case, from each study plot, a single tree having the maximum diameter, height, crown depth and diameter was selected.

A total of five land use types, representing all the study plots, was found. These were coded as follows: agricultural field (1), fallow field (2), grazing area (3), none-grazing area (4) and enclosures (5). A higher code indicates a lower land use intensity level. Since trees were not found in the agricultural areas, these could not be included in the analysis. Spearman rank correlation coefficients were used to investigate the correlation between plant morphological traits (height, dbh, crown depth and crown diameter) and land use intensity (the five land use types).

5.3 Results

5.3.1 **Tree size variation**

The range in tree diameter, tree height, crown depth and crown diameter of Boswellia trees was different among the five study areas (Figure 5.1). The maximum tree diameter of all plants pooled per site, ranged between 36 cm in Adi-Ketina and 46 cm in Atawen and the maximum tree height ranged between 6.5 m in Ferhen and 12.5 m in Shilalo. At lower altitude (e.g. at Shilalo and Molki) taller trees with deeper crowns were found than at the higher altitude sites (e.g. Adi-Ketina, Atawen and Ferhen). While trees with the smallest maximum crown depth were found in Adi-Ketina, those with the largest were found in Shilalo. The largest maximum crown diameter was found in Atawen and the smallest one in Adi-Ketina (Table 5.1).

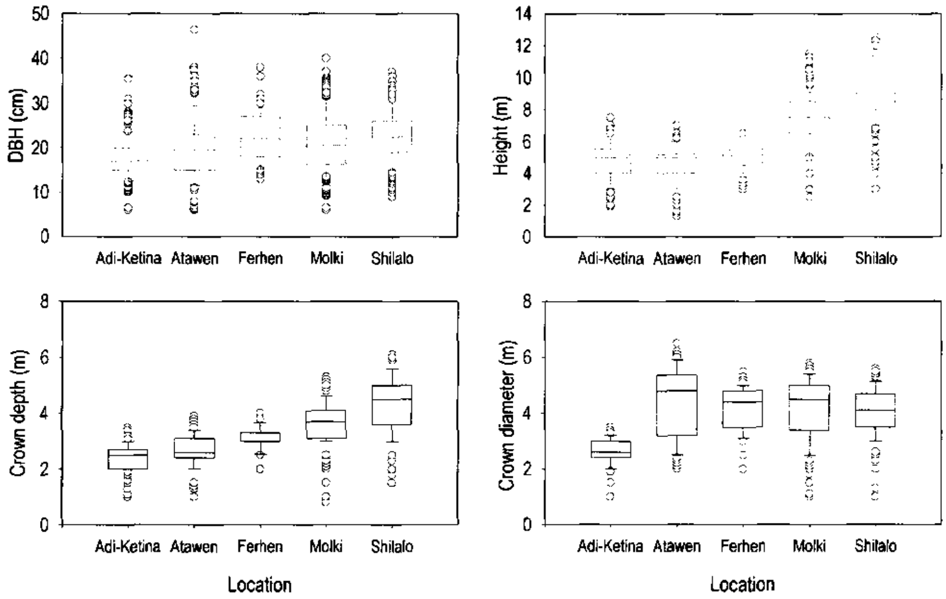

Figure 5.1 Box plots of dbh, tree height, crown depth and crown diameter of trees and saplings (≥4 cm dbh) of *Boswellia papyrifera* plants in five locations of Eritrea. The upper and lower borders of the box are the 75th and 25th percentiles, respectively. The black horizontal line in the box is the median and error bars represent the 10th and 90th percentiles. The circles represent outliers.

5.3.2 Tree development

The non-linear regression models describe the relationship between diameter and height, crown diameter and crown depth well with a coefficients of determination between 0.5 and 0.9 (Table 5.1). In general, the tree height is better predicted by the model than both crown depth and crown diameter. For all three variables, the model is better within a site than across all sites. The table shows that the asymptotic maximum height of Boswellia trees varies among the different study areas. In terms of tree height, the five areas can broadly be categorised into two groups. The tallest trees were found in Molki and Shilalo in the lowlands and the shorter trees in Adi-Ketina, Atawen and Ferhen in the highlands. Pooling of all trees together shows that the overall asymptotic maximum height of the species in Eritrea is about 10 m. The changes in tree height in relation to dbh are described in Figure 5.2a.

Table 5.1 The results of the non-linear regression models (equation 5.1) used to describe the relationship between dbh and height, crown depth and diameter of *Boswellia papyrifera* at five sites and when all sites are pooled. The asymptotic max. size (with s.e.) of a morphological characteristic is given . n: total number of plants used. α and β are model coefficients; r^2 is the coefficient of determination.

morphological characteristics	location	asymptotic max. size	s.e	α	β	r^2	n
height (m)	Adi-Ketina	6.6	0.6	0.02	1.4	0.90	253
	Atawen	6.2	0.5	0.20	0.7	0.88	259
	Ferhen	6.1	0.4	0.02	1.5	0.88	83
	Molki	11.1	1.2	0.06	1.0	0.78	296
	Shilalo	12.0	0.9	0.04	1.1	0.79	303
	all sites	10.1	0.7	0.02	1.2	0.72	1194
crown depth (m)	Adi-Ketina	4.3	1.2	0.07	0.9	0.57	183
	Atawen	5.1	1.1	0.07	0.8	0.79	171
	Ferhen	5.3	3.8	0.10	0.7	0.59	79
	Molki	6.6	1.3	0.06	0.9	0.71	284
	Shilalo	5.9	0.4	0.01	1.5	0.66	293
	all sites	5.7	0.5	0.02	1.2	0.53	1010
crown diameter (m)	Adi-Ketina	3.9	0.4	0.05	1.1	0.69	183
	Atawen	6.2	0.2	0.01	1.6	0.78	171
	Ferhen	5.2	0.2	0.01	1.8	0.78	79
	Molki	5.4	0.1	0.002	2.1	0.77	284
	Shilalo	5.2	0.2	0.01	1.6	0.63	293
	all sites	5.6	0.2	0.01	1.6	0.61	1010

The crown size of Boswellia trees also varies among the five locations. The asymptotic maximum crown depth of the species ranges between 4.3 m in Adi-Ketina and 6.6 m in Molki. The crown depth follows a similar trend as that of height. The deepest crowns are found in locations with tallest trees, e.g. in Molki and Shilalo. When all trees from all five areas were pooled, the crown depth reaches a maximum size of 5.7 m.

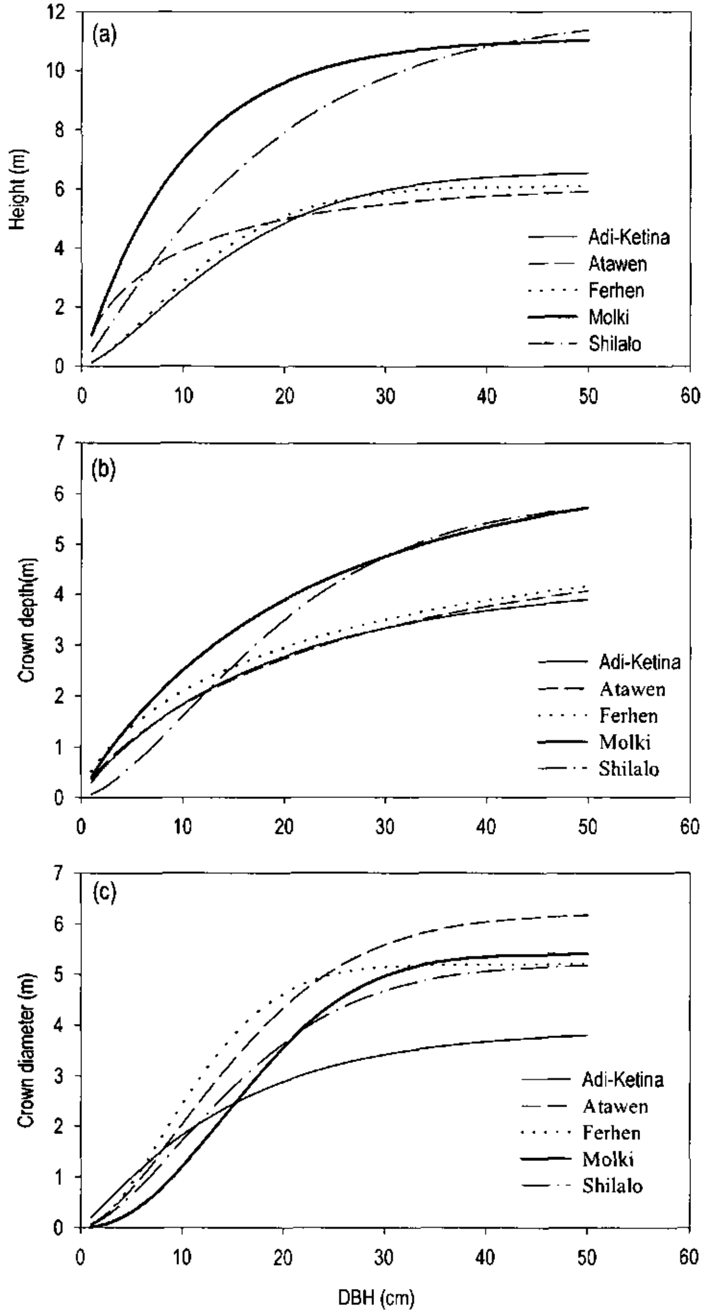

Figure 5.2 The changes in height (a), crown depth (b) and crown diameter (c) (m) in relation to dbh (cm) increment of *Boswellia papyrifera* trees in five areas of Eritrea.

The results of crown diameter measurements are not consistent with those found in the case of tree height and crown depth. Trees with the narrowest crowns were found in the stand of Adi-Ketina and the widest ones in Atawen (6.2 m), both of which are situated within a similar altitude and agroecological zone (Figure 5.3.c). In the remaining three areas (Ferhen, Molki and Shilalo), the crown diameter lies within this range. It is, therefore, difficult to classify the study areas in terms of this specific morphological trait. The crown diameter of Boswellia is much more variable than both height and crown depth.

The changes in height, crown depth and crown diameter with increase in diameter are different at the five sites. At the lowland sites, Molki and Shilalo, height growth is much faster per unit of diameter and reaches a higher values than at the other sites. At a dbh of 10 cm, for example, tree height at Molki and Shilalo and at Adi-Ketina, Atawen and Ferhen are 7.0, 4.7, and 2.6, 3.9 and 2.9, respectively. Crown depth follows a similar pattern except that it has a slow start at Shilalo. At most sites, crown diameter growth starts to take off after the diameter has reached a value of about 5 cm (Figure 5c).

5.3.3 **Tree size in relation to land and soil properties**

All four morphological characteristics (dbh, height, crown depth and crown diameter) of all *Boswellia papyrifera* plants in the five study areas lumped are positively correlated among themselves. Tree diameter and crown diameter are positively correlated. The best correlation is between tree height and crown depth, while the weakest is between tree height and crown width (Table 5.2).

All four maximum tree measurements were negatively correlated with altitude and positively with the organic matter (diameter not significantly) and the exchangeable Ca and Mg content. This means that the size of Boswellia trees decreases with altitude and increases with organic matter and exchangeable Ca and Mg. In addition tree height and crown depth are positively related to soil depth and soil temperatures and negatively with bulk density. Crown depth is also influenced by sand and silt content. The tree height and crown diameter are positively correlated with available phosphorous.

The Pearson correlation coefficients (Table 5.2) show that altitude affects most tree height and crown depth. Further linear regression analyses of the relationship between maximum plant size and altitude show that especially tree height and crown depth sharply decrease with altitude (Figure 5.3 b, c) and that dbh and crown diameters are far less affected by altitude (Figure 5.3 a,d).

Table 5.2 Pearson coefficients of correlation between maximum Boswellia tree measurement per plot and the environmental variables and among these measurements themselves. The analysis is based on data of all *Boswellia papyrifera* plants in the five study areas pooled together. The significance levels:* P< 0.05, ** P<0.01.

environmental variable	stem diameter	height	crown depth	crown diameter
altitude (m a.s.l.)	-0.27**	-0.85**	-0.87**	-0.35**
slope (°)	0.13	0.09	0.09	0.17
soil depth (cm)	0.12	0.25**	0.31**	0.08
soil temperature(°C)	0.15	0.69**	0.65**	0.16
bulk density (g/cm^3)	-0.08	-0.42**	-0.41**	-0.11
sand (%)	-0.05	0.17	0.29**	-0.03
silt (%)	0.11	-0.17	-0.25**	0.16
clay (%)	-0.18	-0.11	-0.25**	-0.36**
pH	-0.06	-0.13	-0.18	-0.10
organic matter (%)	0.16	0.52**	0.49**	0.26**
P (ppm)	0.11	0.20*	0.23	0.28**
Na (m.e. per 100 g soil)	-0.17	0.00	-0.06	-0.15
K (m.e. per 100 g soil)	0.27**	-0.01	0.01	0.21*
Ca & Mg (m.e. per 100 g soil)	0.33**	0.32**	0.34**	0.34**
EC (μS/cm^2)	0.04	0.11	0.16	-0.01
height (m)	0.44**			
crown depth (m)	0.52**	0.92**		
crown diameter (m)	0.65**	0.43**	0.54**	

5.3.4 Tree size in relation to land use types

No clear trend was found on the effects of land use on the size of Boswellia plants, except that the few trees found in fallow areas were larger than those found in the other land use types (Figure 5.4). Also when the maximum values of the growth characteristics are considered, no clear effects of land use can be observed. Both in Figure 5.4 and Table 5.3 agricultural land use type has been omitted because of absence of Boswellia on crop land.

The relationship between plant size and land use types was analysed at two levels i.e. all plants lumped in a given plot and taking plants with the maximum size per plot. The land use types were ranked from the lowest (fallow) to the highest (enclosures). When all Boswellia plants were lumped, Spearman rank correlation between land use types and plant size were significantly negative correlated for dbh and crown diameter only (data not shown). When the maximum plant measurements were used no correlation was found.

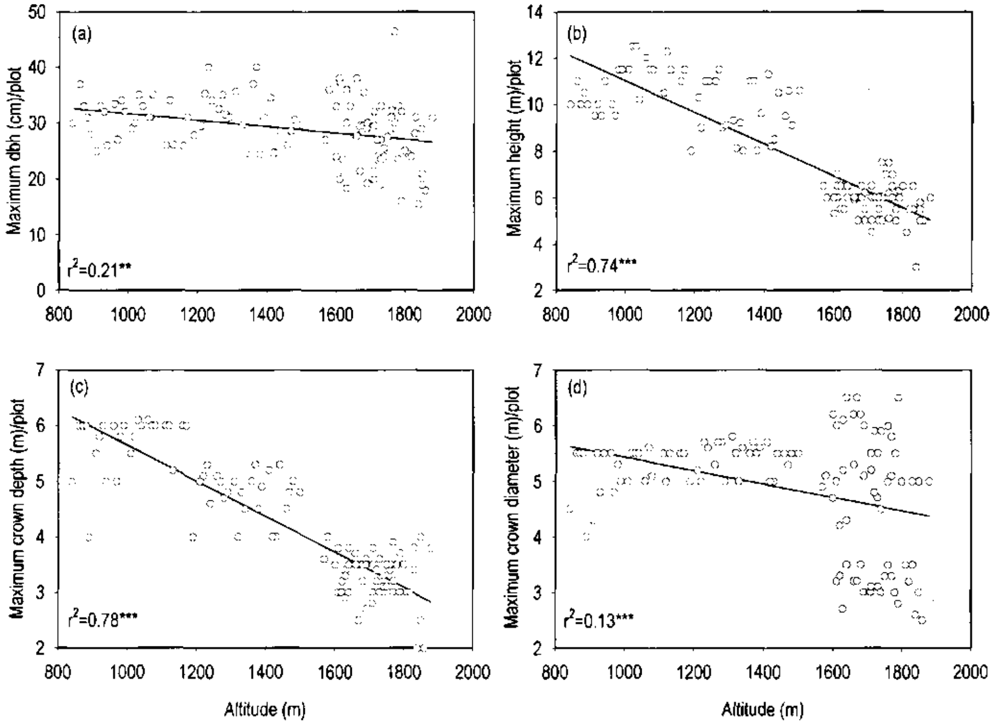

Figure 5.3 The relationship between altitude and maximum dbh (a), height (b), crown depth (c), and crown diameter (d) of *Boswellia papyrifera* trees (n=110). Level of significance: ***: P<0.001 and **P<0.01. The r^2 is the coefficient of determination.

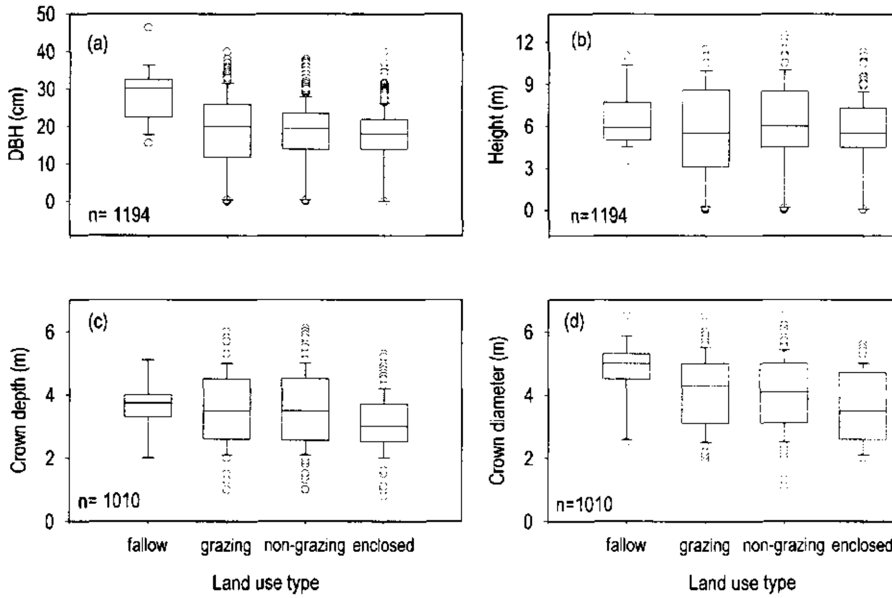

Figure 5.4 Box plots of dbh, tree height, crown depth and crown diameter of all *Boswellia papyrifera* plants pooled in four land use types in Eritrea. The upper and lower borders of the box are the 75th and 25th percentiles respectively. The black horizontal line in the box is the median and error bars represent the 10th and 90th percentiles. The circles represent outliers.

5.4 Discussion

The increase in height, and the vertical expansion of the crown and side-ways of *Boswellia papyrifera* in all five areas follows a similar pattern. There is more or less a rapid increase in plant height, crown depth and diameter at lower dbh. At a later stage of the tree development, height growth and crown extension gradually decreases with increasing diameter. This situation is widely reported among many tree species (e.g. Niklas 1994, Thomas 1996, King 1996, Sterck and Bongers 1998). It means that at earlier stages of development of *Boswellia papyrifera,* trees invest more of their biomass in height growth and in crown spread. At later stage, there is a shift towards the expansion of the stem diameter.

The present study shows that the morphological characteristics of *Boswellia papyrifera* differ among the five sites studied. When trees grow from seedlings to an adult tree, they undergo several changes in their morphology. These developmental changes largely reflect the inherent properties of the concerned species but are also influenced by the environmental conditions under which they grow (Hallé et al. 1978, Bongers and Sterck 1998, Bullock

Table 5.3 Maximum tree dbh, height, crown depth and crown diameter of Boswellia plants found under four land use types in the five study areas in Eritrea.

		location				
morphological characteristics	land use type	Adi-Ketina	Atawen	Ferhen	Molki	Shilalo
dbh (cm)	fallow	18.0	46.4	31.0	35.3	-[1]
	grazing	28.1	33.0	38.0	40.0	37
	non-grazing	31.0	38.0	-	37.0	35
	enclosure	35.5	-	30.0	40.0	-
height (m)	fallow	5.0	7.0	6.0	11.0	-
	grazing	7.0	6.2	6.5	11.5	11.5
	non-grazing	7.5	6.5	-	11.0	12.5
	enclosures	7.5	-	6.5	11.3	-
crown diameter (m)	fallow	2.0	3.9	4.0	5.1	-
	grazing	3.4	3.6	4.0	5.3	6
	non-grazing	3.5	3.8	-	5.0	6.1
	enclosure	3.5	-	3.7	5.3	-
crown depth (m)	fallow	2.6	6.5	5.0	5.3	-
	grazing area	3.5	6.5	5.5	5.8	5.5
	non-grazing	3.5	6.5	-	5.7	5.6
	enclosure	3.5	-	5.3	5.7	-

[1] the land use was not represented by any of the sample plots

2000). The distinction between these two factors is difficult however (Coleman et al. 1994). The occurrence of larger trees in Molki and Shilalo and shorter ones in the remaining areas is mainly attributed to site conditions. This phenomena has also been observed by others (Horn 1971, Barthélémy et al. 1995, 1997; Bongers and Popma 1988, Clark and Clark 1992).

Climatically, Adi-Ketina, Atawen and Ferhen are in the highlands with cooler temperature whereas Molki and Shilalo are located in the warm lowlands. The decrease in stem diameter, height, crown depth and crown diameter with altitude clearly shows the influence of altitude on all four morphological characteristics of *Boswellia papyrifera*. The positive correlation between soil temperature and Boswellia tree size suggest that the species grows better in the lowlands with warmer temperatures than in cooler highland (Table 5.2). This trend is widespread in most of the mountain vegetation of Africa where the vegetation stature diminishes from the lower slope to the summit. This general trend is however modified by local site conditions such as aspect of the soil and the over all pattern of the local climate (White 1983, Crawford 1990). At higher altitude and at exposed sites, wind may play a significant role in shaping the height of trees and crown characteristics (Barthélémy et al. 1995, 1997; Sterck and Bongers 1998).

It was thought that the length of the growing period (LGP) would be another important factor determining the tree size of *Boswellia papyrifera*. But when comparing the highland data of Ferhen with an LGP of 45 days and those of Adi-Ketina and Atawen both with a LGP of 95 days, this is apparently not the case (Table 5.1). As expected (minor) positive effects on growth were found of soil fertility parameters e.g. organic matter, exchangeable Ca and Mg contents and soil depth (Table 5.2).

That land use, especially grazing, has no clear effect on tree size, is most likely due to the fact that almost all measured trees were already above grazing height, a stage which the heavily browsed ones have never reached. The presence of few large isolated trees or left over in fallow fields probably reflects absence of competition from other trees (Weiner and Thomas 1992).

The role of tree management could not be investigated in this study. Harvesting of leaves and branches for fodder and fuel and especially tapping are certainly key factors determining tree size. In analogy with the well documented evidence that latex tapping in rubber (*Hevea brasiliensis*) is at the expense of vegetative growth (Simmonds 1989, Premakumari et al. 1997), similar effects in *Boswellia papyrifera* can be expected. Because of unknown and variable management practices in the past this cannot be studied on existing tapped and non-tapped trees. For this research, long term trials with uniform Boswellia trees, from the tappable age onwards subject to different tapping regimes, are needed.

5.5 Conclusion

The morphological characteristics of *Boswellia papyrifera* trees vary considerably between the lowlands and highlands. The distinction in tree size between the lowland and the highland is clear. In highlands, trees are short and in the lowlands tall trees with deep crowns are found. Apparently, the main factor affecting the size of Boswellia trees in Eritrea is altitude, e.g. temperature. There are indications that tree size increases with organic matter and exchangeable Ca and Mg and soil depth.

No clear effects of land use could be established. It is thought that land use, especially grazing, plays an important role during the establishment phase only, but not later on when trees are above grazing and browsing height. The effect of management practices, e.g. harvesting of leaves and branches and tapping could not be established in this study. It is likely that tapping is on the expense of vegetative growth. Experiments with uniform trees, and from tappable age onwards subject to different tapping regimes, are needed to investigate this hypothesis.

CHAPTER 6

6 Population structure of Boswellia stands

6.1 Introduction

The most important factors determining the occurrence of *Boswellia papyrifera* stands are altitude (temperature regimes), the amount of rainfall, and the length of growing period. Altitude sets the upper and lower distribution limits of the species at macro-level. Within its climatological distribution range, however, its abundance is largely influenced by land use practices at local level, topography and soil properties especially soil texture, organic matter content and pH (see Chapter 4). In areas where the species occurs, the physiognomy of its stands is heterogeneous and there are clear signs of widespread decline in its distribution and abundance as well as lack of regeneration in most places. This decline is related to various human induced factors, directly or indirectly. The most important factors are land clearing, grazing, and possibly tapping.

There is a widespread degradation of the Boswellia stands in Eritrea. In most stands, regeneration is lacking but this has not been quantitatively documented and it's causes is not yet fully understood. The historical records of frankincense production in the country show that there has been a gradual decline in the annual frankincense production for export presumably because of the decline in the abundance of gum yielding Boswellia trees. These observations need further investigation through a regeneration diagnostic study involving a systematic collection of data on population structure of the species in different areas of the country. The description and analysis of population structure is a widely used method to determine the regeneration of tree species. The population structure reflects its current size class distribution and its long-term population dynamics as well. This approach of regeneration study provides a clear picture about the current regeneration status of the species and it is a foundation for further species conservation and management (Richards 1996, Peters 1996).

After describing the population structure of Boswellia stands in areas covering different ecological settings, it is equally important to identify the main factors affecting its regeneration. The regeneration constraints may not be the same across the various stands of *Boswellia papyrifera* and these factors need to be studied in relation to local site conditions. In order to enhance the natural regeneration of the species in the future, these regeneration constraints should be identified so as to relieve the species from these factors in the different locations.

The main objectives of the present study are:

- to analyse the population structure of representative stands in Eritrea and by doing this,
- to investigate the extent in which natural regeneration takes place, and
- to determine the effects of site conditions, with emphasis to land use, on the population structure and natural regeneration.

6.2 Materials and Methods

6.2.1 Selection of study areas

Based on the previous studies undertaken on the macro- and micro-distribution of *Boswellia papyrifera*, five representative Boswellia woodlands were identified to investigate the population structure of the species across its entire altitudinal distribution range. The study areas selected for this particular study are Adi-Ketina, Atawen, Molki, Shilalo, and Ferhen. These study areas were selected on basis of the availability of representative Boswellia stands accessibility and altitude range covered. Table 6.1 summarises the information on the five study areas.

Table 6.1 Research areas and number of $400m^2$ sample plots used in the study of population structure of *Boswellia papyrifera* in Eritrea.

study area	agroecological zones	altitude range (m a.s.l.)	nr of sample plots	total sample plot area (ha)
Shilalo	moist lowland	800 - 1100	29	1.16
Molki	moist lowland	1100 - 1500	31	1.28
Adi-Ketina	moist highland	1600 - 2000	34	1.36
Atawen	moist highland	1500 - 1800	24	0.96
Ferhen	arid highland	1600 - 2000	26	1.04

6.2.2 Placement of sample plots

In each study area, a hypothetical perpendicular line was first drawn between the highest and the lowest altitude limit of the Boswellia stands. The altitude range covered was then divided into narrower altitude intervals of 100 m. Within each altitude range, 20 m x 20 m sample plots were placed at random (Mueller-Dombois and Ellenberg 1974). The narrow altitude intervals were planned to avoid local climatic and edaphic variations (Van der Hammen et al. 1989). For each plot, the altitude, topographic features, soil properties and the land use types were also described (see Chapter 4 for further details).

6.2.3 **Plant measurements**

In each sample plot, the diameter of all Boswellia plants (trees[1], saplings[2], seedlings[3], and germinants[4]) were systematically measured. For trees and saplings, the diameter at breast height (dbh) were measured at 1.3 m above the ground using a diameter tape. For seedlings and germinants, basal diameters were taken at the base of each individual plant using callipers. Both germinants and seedlings have similar diameter but essentially differ by the presence or absence of the cotyledons. While germinants retain their cotyledons during the first growing season, seedlings lack them and develop well-developed leaves.

With the intention of giving more emphasis to the juvenile development stage of Boswellia individuals and to use them as indicators of natural regeneration in the different areas, smaller diameter class intervals were used especially for plants having diameters below 8 cm. For that reason, all individual plants within each sample plot were categorised into one of the following nine size classes: <1 cm, 1-2, 2-4, 4-8, 8-16, 16-24, 24-32, 32-40, >40 cm. These size classes were used to construct size class frequency diagrams per plot.

6.2.4 **Comparison between sites and land use types**

To identify regional differences in population structure of *Boswellia papyrifera* stands size frequency distribution diagrams were constructed for each of the study areas. All plots found within a study area were lumped together and the percentage of individuals in each of the nine-size classes described above was calculated.

To describe the effect of land use type on the population structure, size class distributions were calculated for each land use type per site. Five land use types were recognised. These are agricultural, fallow, grazing, non-grazing and enclosed areas. The fallow areas represent abandoned agricultural fields in the *Boswellia papyrifera* woodland area. While grazing areas are readily accessible to livestock throughout the year, the non-grazing areas are inaccessible to livestock owing to their topographic positions. The enclosures are recently introduced conservation areas where trees are protected against grazing and the collection of firewood and construction materials. All individual sample plots in each of the study area were categorised in these five land use types. All plants were classified into one of the nine size classes per study area. All plots found within a land use type were lumped together and the percentage of individuals in each of the nine-size class was calculated.

[1] Trees are plants dbh >8 cm
[2] Saplings are within the range of dbh ≥4-8 cm
[3] Seedlings all Boswellia plants dbh < 4 cm excluding germinants
[4] Germinants are characterised by the presence of cotyledons and are less than three months old

6.3 Results

6.3.1 Differences in population structure among study areas

As the number of sample plots varied over study areas and land use types, and hence the total areas covered per site differed, the population density was calculated on a ha basis. Taking all individual plants, irrespective of their size classes into account the highest plant population density is found in Atawen and the lowest in Ferhen (Table 6.2).

Table 6.2 The total number of *Boswellia papyrifera* plants in different size classes recorded at five observation sites in Eritrea.

study area	size class intervals (cm)									nr of plants	
	<1	1-2	2-4	4-8	8-16	16-24	24-32	32-40	>40	site	ha
Adi-Ketina	71	0	0	2	73	93	13	1	0	253	186
Atawen	88	0	0	13	42	80	25	10	1	259	270
Ferhen	5	0	0	0	9	43	23	3	0	83	80
Molki	10	2	0	3	67	138	62	14	0	296	239
Shilalo	8	2	0	3	43	143	92	12	0	303	261
nr of plants per size class	182	4	0	21	234	497	215	40	1	1194	1032
mean	36.4	0.8	0.0	4.2	46.8	99.4	43.0	8.0	0.2	238.8	206.4
standard deviation	39.8	1.1	0.0	5.1	25.3	41.8	33.1	5.7	0.4	89.8	66.1

The number of germinants, seedlings, saplings, and trees among these areas is different, and hence it is important to compare the figures using certain size class limits. If the tree density alone is taken into account, the highest tree population density is found in Shilalo and the lowest in Ferhen. Sparsely distributed large individual trees dominate the Boswellia stand in Ferhen. The absence of plants in the size class intervals between 1 and 8 cm and the almost total absence of trees larger than 32 cm also characterise the Boswellia stands in Eritrea.

There is a consistent size class distribution trend in the Boswellia stands in all five study areas (Table 6.2 and Figure 6.1). The size class intervals (1-2 and 2-4 cm) are empty or nearly empty in all five areas. Sizeable numbers of individuals in the small size classes (<1 cm) are found only in the stands of Atawen and Adi-Ketina. These are recently germinated individuals. In both areas the individuals in the small size class with basal diameter (bd<1 cm) constitute about one third of the total number of plants of both areas. In the other three areas also, these recent germinants are almost absent. Of the total number of saplings in the fives study areas, 62% were found in Atawen alone and the remaining were unequally distributed in the remaining four areas. In all areas, the medium sized trees (16-24 cm) are most abundant.

Looking at the tree population (dbh ≥ 8 cm) of each area, the largest number are found in Shilalo and Molki, which represent the main *Boswellia papyrifera* woodlands in the south western lowlands of Eritrea. In Ferhen, the total number of trees irrespective of their size is very low. This is probably due the dry climate in Ferhen, which is situated in the northern most part of the *Boswellia papyrifera* woodlands.

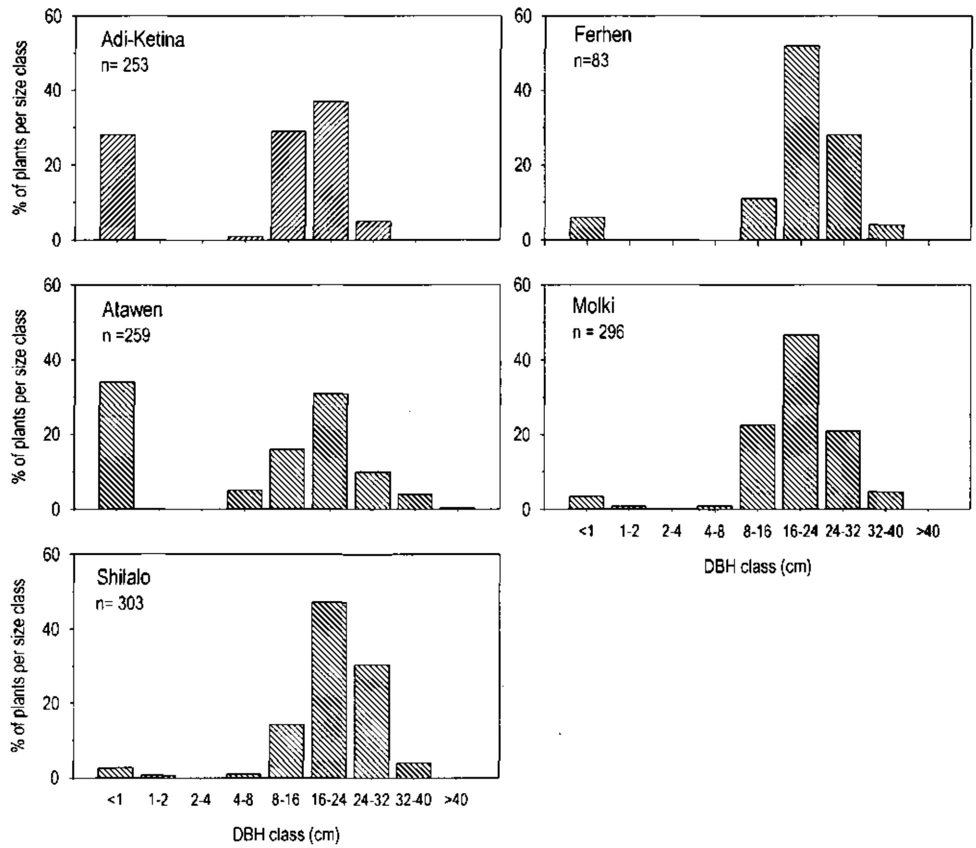

Figure 6.1 The diameter frequency distribution of *Boswellia papyrifera* plants at five sites in Eritrea. The upper diameter class includes the upper limit. n = number of trees.

6.3.2 Population structure in relation to land use

The diameter frequency distribution of Boswellia plants in the five land use types per study area is given in Table 6.3. All plots that are categorised within the agricultural areas were found devoid of Boswellia trees. In these areas trees have been deliberately cleared for cultivation of arable crops. Also in fallow areas very few trees were found. This population is primarily composed of large isolated trees without any juveniles, suggesting the existence of heavy grazing pressure in those areas

The grazing areas hardly contain juvenile individuals except for Atawen where a considerable number of germinants and younger seedlings is found. These plants (<1 cm) are in contrast are well represented in the non-grazing areas at both Adi-Ketina and Atawen and in the enclosed area of Adi-Ketina. Irrespective of the type of land use, the stands of Molki, Shilalo and Ferhen lack germinants which is a clear evidence of lack of regeneration in those areas. A more detailed comparison of the results is complicated by the fact that not all land use types are present at each site or represented in the observation plots used in this study.

Table 6.3 The percentage of *Boswellia papyrifera* plants per diameter class under different land use types at five sites in Eritrea.

		sites				
land use type	diameter	Adi-Ketina	Atawen	Ferhen	Molki	Shilalo
agricultural area	<1->40	-	-	-	-	-
fallow	<1	-	-	-	-	(1)
	1-2	-	-	.	-	
	2-4	-	-	-	-	
	4-8	-	-	-	-	
	8-16	50.0	-	-	-	
	16-24	50.0	-	25.0	25.0	
	24-32	-	25.0	75.0	25.0	
	32-40	-	50.0	-	50.0	
	>40	-	25.0	-	-	
	nr of plants	2	4	4	4	
grazing	<1	-	28.0	3.6	-	-
	1-2	-	-	-	-	-
	2-4	-	-	-	-	-
	4-8	3.3	4.0	-	-	-
	8-16	43.3	18.0	14.3	-	8.2
	16-24	43.3	32.0	42.9	12	43.9
	24-32	10	15.0	35.7	44	40.8
	32-40	-	3.0	3.6	44	7.1
	>40	-	-	-	-	-
	nr of plants	30	100	28	25	98
non-grazing	<1	30.	38.7	(1)	2.0	3.9
	1-2	-	-		-	1.0
	2-4	-	-		-	-
	4-8	-	5.8		1.0	1.5
	8-16	22.9	15.5		21.6	17.1
	16-24	41.4	31.0		55.9	48.8
	24-32	5.7	5.8		18.6	25.4
	32-40	-	3.2		1.0	2.4
	>40	-	-		-	-
	nr of plants	70	155		102	205
enclosed	<1	33.1	(1)	7.8	4.8	(1)
	1-2	-		-	1.2	
	2-4	-		-	-	
	4-8	0.7		-	1.2	
	8-16	28.5		9.8	27.3	
	16-24	33.1		58.8	46.7	
	24-32	4.0		19.6	18.8	
	32-40	0.7		3.9	-	
	>40	-		-	-	
	nr of plants	151		51	165	

(1) the blank space in the column indicates that this type of land use is not represented in the sample area

6.3.3 Relationship between size classes

The relationship between seedlings and adult trees could be established at Adi-Ketina and Atawen (Figure 6.2a-d), but not in Ferhen, Molki and Shilalo where hardly any seedlings were found.

The expectation that plots with a larger number of trees had also a higher number of seedlings was not fulfilled. There is no clear relation in the stand of Adi-Ketina and a more or less negative relation between seedling number (young regeneration) and adult trees per plot in Atawen. The trend in the relationships between saplings and saplings plus trees is similar in both areas (Figure 6.2c,d). The number of seedlings per unit tree number per plot reaches higher values in Atawen than at Adi-Ketina.

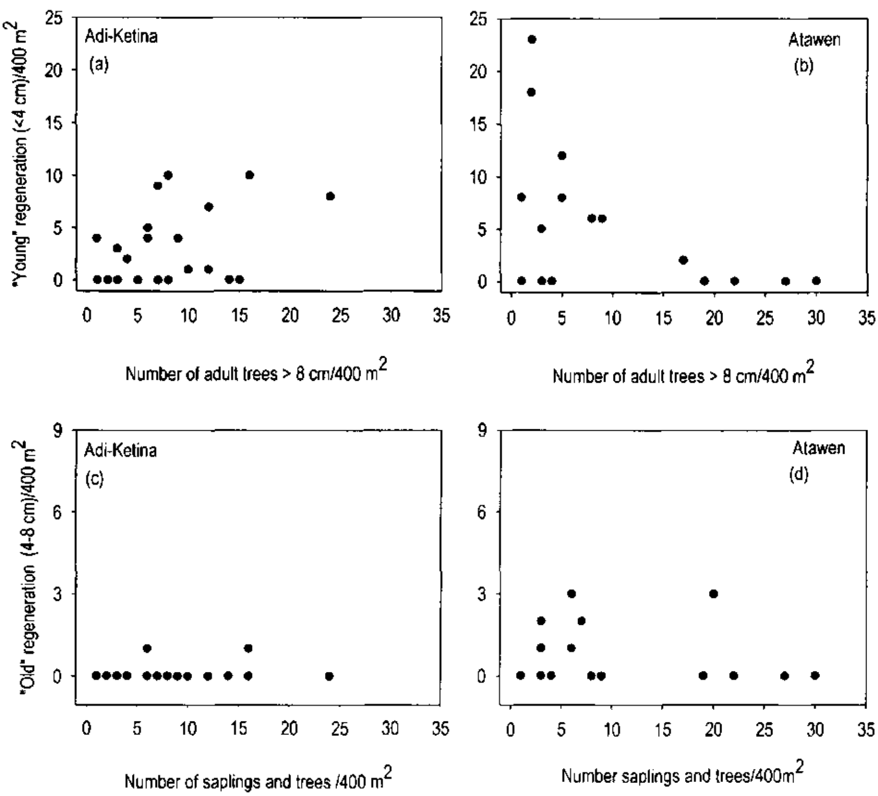

Figure 6.2 The relationship between number of adult trees and young regeneration (< 4cm) (a, b) and the relationship between number of saplings and trees and old regeneration (4-8 cm) (c, d) per $400m^2$ sample plot in Adi-Ketina and Atawen, Eritrea.

6.3.4 Size class distribution in relation to altitude

The size class distribution of *Boswellia papyrifera* is similar along the entire altitude range of the species in Eritrea. At all altitudes, regeneration is absent or very scars, and the population is made up of larger sized trees (Figure 6.3). The altitude range of 1500-1700 m is the only exception where germinants were found. Also at 1700-1900 m germinants are available but their number is very low. In this altitude range, the species also has the maximum abundance (see Chapter 4 for details on the abundance of the species in relation to altitude).

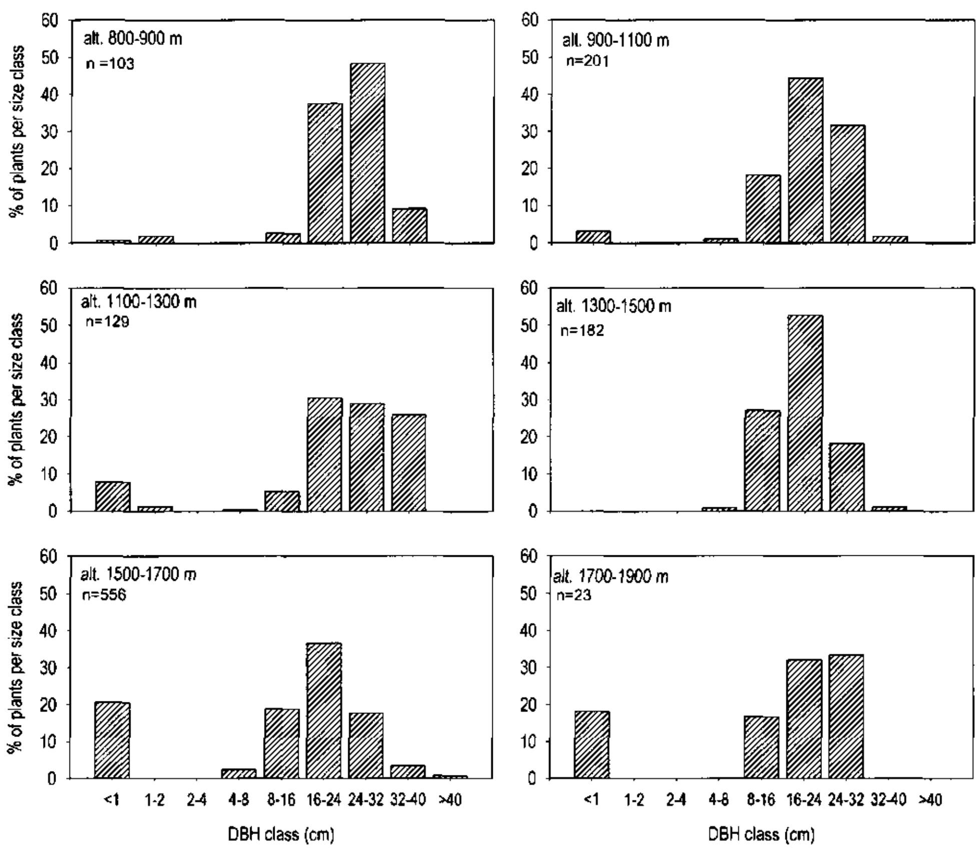

Figure 6.3 The percentage of *Boswellia papyrifera* plants per size class from various altitude intervals in Eritrea. n = number of trees.

6.4 Discussion

In this study, it is very important to note that the population distribution described in the previous sections is based on size class distribution and not age distribution. In most cases, there is a good relationship between size and age of trees (Poorter et al. 1996, Smith et al. 1997). Therefore, the population structure of *Boswellia papyrifera* is taken as the reflection of its regeneration process at a certain moment in time (see also Kumar and Pandey 1993, Condit et al. 1998).

The five Boswellia stands covered in this study are predominantly composed of larger trees and show lack of regeneration reflected by the absence of seedlings and saplings both in absolute as in relative (compared to the adult tree numbers) terms. Some recent regeneration has been observed in only two (Adi-Ketina and Atawen) out of the five areas investigated. There are several possible reasons for these variations in size class distribution. Differences in size class distribution could arise due to (1) size specific recruitment, growth and mortality, provided local conditions are the same (Swaine 1997), (2) different local conditions giving rise to differences in population dynamics (recruitment, growth and mortality) (Poorter et al. 1996, Hulme 1996, Richards 1996) (3) lack of regeneration sites in space and time (Hubbell and Foster 1986), and human induced factors.

Some important local environmental conditions that adversely affect the abundance of recruitment include factors related with soil, climate, and the local topography. The soils and local topography where *Boswellia papyrifera* occurs do not vary largely. The climate of Eritrea is characterised by a long dry season, erratic rainfall, and recurrent droughts (Hien 1995). The areas of Adi-Ketina and Atawen which present some recruitment, are found in moist areas similar to those found in Shilalo and Molki but differ in altitude. As discussed later, this factor in itself does not offer an explanation for the differences observed.

There are several human induced factors which affect the population structure of the Boswellia stands. The main ones are land clearing, grazing and tapping trees for gum. The first is the extreme case where trees are completely removed from cultivated land. The second is grazing which affects seedling survival and establishment as well as sapling growth and development. The negative impact of grazing on the regeneration of woody plant species is well-documented (Gijsbers 1994, Pilarski 1994, Breman and Kessler 1995). Studies on the restoration of montane tree species in the northern highlands and other areas of Eritrea showed that grazing remains a bottleneck to the regeneration of woody plant species in the country (Jones 1991, FAO 1997b). Grazing disrupts regeneration both directly and indirectly. Directly, it involves the removal of the whole plant or parts of the vegetative or reproductive structures of a plant. Indirectly, livestock trample the soil surface resulting in seedling mortality and in soil compaction, which limits recruitment and seedling establishment (Crawley 1983, 1992, Breman and Kessler 1995, Barnes et al. 1998). In Eritrea, the long dry season and recurrent droughts exacerbate the consequences of grazing. Slow growing *Boswellia papyrifera* seedlings are unable to escape grazing during the prolonged juvenile stage of their development. Livestock can easily damage germinants and young seedlings. Their leaves are succulent and plants lack defensive morphological structures such as thorns or spines.

The fact that regeneration is absent in some non-grazed areas (e.g. the enclosed sample plots at Molki and Ferhen and the non-grazing area in Shilalo) while it is present in others (enclosed area in Adi-Ketina established in 1994), shows that grazing is not the only factor determining the absence of regeneration. Unlike in the Atawen area where more advanced regeneration (dbh 4-8 cm) was found, in Adi-Ketina the regeneration is mainly composed of recent recruitment (<1 cm). This finding indicates that the *Boswellia papyrifera* stand in Adi-Ketina was under pressure for a longer period of time resulting in lack of advanced regeneration.

A third important factor which affects the population structure of Boswellia stands is tapping of trees for gum. Seedling abundance depends, among other factors on the availability of viable seeds. These may come from the soil seed bank, or from the seed rain (from the local trees or from elsewhere). A large proportion of seeds reaching the ground is usually destroyed by insects or become infected by fungi (Kimmins 1996, Richards 1996). In spite of the enormous losses, it is normally expected that some germinate and contribute to the population (Ng 1978).

Germination tests (Ogbazghi unpublished data) have shown that seeds from healthy looking Boswellia trees in tapped stands showed a very low germination percentage while those from un-tapped trees had a very high germination percentage. Most seeds coming from the tapped stands were empty. As trees in the stands in Ferhen, Molki, and Shilalo were continuously tapped this may be the reason for the lack of recruitment in those areas. In Ferhen which is located in the driest part of the woodland, complete lack of recruitment, young seedlings, and saplings suggest that the effects of tapping has been aggravated by the dry climatic condition of the area.

There is lack of regeneration across the entire altitude gradient where Boswellia occurs except in areas located at 1500-1700 m. The occurrence of recruitment at this altitude reflects the fact that these stands are untapped (e.g. those of Adi-Ketina and Atawen) rather than being the consequences of altitude per se. The presence of this recruitment coincides with the maximum abundance of the species as found on the western escarpment with less intensive land use.

6.5 Conclusion

The population structure of *Boswellia papyrifera* demonstrates that there is a serious lack of regeneration in all the five study areas. There is a general trend of not having young plants. Some recruitment was found in un-tapped stands. The germinants, seedlings and also the saplings found in these untapped areas resulted from recent recruitment and seedling establishment. Their long term performance in the face of the current land use and environmental conditions remains to be seen. For this, long-term monitoring of population dynamics is needed.

Based on the population structure analysis, it is hypothesised that lack of establishment is primarily caused by grazing pressure but that absence of recruitment is largely caused by lack of viable seed production by the mother trees as the result of tapping. In addition to these factors, inadequate soil moisture and lack of safe sites may be important. These hypotheses are dealt with in Chapter 7.

CHAPTER 7

7 Possible reasons for lack of regeneration of *Boswellia papyrifera*

7.1 Introduction

In the population structure studies (Chapter 6), it was found that regeneration was lacking in almost all parts of the *Boswellia papyrifera* stands in Eritrea. In five areas studied, at only two areas recruitment was found, while seedlings and saplings were invariably absent in all remaining areas. Recruitment was mainly confined to areas not accessible to livestock. This allows for the conclusion that grazing through removal and trampling of aerial parts of the plants is a major factor limiting the regeneration of *Boswellia papyrifera*. However, in some of the non-grazed plots and permanently enclosed plots regeneration did not take place suggesting that other regeneration constraints are also involved. One of those factors may be the non-availability of viable seeds. The author, while collecting seeds for nursery and establishment trials repeatedly found that *Boswellia papyrifera* trees flower regularly and produce fruits but that the seeds from tapped stands were empty and viable seeds could only be obtained from non-tapped trees.

In this chapter both the grazing and tapping issues are studied in depths with the following two hypotheses:

- where viable seeds are produced, lack of seedlings in the Boswellia stands is due to high seedling mortality resulting from grazing
- tapping of trees for gum, especially intensive tapping gives rise to the production of empty, non-viable seeds that leads to lack of recruitment.

In this chapter, first, the effect of grazing and establishment will be analysed (section 7.2) and then the effect of tapping on seed production and seed viability will be treated (section 7.3).

In the analysis of the effects of grazing and tapping on the life cycle of *Boswellia papyrifera*, it is important to have a general framework describing the life cycle of the species. This enables to grasp how each factor intervenes in the cycle and its consequence for the regeneration of the species. The life cycle of the species like other sexually reproducing tree species consists of four major stages i.e. seed, seedling, sapling, and tree. Each life stage is influenced by biotic and abiotic environmental factors. Besides, human induced factors, in this case grazing and tapping trees for gum, are thought to influence the cycle. The development stages at which these factors affect the life cycle and hence the regeneration process are shown in the conceptual framework (Figure 7.1) which was already presented in Chapter 1.

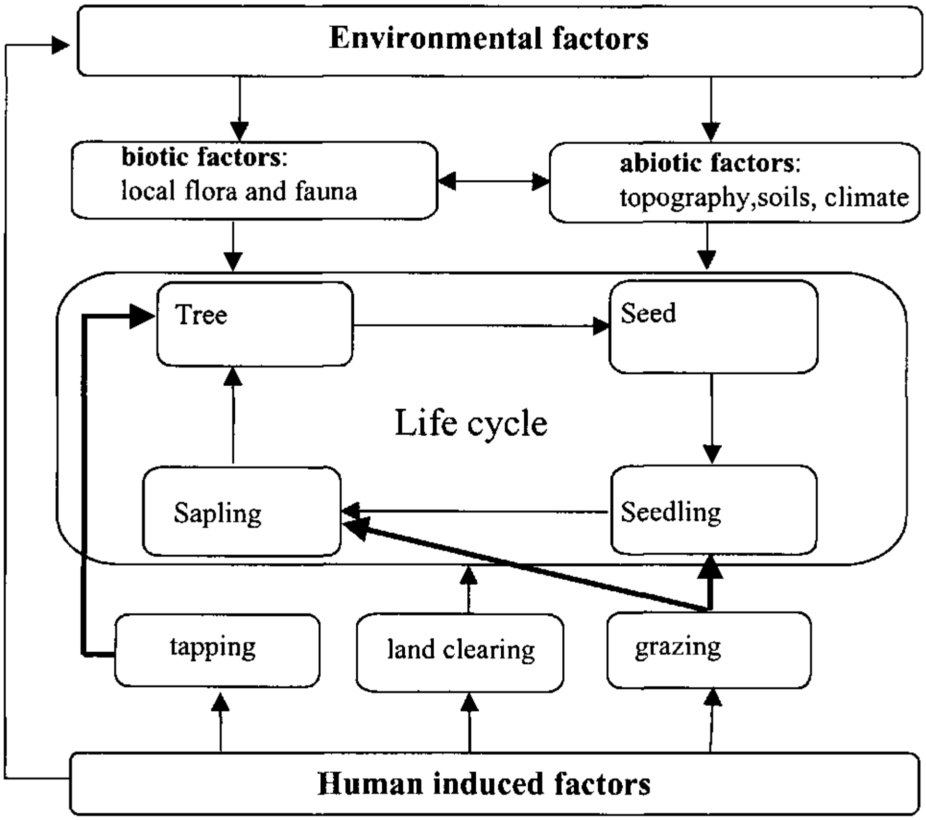

Figure 7.1 Conceptual framework used in the analysis of the regeneration process of *Boswellia papyrifera*. The relationships indicated by the bold arrows are discussed below.

7.2 The effect of grazing on establishment

Many trees and shrub species are important sources of fodder in the Sahel region, particularly during the long dry season (Le Houérou 1980, Floret and Le Floc'h 1980). The tree cover in this region is becoming thinner and thinner and in many places, there is lack of regeneration caused by overgrazing and browsing (Gillet 1968,1980). Eritrea experiences a similar situation in that the natural regeneration of the major tree species in the country is adversely affected by grazing. Reconnaissance studies in Eritrea (FAO 1994, 1997b) and a study on restoration of two afromontane tree species (Jones 1989) clearly indicated that the natural regeneration of tree species is constrained by overgrazing. The exclusion of livestock through enclosures have helped to restore natural plant succession and consequent establishment (Namddeo et al. 1989). In Eritrea, reforestation efforts through hillside closures[5], establishment of plantations and planting trees at community and household-level have been undertaken for the last two decades. Today, the Ministry of Agriculture uses enclosures to rehabilitate degraded vegetation. In total more than 120,000 ha of land, some times with *Boswellia papyrifera* stands, have been enclosed (FAO 1997b). There are indications that the vegetation cover of the woody plants is improving but the performance of individual species is unknown.

The main objectives of the present study were to evaluate the recruitment, establishment and growth of *Boswellia papyrifera* plants (dbh<10 cm) in enclosed and non-enclosed areas and in grazing (accessible to livestock) and non-grazing areas (inaccessible to livestock).

7.2.1 **Materials and Methods**

Site selection, establishment of observation plots and plant measurements

The study was undertaken in the moist highlands at Adi-Ketina and Atawen from July 1997 till July 1999. These areas (described in Chapter 4) were selected because of the presence of untapped Boswellia stands and sites protected from grazing.

In Adi-Ketina, some of the *Boswellia papyrifera* stands have been protected by enclosures from grazing since 1994. Within an enclosure, collection of wood for fuel or construction and grazing by livestock are illegal activities. In addition, tapping of Boswellia trees for gum has been banned inside and outside the enclosure. Since these enclosures are not fenced, livestock occasionally grazes along the edges of the area. Because of this, a grazing pressure gradient is created from the central (enclosed area) to outside the enclosed area.

Before placing the permanent plots, the boundary of the enclosure was delineated in collaboration with the forest guards. Subsequently, the study area was divided into three sections: central (non-grazed), border (moderately grazed), and non-enclosed (heavily grazed). In each of these three sections eight permanent quadrats each measuring 20 m x 20 m were laid out.

In Atawen, where no enclosures are found, five observation plots (of the same size as those in Adi-Ketina) were located at sites accessible to livestock and five at sites not accessible to livestock.

[5] Enclosures are large areas legally protected against grazing and all sorts of human activities. Forest guards hired by the government watch these enclosures against intruding livestock and humans.

The first plant measurements were made at the beginning of the rainy season in July 1997 and repeated one and two years later. For plants with a dbh ≤ 4 cm their height was measured with a measuring rod and the basal diameter with callipers. For plants with a dbh between 4 and 10 cm, height was determined with a telescopic pole and dbh with a diameter tape. Trees with a diameter ≥ 10 cm were only counted. All individuals were labelled and mapped and the boundaries of the plots marked with waterproof paint.

Data analysis

Individuals were classified as germinants, seedlings, saplings, and trees as described in Chapter 4. A two-way analysis of variance was used to see whether the initial differences in population composition between grazed and non-grazed areas had changed in subsequent years. The mortality and the growth of individuals from one size class to the next higher size class were analysed using a transition matrix (Bruner 1973, Miles et al 1985, Tohru 1991). As Boswellia plants are slow growing a narrow size class interval of 0.5 cm was used for plants with basal diameter less than 1 cm and a 1 cm interval was used for plants with larger basal diameters. The mortality per size class was calculated as the ratio between the number of dead individuals and the total number of individuals per size class and expressed in percentage.

7.2.2 **Results**

Plant numbers under different grazing regimes

The initial (1997) population composition showed much higher recruitment in non-grazed plots than in grazed ones. At Atawen higher numbers of germinants, seedlings and saplings were found than at Adi-Ketina. This reflects that at Atawen the inaccessibility of sites to livestock is a permanent condition and that tapping was discontinued much earlier (in 1983) than at Adi-Ketina were enclosures and non-tapping were recently introduced (in 1994). In the non-grazed plots at both sites the number of seedlings increased from 1997 onwards, while the number of germinants and saplings remained much the same. At Adi-Ketina recruitment clearly decreased with increasing grazing intensity (Table 7.1 and Figure 7.2). Statistical analysis showed that the negative effect of grazing on the number of seedlings and germinants was highly significant at both sites and that the increase in the number of seedlings with time was only significant at Atawen (Table 7.2).

Table 7.1 The total number of germinants, seedlings and sapling in permanent observation plots with different grazing intensity at Adi-Ketina and Atawen in the period 1997-1999.

		Adi-Ketina			Atawen	
	year	non-grazed	moderately grazed	grazed	non-grazed	grazed
germinants	1997	90	31	4	105	43
	1998	87	18	4	103	37
	1999	105	17	3	108	26
seedlings	1997	11	35	2	43	9
	1998	44	22	5	79	19
	1999	60	16	4	114	17
saplings	1997	1	0	0	22	7
	1998	1	0	0	22	7
	1999	1	0	0	21	6
total area m^2		3200	3200	3200	2000	2000

Table 7.2 Two-way ANOVA showing the effects of grazing and year on the number of germinants and seedlings of *Boswellia papyrifera* in Adi-Ketina (n=24) and Atawen (n=10).F-values and coefficient of determination (r^2) are given. Level of significance: ns, not significant; ** P<0.01 and ***P<0.001.

location	number /400 m^2	grazing		year		grazing * year		r^2
		F	P	F	P	F	P	
Adi-Ketina	germinants	34.4	***	0.1	ns	0.3	ns	0.45
	seedlings	5.8	**	0.6	ns	2.0	ns	0.15
Atawen	germinants	171.6	***	0.6	ns	1.3	ns	0.86
	seedlings	489.7	***	63.4	***	40.4	***	0.96

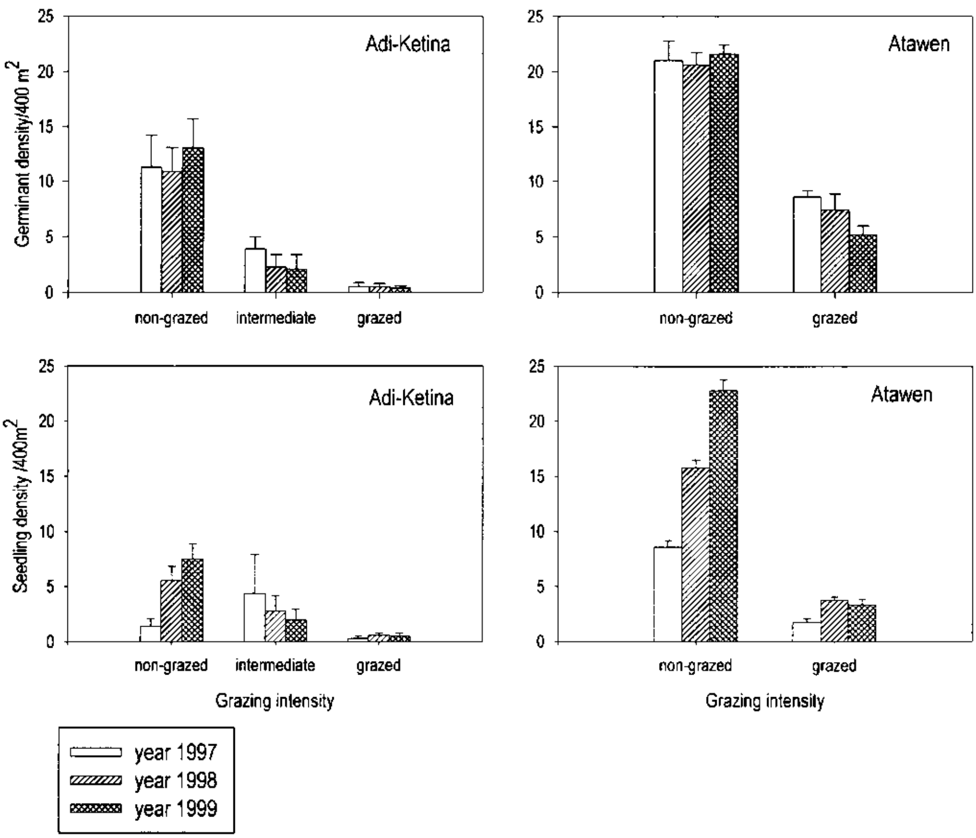

Figure 7.2 Mean number of *Boswellia papyrifera* plants per 400m^2 plot in the permanent plots differing in grazing intensity during three consecutive years. Bars are shown with the standard error of the mean based on n=8 for Adi-Ketina and n=5 for Atawen .

Annual mortality and annual transition rate

The analysis of the transition of individuals from one size class to the next higher one showed at both sites very high death rates of germinants and slow growth of the surviving ones.

In Adi-Ketina, where the juvenile population mainly consisted of germinants and seedlings the growth rate of both was very low, resulting in the transition of a small number of individuals to the next size class. The high mortality rate (67%) of the smallest Boswellia plants (bd< 0.5 cm) decreased with size to about 18 % for plants in the 2-3 cm bd class and 0 in the 6-7 cm class (Table 7.3).

Table 7.3 Annual mortality and annual transition rate of individuals per basal diameter (bd) class of *Boswellia papyrifera* individuals at Adi-Ketina. y_0 and y_1 represent measurements of plants in two consecutive years. Data refer to transition from 1997 to 1998 and from 1998 to 1999.

bd (cm)						y_1			
y_0	<0.5	0.5-1	1-2	3-4	4-5	5-6	6-7	mortality(%)	n
<0.5	1.7	31.5						66.8	235
0.5-1.0		49.0	15.6					35.4	96
1.0-2.0			76.5	2.9				20.6	34
2.0-3.0					*				
4.0-5.0									
5.0-6.0									
6.0-7.0							100	0.0	4
nr of plants	4	121	41	1	0	0	4	198	369

*the blank space in the Table shows that plants in that diameter class were not found.

Table 7.4 Annual mortality and annual transition rate of individuals per basal diameter (bd) class of *Boswellia papyrifera* individuals at Atawen. y_0 and y_1 represent measurements of plants in two consecutive years. Data refer to transition from 1997 to 1998 and from 1998 to 1999.

bd (cm)							y_1							
y_0	<0.5	0.5-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	>10	mortality(%)	n
<0.5	9.3	26.6											64.1	289
0.5-1		57.7	16.9										25.4	71
1-2			79.2	8.3									12.5	24
2-3				73.7	21.1								5.2	19
3-4					80	15							5.0	20
4-5						90	10						0.0	10
5-6							88.9	11.1					0.0	9
6-7								77.3	22.7				0.0	22
7-8									83.3	16.7			0.0	12
8-9										100	0		0.0	7
9-10											87.5	12.5	0.0	8
nr of plants	27	118	31	16	20	12	9	18	15	9	7	1	208	491

In Atawen, the mortality also decreased with an increase in diameter. The highest plant mortality (64%) was recorded for the germinants (bd <0.5 cm). Mortality of individuals above 5 cm basal diameter was zero. The surviving plants grew very slowly and the majority of plants remained in the same size class. Only a small fraction (between 10% and 30 %) of all the plants inventoried moved to the next higher size classes (Table 7.4).

7.2.3 **Discussion**

The study shows that seedling establishment is better in areas protected from and inaccessible to livestock. Livestock grazing on germinants and young seedlings results in the removal of the whole plant or retarded growth and development. The seedlings of *Boswellia papyrifera* are succulent and palatable to browsers, and almost all germinants and seedlings are browsed by domestic animals during the first few months of their life. Germination of Boswellia is epigeal, which makes it vulnerable to browsing and trampling. In addition, a severe defoliation in combination with drought may also lead to stunted growth, or ultimately to the death of young seedlings (Benjamin 1980, Crawley 1983, Bendz 1990).

The grazing pressure is exacerbated by the fact that *Boswellia papyrifera* seedlings grow slowly. In three years, seedlings attained a maximum height of about 15 cm and a basal diameter of 1.5 cm, which means that the seedlings are vulnerable to grazing during a long period. Presence of a large number of germinants in the enclosed area in Adi-Ketina shows that there is spontaneous regeneration and that the stand in the central part of the enclosures has the potential for recovery provided it remains protected against livestock.

In comparing the population data of the two study areas it can be observed that the regeneration is much more abundant and advanced (presence of saplings) in Atawen than in Adi-Ketina. This reflects the fact that areas inaccessible to livestock have always existed in Atawen and that a ban on tapping was introduced much earlier than in Adi-Ketina where only recently (1994) enclosures were established. The low transition rates underline that regeneration is a slow process. The proposed six month to one year grazing restrictions to allow regeneration of tree crowns of some Sahelian trees species (Boudet and Toutain 1980) is apparently insufficient for *Boswellia papyrifera*. The high death rates of the germinants, also in the non-grazed plots, indicate that the conditions during the first growing season are of crucial importance in the regeneration process.

7.3 The effects of tapping on the reproductive cycle of *Boswellia papyrifera*

Tapping of Boswellia trees takes place during the dry season. It starts in September and continues until March. Tapping involves making incisions in the bark and the phloem with a special axe locally known as "mngaf". The gum is left to solidify while on the trees and it is collected every three weeks. Gum olibanum is available in small tears or lumps of white-yellowish-reddish colour. This gum is a mixture of a resin and an acidic polysaccharide (Anderson et al. 1965, Hillis 1989). A typical composition of gum olibanum includes oil (5-9%), resin acids (13-17%), polysaccharides (20-30%) and residues, mainly boswellic acid (40-60%). After collecting the dried gum, the original wound is re-opened to allow a steady flow of the gum. Each tree is revisited and wounded at least seven times per harvest season. Off-season rains may interrupt tapping and gum collection activities.

Theoretically, according to the tappers, the number of tapping points per individual tree is fixed in relation to tree size. Small trees ranging 10-20 cm in diameter should be tapped at four points and larger trees at six points. The tapping points should be facing east and west wards. According to the tappers, this enhances the yield. In spite of these guidelines, over-tapping and use of inappropriate tapping methods by unskilled labourers take place and cause substantial damage to Boswellia trees (Ogbazghi personal observation).

Many people, including the tappers themselves, think that tapping is a non-destructive exploitation system because trees are not felled for wood. This view is challenged in this paper, because of indications that the present intensive tapping practices negatively affect the regeneration of *Boswellia papyrifera* and thus threatens the survival of the species. These indications are that the author could only obtain viable seeds for establishment trials from un-tapped trees (Ogbazghi unpublished data) and that natural regeneration was only found in non-grazing areas with un-tapped Boswellia stands. How tapping affects the reproductive cycle, particularly the production of viable seeds is still unknown. The aim of the present study is to investigate how tapping fits into the phenological cycle of the tree and how it influences seed quantity and quality.

7.3.1 Materials and Methods

The effect of tapping on seed viability at stand-level

The effect of tapping on viable seed production at stand level was studied in the stands of Adi-Ketina, Atawen, Ferhen, Molki, and Shilalo (for details about these sites see Chapter 4). These areas represent the whole altitude range of *Boswellia papyrifera* stands. Among the five study areas, three stands are tapped every year (Ferhen, Molki, and Shilalo). At the start of the study, in 1997, tapping had been abandoned in Adi-Ketina since 4 years and in Atawen since 14 years. Seeds were collected from the five study areas for three consecutive years (1997-1999). From each area, 200 randomly selected seeds were put to germinate in growth chambers. Before placing seeds in the germination chambers, they were soaked with tap water for 12 hours, which provides the best condition for germination of *Boswellia papyrifera* (Ogbazghi unpublished results). The conditions inside the cabinet were 12 hours minimum night and maximum day temperatures of 20°C and 30°C, respectively, and a relative humidity of 80%. The moisture levels of the petri dishes were kept constant by watering throughout the experimental period. Every day the germination was monitored and the number of germinated seeds recorded (Hartmann et al. 1990).

The effect of tapping on flowering and seed production at tree level

Field experiments simulating the present gum exploitation systems in Eritrea were carried out in three areas. Trees at Atawen were untapped for fourteen years, at Adi-Ketina for four years and at Ferhen trees were tapped every year. All areas are located at an altitude of 1600 m a.s.l. and found under similar topographic and soil conditions. The phenological cycle is described by following the different phenophases in the same area (Grouzis and Sicot 1980).

In each study area, a homogeneous area was delineated for the selection of trees. Within each area, trees having diameters of 10, 20 and 30 cm were randomly selected and mapped. For each diameter class, fifteen trees were taken and labelled. These trees were then allocated to three different tapping categories (n=5 per tapping intensity): un-tapped, tapped at six points, and tapped at twelve points. Following the local practices the selected trees were tapped at an interval of three weeks and the gum obtained from each tree was collected. The experimental design consisted of three sites, three size classes, three tapping intensities and five trees making it forty-five trees per study area.

In this experiment, two sets of data were gathered. In the field, the number of inflorescences per tree was counted during the peak flowering period. The number of fruits and seeds per tree was estimated by taking five randomly selected inflorescences, one from the centre and four from corners of the crown. The fruits and seeds of these five inflorescences were taken to the laboratory for further seed analysis and germination experiments. Seed length and width were determined on thirty randomly selected seeds per tree. Furthermore, the seed dry mass (the weight in g of 1000 seeds) was determined.

A total of 200 seeds from each tree were put to germinate. The 200 seeds (50 seeds per dish) were placed in dishes lined with moist filter papers and placed inside a germination cabinet. The conditions inside the cabinet were 12 hours minimum night and maximum day temperatures of 20°C and 30°C, respectively, and a relative humidity of 80%. The moisture level of the petri dishes was kept constant by pouring enough water to keep them moist throughout the experimental period. Germination percentage was calculated as the cumulative germination percentage 27 days after sowing (Hartmann et al. 1990). The mean and standard errors of the number of inflorescences, fruits, seeds and of seed length, seed width, seed mass and germination percentages per tree are described using histograms. All statistical analyses were carried out with SPSS 98.

7.3.2 **Results**

Tapping in relation to the phenological cycle of *Boswellia papyrifera*

In Eritrea, the phenological cycle of *Boswellia papyrifera* is largely controlled by a distinct seasonal precipitation regime. The dry season in the Boswellia areas starts in late September and lasts for about nine months (mid September- mid June). Boswellia trees remain leafless for part of the dry season. Leaf development occurs at the beginning of the small rains in late March (Figure 7.3). The floral buds develop at the end of the branchlets after leaf fall. Flowers start to emerge at the second half of November and most trees are in flower in December. Fruits mature in January and February. Tapping activities start before the emergence of the floral buds and coincide with the whole reproductive cycle. It starts in September (end of the wet season) and ends in March when trees start to flush (Figure 7.3). Tapping activities are interrupted occasionally by off-season rains and it is completely stopped during the wet season.

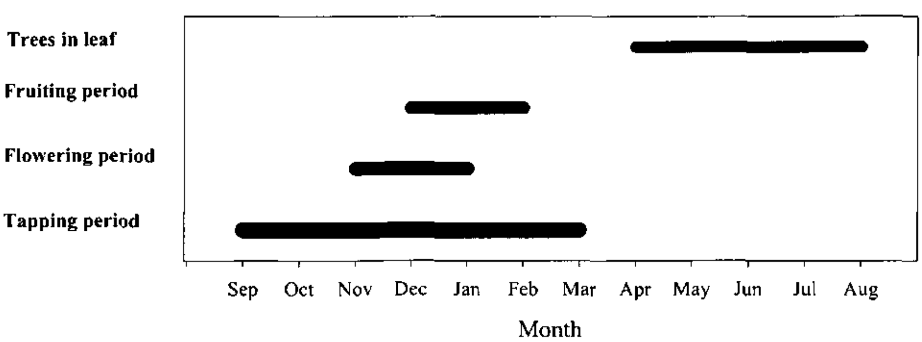

Figure 7.3 Tapping calendar in relation to the phenological cycle of *Boswellia papyrifera* in Eritrea.

Germination of seeds from different sites

Germination of Boswellia seeds in the laboratory began five days after sowing and lasted for about twelve days. The observations lasted for four consecutive weeks. The total germination percentage, however, did not increase after two weeks (Figure 7.4). Seeds from un-tapped stands had high germination rates, Atawen (94%) and Adi-Ketina (80%) compared to seeds from tapped stands for which the germination percentage were between 14% and 16% (Table 7.5). Within un-tapped sites, germination was higher at Atawen where tapping was abandoned a longer time ago. The low germination percentage in tapped stands is due to the high number of empty seeds and low seed viability (Table 7.5). Between 20 and 25% of the bulk seeds were attacked by insects irrespective of tapping history.

Table 7.5 Quality of *Boswellia papyrifera* seeds collected from five sites. Seed quality is given in three classes: healthy and full, healthy looking but empty and seeds infested or attacked by insects, and as a percentage germination of healthy and filled seeds. Values in percentage, n=200 seeds per provenance.

		% of seeds			
seed source	tapping history	healthy and filled	healthy and empty	infested by insects	germinated (based on healthy & filled seeds)
Ferhen	tapped	18.5	61.5	20.0	15
Molki	tapped	20.0	56.0	24.0	16
Shilalo	tapped	21.5	54.0	24.5	14
Adi-Ketina	un-tapped	54.0	23.5	22.5	80
Atawen	un-tapped	66.0	15.0	19.0	94

Effect of tapping on reproduction at tree-level

Tapping resulted in a reduction in number of inflorescences, number of fruits per inflorescence, seed mass and germination rate irrespective of tree size (dbh), while tree size had a positive effect on these characteristics (Appendix 8). These effects were far more pronounced on the sites Atawen and Adi-Ketina, where tapping had been discontinued 14 and 4 years, respectively before the experiment began, than at Ferhen were annual tapping had continued (Figure 7.5). At Atawen and Adi-Ketina, the negative effect of tapping increased with tapping intensity (e.g. with the number of incisions per stem). The negative effect on germination was higher in Atawen than in Adi-Ketina: it apparently increased with the length of the period that trees had not been tapped. At Ferhen, all reproduction values were low and hardly differed between tapped trees and trees which were not tapped in the season that the observations were made. The overall low reproductive capacity of the trees in

Ferhen clearly reflects the negative effect of annual tapping throughout the dry season, which is the common practice in Eritrea. For the statistical analysis of the effects of tapping and tree size, the reader is referred to Appendix 9.

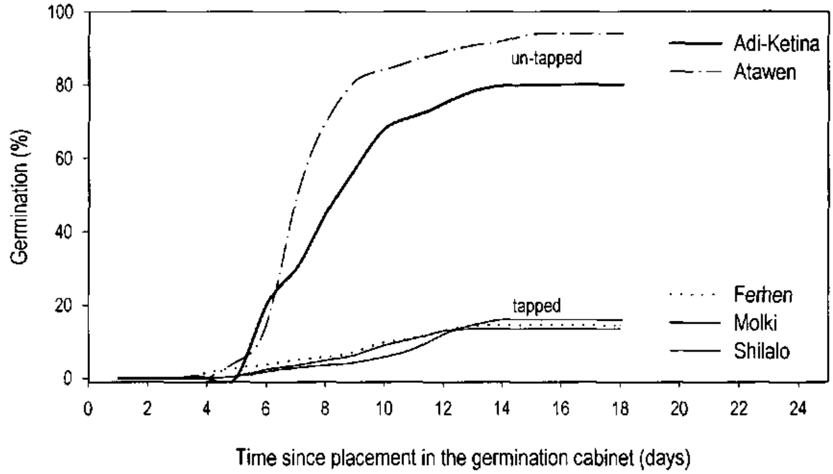

Figure 7.4 Cumulative germination percentage of seeds collected from tapped (Ferhen, Molki and Shilalo) and un-tapped (Adi-Ketina and Atawen) *Boswellia papyrifera* stands.

7.3.3 **Discussion**

The gum exploitation technique in Eritrea has a negative impact on natural regeneration of Boswellia at stand- and tree level. At stand level, seeds from tapped stands were found non-viable causing lack of recruitment in the tapped stands. At Ferhen, for instance, almost 2/3 of the total seed lot was empty and about 1/5 was attacked by insects, and the germination percentage of fully developed seeds was very low (Table 7.5).

At tree level, tapping resulted in a reduced reproductive performance and reduced germination percentage. The low germination percentage of seeds from tapped trees also indicates that seed development was influenced by the extraction of gum from the mother tree. The flower and seed set occurs when gum is extracted from the mother trees (see Figure 7.3). It has been suggested that the conditions of the mother plant at the time of flowering determine the fate of the progeny (Larcher 1995). Weak, senescent and environmentally stressed plants produce ovules that are either underdeveloped or unable to develop into normal seeds. Gums are primarily composed of sugars and proteins containing boswellic acids (Hillis 1987, 1989). The removal of reserve food from the mother plant may have resulted in a lack of sufficient carbon to produce viable seeds (Kramer and Kozlowski 1979, Crawley 1983).

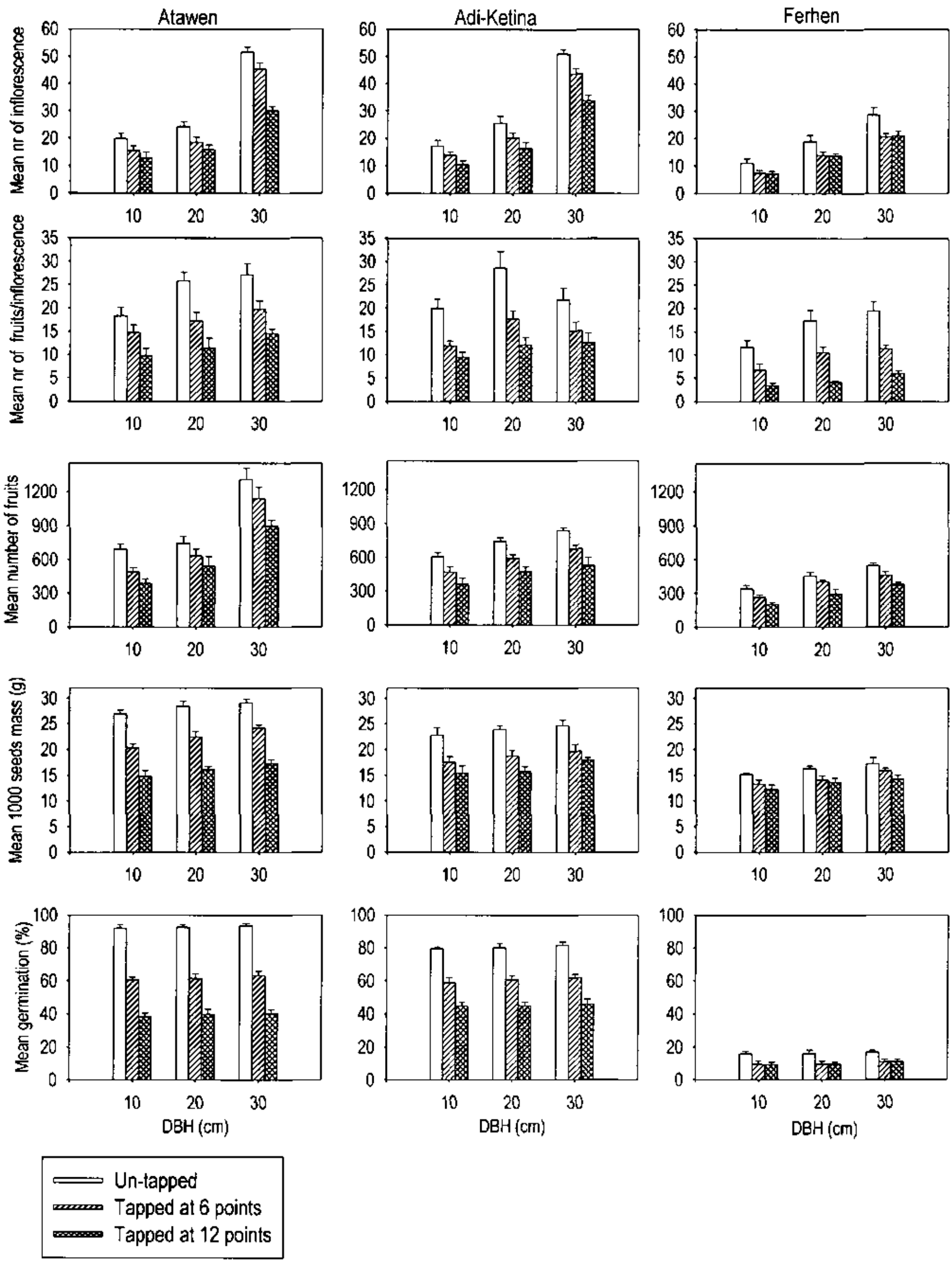

Figure 7.5 Reproductive characteristics of *Boswellia papyrifera* trees of different dbh classes with different tapping regimes at three locations in Eritrea.

The appearance of floral buds in both tapped and untapped Boswellia trees at both stand and tree level give the impression that tapping does not completely disrupt the reproductive cycle of the species. Annually, trees were seen in flower. Tapping, however, quantitatively reduced the number of reproductive parts which shows that overexploitation of the species for gum has both short and long-term effects on the regeneration of the species. In the short term it may be manifested by non-viable seeds but in the long-term, the reproductive cycle may be blocked.

The study also revealed that the germination success differed among the three areas investigated depending on their tapping history. The non-tapped (control) trees in Ferhen, which were tapped annually before the start of experiment, had the lowest germination percentage followed by the control trees at Adi-Ketina and Atawen where tapping has been abandoned, respectively four and fourteen years ago. This suggests that the tapping cycle has a long-term impact on the overall regeneration process. The longer trees are being tapped the worst is the seed quality produced. Because of this, the trees in Ferhen, which were tapped annually, had a very low germination percentage and an overall poor seed quality. Germination success of non-tapped control trees in Atawen is nearly 100%. This indicates that stands need between 4-14 years to recuperate in order to attain their full potential for viable seed production.

There are few cases were harvesting of plants or plant parts are considered sustainable at levels of individual organisms (Ros-Tonen et al. 1995, Broekhoven 1996). The extraction of plant elements without killing the plant itself is generally considered sustainable. However, this is not always true, as the extraction of fluids of latex producing plant species has resulted in local extinction. According to Dominguez and Gomez (1990), cited in Ros-Tonen et al. (1995), Quinine (*Cinchona Sp.*) producing species became extinct in parts of Amazonia because of overexploitation. Moreover, rosewood oil of Lareto was depleted five years after its exploitation started (Coomes 1991). In tropical primary forest, the rubber tree has been tapped for more than a century but only very few observations exist on the consequence of tapping on the survival, biomass increment, life expectancy and reproduction including the number of seeds and seed size (Hall and Bawa 1993). In the same region, however, mortality of tapped trees has been reported in northern Bolivia (Ros-Tonen et al. 1995).

7.3.4 **Conclusion**

In areas with adequate supply of viable seeds, grazing is the main factor limiting the natural regeneration of *Boswellia papyrifera*. In view of the slow initial growth of Boswellia plants, long-term measures are needed to protect germinants, seedlings, and probably saplings, from grazing. Establishment of enclosures is a promising approach to regenerate existing

Boswellia stands if the ban on grazing is strictly implemented over a long period. The length of this period has still to be determined. In view of the fact that also in non-grazed plots high mortality of germinants occurred in the first growing season, additional measures might be needed to optimise regeneration conditions.

In areas unaffected by livestock grazing, lack of viable seeds due to tapping is the major cause for lack of recruitment. Tapping, through its effects on the various reproductive processes of *Boswellia papyrifera* trees, disrupts the regeneration process at the seed production stage. The mechanism by which tapping affects the seed production is not well understood. Especially the physiological basis of this mechanism should be further investigated.

A less intense gum extraction mechanism should be introduced to minimise the adverse effects of the exploitation. In this respect, the optimum number of tapping points per tree diameter should be defined. The present study suggests that the number of tapping points should be less than six points per tree. Moreover, the tapping cycle should be further investigated to define the recovery time needed for plants after a tapping period. In order to recover, trees probably need at least a four year resting period. As this time seems to be long, as an alternative un-tapped mother trees might be permanently retained on strategic locations in the woodlands in a way that allows a good seed dispersal.

The influx of hired tappers from outside the Boswellia areas exacerbate the problem of over-tapping. These migrant workers lack sufficient knowledge of tapping procedures and are in many cases not interested in the fate of the trees. The combined lack of awareness, lack of skill and tree tenure lies at the heart of the shortcomings of the present exploitation system of *Boswellia papyrifera*.

CHAPTER 8

8 General discussion

8.1 Review of results

Boswellia papyrifera is a deciduous tree species growing in drier parts of Africa. The centre of diversity of the genus Boswellia lies in northeast Africa. The distribution of the species is entirely within the Sudanian and Sahelian centre of endemism that forms more or less a continuous vegetation belt stretching from North Nigeria eastwards till it reaches the highlands of Eritrea and Ethiopia in the east (Keay 1959, White 1983, Vollesen 1989).

In spite of the ecological diversity found in Eritrea, the geographical distribution of *Boswellia papyrifera* is limited to areas in the southwestern and southern part of the country. Here it is found in areas between 800 and 1850 m a.s.l., with a mean annual rainfall between 375 and 750 mm and a dependable length of growing period (DLGP) of 45 – 100 days. The mean annual maximum and mean minimum temperatures corresponding with the higher altitude limit are about 25 and 14°C, respectively and with the lower limit about 32 and 20°C, respectively. Based on a survey including 113 villages it was found that the probability of the occurrence of *Boswellia papyrifera* increases to a value of 1 when mean annual maximum and minimum temperatures reach values higher than 30 and 18°C respectively, the annual rainfall is at least 500 mm and the DLGP exceeds 60 days. These conditions are close to those found at Barentu (Appendix 2), which are considered to be a representative for the climatic conditions in the moist low lands where the largest Boswellia trees were found (Chapter 5).

The above mentioned climatic limits are subject to the prevailing conditions in southwestern Eritrea. They explain why *Boswellia papyrifera* has not spread into and across the central highlands (too low minimum temperatures) and into the arid lowlands (lack of rainfall) but they cannot be considered as absolute limits. In controlled condition experiments, young Boswellia seedlings showed the highest growth rate at a constant day and night temperature of 35°C (the highest experimental temperature), hardly any growth at temperatures below 15°C and death of seedlings below 10°C. This indicates that the upper temperature limit certainly exceeds 32°C and most likely also 35°C. The 100 day upper limit for the DLGP does not imply that a longer period is not suitable for the species. A prolonged growing season, however, is certainly not suitable as *Boswellia papyrifera* requires a marked dry season for flowering and fruit setting. This is a common phenomenon in tropical freely branching tree species, which need a period of quiescence in shoot growth for flower differentiation. In Boswellia, the balance between vegetative and generative growth was found to be very sensitive. This was observed at Ferhen when erratic rains in November

1998 triggered off new leaf growth and suppressed flowering, The macro distribution study has confirmed the general idea that the Boswellia area has decreased over the last 50 years. Especially in the transition zone between the moist and arid lowlands, the species has disappeared, probably as a result of a combination of population pressure and recurrent droughts.

The micro distribution study conducted at three highland- and two lowland Boswellia sites indicated that the main environmental factors, locally affecting the distribution and abundance of the species, are in order of importance altitude, land use intensity, soil organic matter content and slope angle and to a lesser extent also silt content and pH of the soil. At the three highland sites, the abundance decreased with altitude while the reverse trend was observed at the lowland sites. When the results of all sites were combined a maximum population density was found between 1500 and 1600 m (Chapter 4). These results, however, are highly dependent on the choice of the sites. If for example three lowland sites and two highland sites had been chosen a maximum at lower altitude would have been found. The fact that in the lowlands, situated between 800 and 1400 m, the abundance increases with altitude and slope is probably mainly due to land use. At the flat bottom land and gentle lower slopes most Boswellia stands have been cleared for crop production. Intensive livestock grazing has resulted in a situation in which Boswellia is only found on steep upper slopes and ridges which are not accessible to livestock. In areas with vertisols, flat areas are seasonally waterlogged and this may be another reason why under those conditions the species is found on slopes.

After the studies on the occurrence and abundance of *Boswellia papyrifera* at regional and site level, tree growth and population structure were studied in different environments. As a general trend it was found that at earlier stages of development *Boswellia papyrifera* invests more of its biomass in height and crown depth and at a later stage in stem diameter growth. This can be considered as a strategy to shorten the time that the species might be subject to livestock browsing. So far, no growth analysis studies have been made but some information on seedling growth has become available from the population studies reported in Chapter 6 and recent establishment trials (Ogbazghi unpublished data). These trials indicate very slow initial growth of the aerial parts, but a marked development of a thick taproot. The reserves stored in the taproot enable the plant to re-sprout after the dry season in which plants die back to soil level. The time it takes before a permanent stem is formed is not yet known. The priority given to root development makes the plants well adapted to a short growing season. The observations on mature trees showed that growth is strongly affected by altitude. The maximum tree height at the lowland sites was twice the value found at the high land sites. Furthermore, a strong negative linear relationship was found between mean tree height and crown depth and altitude. This suggests that the species grows better in the warm moist lowlands than in the moist highlands.

The most important outcome of the population study is the lack of natural regeneration of *Boswellia papyrifera*. In almost all stands of the five study-areas seedlings and saplings were absent and only larger trees were found. Only at two sites with untapped trees recruitment was found in plots not accessible for or closed to livestock. This prompted further research on the effects of grazing and tapping on regeneration (Chapter 7).

The effect of grazing is well illustrated by the 1997 observations at Adi-Ketina where in non-grazed areas 280 germinants per ha were found versus 12 in grazed plots. Detailed population studies revealed that also in the non-grazed plots about 60 % of the seedlings died during the first year. This indicates that growing conditions during this period play a crucial role. Non-published results of establishment trials suggest that survival largely depends on adequate moisture supply during the first months after germination. Furthermore, the population study data showed that tree mortality decreases with increasing basal diameter and virtually stops when a diameter of 3 cm is reached. Field observations over a three year period revealed that most seedlings remained in the same basal diameter class during this period, illustrating that it will take several years before seedlings reach the low mortality stage.

The tapping studies at stand level clearly showed that tapped trees hardly produced viable seeds. Most seeds were empty and most of the filled ones failed to germinate. Observations on individual trees indicated that tapping resulted in a reduction in inflorescence, number of fruits, seed mass and seed viability. When tapping was resumed after a resting period this effect was directly apparent. The germination percentage immediately dropped from over 90 % in the control trees to about 60 % in trees tapped at six points and to 40 % in trees tapped at 12 points. These percentages are still high enough to produce recruitment. Annually tapped trees, however, produced hardly any viable seeds. With germination rates of about five percent and a high seedling mortality, tapped trees apparently cannot provide recruitment. How tapping affects flowering, fruit and seed production and seed viability is not yet known. It is likely that competition for assimilates for gum production and for generative growth and seed filling is involved. In rubber (*Hevea brasiliensis*) the competition for assimilates between latex production and vegetative growth is well documented. By regulating the tapping-intensity a good balance between these processes was found, which has turned latex tapping into a sustainable production system. In *Boswellia papyrifera* the competition is more complicated because it probably involves competition between three processes: vegetative growth, gum production and generative growth. The favourable effect of tapping rests suggests however that tapping regimes can be developed in which acceptable levels of gum and viable-seed production can be combined. A practical solution for the lack of viable-seed production in the existing stands could be to retain untapped mother trees as a seed source for recruitment.

8.2 Conclusions

The main conclusions covering the objectives and hypotheses are:

1. The occurrence of *Boswellia papyrifera* is restricted to the southwestern and southern part of Eritrea. Here it is found in areas between 800 and 1850 m. a.s.l. with a mean annual rainfall of 350 –700 mm and a DLGP of 45–100 days. There is more or less a continuous belt with Boswellia woodlands in the moist lowland and part of the moist highland agroecological zone and a small separate Boswellia area further north in the arid highland zone. Boswellia has disappeared from the transition zone between the moist lowland and arid highlands and this explains the isolated position of the population in arid highland zone.

2. The future existence of the natural Boswellia woodlands is threatened for two reasons:
   - a decline in area as a result of land clearing for agriculture. Under the present concession-based exploitation system farmers have no interest in keeping Boswellia trees on their fields.
   - a lack of natural regeneration in the remaining Boswellia stands. The present systems of intensive annual tapping throughout the dry season leads to low production of mainly non viable seeds. Where viable seeds are produced seedlings and saplings usually are destroyed by livestock.

3. Establishment of enclosures in which no tapping and grazing is allowed was found to be an effective measure to reintroduce and promote natural regeneration in existing Boswellia woodlands.

8.3 Recommendations

Measures to counteract the decline and degradation of the Boswellia woodlands

As the land clearing problem and its underlying causes can not be solved in the near future practical measures and research efforts should be directed towards solving the regeneration problem. First of all the enclosure system should be examined on the following points:

- How long should trees be left untapped before they have regained their full viable seed producing capacity, and how long after tapping has been resumed will seed production remain adequate for natural regeneration?
- Is the retention of strategically situated untapped mother trees as permanent seed sources for recruitment a feasible and effective alternative for a tapping ban on complete Boswellia stands?
- How long does it take for new seedling classes to develop into trees with enough branches above browsing height and a ban on grazing can be lifted?
- Is a cut and carry grass harvesting system an alternative for a ban of grazing, can it be implemented with minimal damage to recruitment and is it acceptable to farmers ?
- Which additional measures have to be taken in the enclosures to reduce seedling mortality during establishment?

If this research is conducted in the existing permanent observation plots at Adi-Ketina and Atawen (Chapter 7) within a few years recommendations can be made for establishment of better defined enclosure systems.

In the longer term, a comprehensive research effort should be made to arrive at a sustainable tapping system. This requires trials with uniform trees in which the effects of combinations of tapping intervals between- and within seasons, and the number of tapping points per tree on gum yield and seed production are investigated. However, as long as the tappers can not be forced to adhere to a less intensive-tapping regime, improved exploitation systems cannot be implemented. A detailed outlook on the future of *Boswellia papyrifera* in Eritrea with emphasis on domestication is given in Appendix 10.

Restoration of former *Boswellia papyrifera* areas

As a second priority attention should be paid to replanting of former Boswellia areas. The basis for this research has already been laid in ongoing nursery- and establishment trials. Long term monitoring of seedling growth and development after field planting is now needed. Before embarking on large-scale replanting, high gum-yielding mother trees have to be identified (and multiplied) for seed supply.

Establishment of a Boswellia research and development unit

The above recommendations outline the research and development actions, which should be taken to halt the disappearance and degradation of the Boswellia woodlands in Eritrea. Given the urgency of the issue and the size of the proposed research programme, the establishment of a special Boswellia research and development unit is strongly recommended.

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Appendices

Appendix 1 Frankincense exported from Eritrea 1962-1998.

year	metric tons
1962	1395*
1963	1962*
1964	1759*
1965	1617*
1966	2035*
1967	797*
1968	739*
1969	1728*
1970	1963*
1971	2351*
1972	1856*
1974	1500*
1992	200**
1996	446**
1997	463**
1998	461**

Source:* Asmara Chamber of Commerce (1974),

** Ministry of Agriculture of Eritrea archives (1998).

For certain years no figures are available.

Appendix 2 Climatic data of meteorological stations in the major agroecological zones of Eritrea.

	Asmara (moist highland)						Nakfa (arid highland)					
	temperature °C						temperature °C					
month	max.	min.	mean	RH* (%)	rainfall (mm)	PET* (mm)	max.	min.	mean	RH (%)	rainfall (mm)	PET (mm)
Jan.	22.7	2.7	12.7	41	5	91	21.0	9.2	15.1	73	4	73
Feb.	23.7	8.1	15.9	39	3	98	21.6	9.5	15.6	71	6	80
Mar	24.9	9.7	17.3	38	10	131	23.7	10.4	17.1	66	8	115
Apr	25.1	11.1	18.1	47	30	131	25.7	12.1	18.9	66	17	128
May	24.9	12.1	18.5	46	21	141	28.4	13.0	20.7	51	36	151
Jun	25.2	12.2	18.7	44	41	132	29.9	16.7	23.3	43	32	156
Jul	21.8	11.8	16.8	68	194	114	28.1	18.2	23.2	59	67	146
Aug	22.0	11.8	16.9	71	162	113	27.3	17.2	22.3	62	110	132
Sep	23.2	10.8	17.0	52	16	114	28.3	15.7	22.0	49	38	127
Oct	21.5	9.8	15.7	56	13	104	24.9	11.2	18.1	60	17	110
Nov	21.3	8.5	14.9	59	25	78	22.3	10.5	16.4	74	10	77
Dec	21.9	7.5	14.7	52	5	76	20.8	8.9	14.9	78	4	64

	Barentu (moist lowland)						Fagena (sub-humid)					
	temperature °C						temperature °C					
month	max.	min.	mean	RH (%)	rainfall (mm)	PET (mm)	max	min	mean	RH (%)	rainfall (mm)	PET (mm)
Jan	32.5	14.8	23.7	45	0	126	18.2	11.2	14.7	n.a	103	57
Feb	31.1	14.6	22.9	40	0	133	19.2	11.6	15.4	n.a	123	63
Mar	35.0	16.1	25.6	37	1	173	20.5	12.7	16.6	n.a	66	87
Apr	37.3	18.8	28.1	36	10	191	23.0	14.4	18.7	n.a	55	107
May	37.5	19.1	28.3	36	22	207	26.1	16.6	21.4	n.a	48	140
Jun	34.0	17.0	25.5	41	74	183	29.0	19.7	24.4	n.a	22	172
Jul	30.3	17.8	24.1	65	142	144	27.0	18.4	22.7	n.a	125	157
Aug	29.1	17.0	23.1	69	178	134	27.3	18.4	22.9	n.a	120	157
Sep	32.0	17.1	24.6	55	78	149	27.6	18.2	22.9	n.a	57	143
Oct	34.3	18.0	26.2	47	8	176	23.7	15.0	19.4	n.a	120	109
Nov	34.0	17.0	25.5	49	3	130	20.4	13.1	16.8	n.a	87	72
Dec	32.3	15.7	24.0	48	0	116	18.4	11.9	15.2	n.a	122	56

	Keren (arid lowland)						Massawa (semi-desert)					
	temperature °C						temperature °C					
month	max.	min.	mean	RH (%)	rainfall (mm)	PET (mm)	max.	min.	mean	RH (%)	rainfall (mm)	PET (mm)
Jan	28.7	12.4	20.6	48	0	119	28.3	22.7	25.5	74	30	108
Feb	29.9	12.8	21.4	42	0	131	27.9	22.6	25.3	76	31	99
Mar	31.6	15.2	23.4	38	2	165	29.5	23.9	26.7	73	17	143
Apr	33.8	16.9	25.4	34	20	177	31.6	25.7	28.7	72	14	168
May	34.8	17.7	26.3	30	29	179	33.8	27.8	30.8	66	6	184
Jun	33.3	16.7	25.0	37	58	171	36.7	29.1	32.9	53	0	194
Jul	28.6	16.9	22.8	56	138	128	37.7	31.2	34.5	53	5	203
Aug	27.3	16.3	21.8	68	150	105	37.8	31.6	34.7	56	7	228
Sep	30.5	15.0	22.8	49	52	129	36.1	29.9	33.0	60	3	195
Oct	31.6	15.5	23.6	34	3	149	33.8	28.1	31.0	62	15	170
Nov	29.9	14.9	22.4	40	4	117	31.5	25.4	28.5	68	18	129
Dec	29.0	13.3	21.2	45	0	108	29.4	23.7	26.6	72	35	112

Source: Civil Aviation Authority, Asmara, Eritrea.* RH, relative humidity, PET, potential evapotranspiration.

	station					
	Asmara	Nakfa	Keren	Barentu	Fagena	Massawa
altitude (m)	2325	1676	1460	1000	1760	10
nr of years for rainfall	50	18	21	47	27	27
nr of years for others data	20	15	14	8	11	27

Appendix 3 Regression equations describing the relationship between altitude and temperature in Eritrea.

minimum temperature (^{o}C)	=	25.3–(0.007 * altitude m a.s.l.)
maximum temperature (^{o}C)	=	36.8–(0.005 * altitude m a.s.l.)
mean temperature (^{o}C)	=	31.0-(0.006 * altitude m a.s.l.)
mean potential evapotranspiration (mm)	=	2069-(0.198 * altitude m a.s.l.)

Source: FAO, 1997.

Appendix 4 *Conversion table of altitude to temperature based on regression equations given in* Appendix 3.

altitude (m a.s.l.)	temperature ^{o}C		
	minimum	maximum	mean
0	25.3	36.7	31.0
200	24.1	35.5	29.8
400	22.9	34.3	28.6
600	21.6	33.0	27.3
800	20.4	31.8	26.1
1000	19.2	30.6	24.9
1200	18.0	29.4	23.7
1400	16.8	28.2	22.5
1600	15.5	26.9	21.2
1800	14.3	25.7	20.0
2000	13.1	24.5	18.8
2200	11.9	23.3	17.6
2400	10.7	22.1	16.4
2600	9.4	20.8	15.1
2800	8.2	19.6	13.9
3000	7.0	18.4	12.7
3200	5.8	17.2	11.5

Appendix 5 The past and present occurrence of *Boswellia papyrifera* in the different regions, sub-regions and villages of Eritrea. For each village, the major agroecological zone and units, altitude, mean annual rainfall, dependable length of growing period (DLGP) and potential evapotranspiration (PET) are given. The + and – signs represent the presence or absence of the species. The AEZ and AEU are agroecological zone and agroecological zone units, respectively.

region	sub-region	village	AEZ	AEU	altitude (m a.s.l.)	rainfall (mm)	PET (mm)	DLGP (days)	occurrence	
									past	present
Anseba	Aditekelezan	Aditekelezan	MH	MH5	2000	507	1673	75	-	-
		Dek mahre	MH	MH5	2200	507	1633	75	-	-
		Ira	MH	MH5	2400	507	1594	75	-	-
	Asmat	Asmat	ArH	ArH1	1800	348	1713	30	-	-
		Ascend	ArL	ArL3	1400	200	1792	15	-	-
		Orota	ArL	ArL7	1590	348	1754	15	-	-
	Elabered	Debresina	MH	MH5	2400	507	1594	75	-	-
		Eden	ArL	ArL5	1489	510	1774	45	+	+
		Ferhen	ArL	MH5	1620	510	1748	45	+	+
		H-Mentel	ArL	ArL5	1468	510	1778	45	+	-
		Seleba	MH	MH5	2049	510	1663	75	-	-
	Gheleb	Ghati	MH	MH5	2000	507	1673	75	-	-
	Habero	Arotay	ArL	ArL5	1590	375	1754	45	+	-
		Gizgiza	ArL	ArL5	1600	460	1752	45	+	+
	Hagaz	Ashera	ArL	ArL5	856	428	1900	45	+	-
		Beggu	ArL	ArL5	1145	428	1842	45	+	-
		Hagaz	ArL	ArL5	880	428	1895	45	+	-
	Halhal	Gengeren	ArH	ArH1	1600	450	1752	45	+	+
		Halahal	ArH	ArH1	1800	450	1713	45	+	+
		Melebso	ArH	ArH1	2000	348	1673	30	-	-
	Keren	Areway	MH	MH5	1700	500	1732	75	+	+
		Fredareb	MH	MH5	1600	500	1752	75	+	+
		Lalmba	ArH	ArH1	2000	500	1673	30	-	-
		Sebab	ArL	ArL5	1409	454	1790	45	+	+
	Kerkebet	Dali	ArL	ArL12	849	100	1901	15	-	-
		Homib	SD	SD10	500	100	1970	0	-	-
		Kerkebet	ArL	ArL3	419	200	1986	15	-	-
		Keru	ArL	ArL12	600	200	1950	15	-	-
		Sawa	SD	SD11	600	100	1950	0	-	-
	Selea	Hndbit	ArL	Arl4	1100	300	1851	15	-	-
Centre	Berik	A-Ghebru	MH	MH1	2300	530	1614	75	-	-
		T-kristian	MH	MH4	2100	530	1653	80	-	-

		Tseazega	MH	MH1	2190	530	1635	75	-	-
	GalaNefhi	Aquadad	MH	MH2	2300	550	1614	75	-	-
		Merhano	MH	MH7	2200	530	1633	75	-	-
	Seregeka	Asheka	MH	MH1	2519	550	1570	75	-	-
		Defere	MH	MH1	1890	550	1695	75	-	-
		Gshnashim	MH	MH1	2150	550	1643	75	-	-
		ShemaN	MH	MH1	2399	550	1594	75	-	-
		Shmangus	MH	MH1	2195	550	1634	75	-	-
		Zager	MH	MH1	2600	550	1554	75	-	-
Gash-Barka	Barentu	Barentu	ML	ML2	1127	516	1846	75	+	-
		Dasse	ML	ML3	1000	516	1871	70	+	+
	Forto	Fmogoraib	ArL	ArL6	600	100	1950	15	-	-
		Girmayka	SD	SD10	800	100	1911	0	-	-
	Gonge	Gogne	ML	ML2	850	600	1901	70	+	-
	Haykota	Hykota	ML	ML3	850	600	1901	70	+	-
	Laelay-Gash	Deda-laelay	ML	ML3	1000	700	1871	70	+	+
		Mchconte	ML	ML3	850	700	1901	70	+	+
		Sheshebit	ML	ML3	1000	700	1871	70	+	+
		Shilalo	ML	ML3	1000	700	1871	70	+	+
		Tokombya	ML	ML2	850	700	1901	70	+	+
	Logo-anseba	Debri	MH	MH6	2000	650	1673	95	-	-
		Mekerka	MH	MH6	2200	650	1633	95	-	-
	Mensura	Aderde	ArL	ArL2	727	400	1925	15	-	-
		Duluk	ArL	ArL1	900	450	1891	45	+	-
		Gerger	ArL	ArL5	1200	400	1831	45	+	-
		Mensura	ArL	ArL1	900	450	1891	45	+	-
	Mogolo	Askobo	ML	ML3	1000	550	1871	70	+	+
		Mogolo	ArL	ArL2	800	400	1911	15	-	-
	Mogoraib	Dige	ArL	ArL3	700	200	1930	15	-	-
	Molki	Alekebya	ML	ML7	1600	600	1752	75	+	+
		Ddoran	ML	ML7	1400	600	1792	75	+	+
		Faulina	ML	ML7	1000	600	1871	75	+	+
		Mai-Lam	ML	ML7	1200	600	1831	75	+	+
	Omhager	Antore	ML	ML3	850	700	1901	70	+	+
		Goly	ML	ML1	850	550	1901	70	+	-
		Hamad	ML	ML1	900	550	1891	70	+	-
		Omhager	ML	ML2	850	700	1901	70	+	-
	Shambuco	Binbina	ML	ML2	889	600	1893	70	+	-
		Shambuco	ML	ML2	1000	600	1871	75	+	+
	Tekloy	Akurdet	ArL	Ar12	700	303	1930	15	-	-
	Tesenay	Alebu	ArL	ArL12	600	309	1950	15	-	-

		Alighedir	ArL	Ar12	600	309	1950	15	-	-
		Teseney	ArL	ArL12	628	309	1945	15	-	-
Debub	Adi-Keih	Awhine	MH	MH3	2239	508	1626	75	-	-
		Kuatit	MH	MH7	2000	560	1673	75	-	-
	Adi-Quala	Atawen	MH	MH6	1800	612	1713	95	+	+
		Betetsion	MH	MH9	2000	612	1673	95	-	-
		May-Tsebri	ML	ML5	1400	612	1792	75	+	-
		Sebu	ML	ML5	1600	612	1752	75	+	+
	Areza	Asherefeto	MH	MH6	2000	606	1673	95	-	-
		Areza	MH	MH6	1920	606	1689	95	-	-
		Endakrstos	MH	MH6	1700	703	1732	95	+	+
		Mai-Dima	ML	ML5	1500	703	1772	75	+	-
	Debarwa	Amadir	MH	MH6	1940	583	1685	95	-	-
		Halhale	MH	MH9	1950	583	1683	95	-	-
		Sheketi	MH	MH4	2100	600	1653	80	-	-
	Decemhare	Korbaria	MH	MH2	2021	600	1669	75	-	-
	Kudoabur	Fchkonte	MH	MH6	1700	700	1732	95	+	-
		Kudoabur	MH	MH6	1900	700	1693	95	-	-
		MLeham	MH	MH6	2100	700	1653	95	-	-
	Mai-aini	Adi-Barin	ML	MH7	1900	430	1693	75	-	-
		Knafna	ML	ML5	1575	430	1757	75	+	-
		Kuatit	MH	MH7	1911	500	1691	75	-	-
	Mai-Mine	Adichigono	ML	ML7	1400	694	1792	75	+	+
		Adi-Gelae	MH	MH6	1690	694	1734	95	+	+
		Adi-Ketina	MH	MH6	1700	694	1732	95	+	+
		Berekit	MH	MH6	1800	694	1713	95	+	-
		Dabre	MH	MH6	2000	694	1673	95	-	-
		Kuhli-Zbei	MH	MH6	1600	694	1752	95	+	+
	Mendefera	Mendefera	MH	MH9	1900	574	1693	100	-	-
	Senafe	Abunambs	MH1	MH3	2600	654	1554	75	-	-
		Agara	MH	MH3	2800	654	1515	75	-	-
		Ambeset	MH	MH3	2364	654	1601	75	-	-
		Mneksyto	MH	MH3	2181	654	1637	75	-	-
		Senafe	MH	MH3	2343	654	1605	75	-	-
		Soira	MH	MH3	3000	654	1475	75	-	-
	Tsorona	Chealo	ML	MH7	1910	491	1691	75	-	-
		Unaandom	MH	MH7	1900	491	1693	75	-	-
	Segeneiti	Afelba	MH	MH2	2221	830	1629	75	-	-
		Akrur	MH	MH7	1900	831	1693	75	-	-
		Digssa	MH	MH7	2165	831	1640	75	-	-

Appendix 6 Methods of soil analysis

type of analysis	method used
bulk density	core sampling method using a steel cylinder, length 5 cm, diameter 5 cm
soil texture	sand fraction by sieving; silt and clay fraction by hydrometer method
pH	determined by glass electrode in 1:1 soil water suspension
organic matter	Walkley and Black wet oxidation method.
available P	Olsen method
exchangeable Na and K	by flame photometry
exchangeable Ca and Mg	atomic absorption method
electrical conductivity	Wheatstone conductance bridge; measurements in 1:1 soil water suspension

Appendix 7 List of plant species found along the altitude range covered by the *Boswellia papyrifera* micro-distribution study.

scientific name	altitude range											
	800-900	900-1000	1000-1100	1100-1200	1200-1300	1300-1400	1400-1500	1500-1600	1600-1700	1700-1800	1800-1900	1900-2000
Acacia asak	-	-	-	-	+	-	-	-	-	-	-	-
Acacia etbaica	-	-	-	-	-	-	-	+	+	+	+	+
Acacia mellifera	-	-	-	+	+	+	+	-	+	+	-	-
Acacia nubica	-	+	-	+	-	-	-	+	+	-	-	-
Acacia senegal	+	-	+	+	+	+	+	+	+	-	-	-
Acacia seyal	+	+	+	+	+	+	+	+	+	-	-	-
Acacia tortilis	-	-	-	+	-	-	-	+	+	+	+	+
Adansonia digitata	-	-	-	+	-	-	-	+	-	-	-	-
Aerva lanata	-	+	-	-	-	-	-	-	-	-	+	+
Albizia amara	-	+	+	+	+	-	+	+	+	+	+	+
Albizia anthelmenthica	-	-	-	-	-	-	-	-	+	+	-	-
Anogeissus leiocarpus	-	-	-	+	-	-	-	-	+	-	-	+
Balanites aegyptiaca	+	+	-	+	+	+	-	-	+	+	-	-
Boscia salicifolia	-	-	-	-	-	+	-	-	+	-	+	-
Boscia ungustifolia	+	+	-	-	+	-	+	+	+	+	-	+
Boswellia papyrifera	+	+	+	+	+	+	+	+	+	+	+	-
Buddlja polystchya	-	-	-	-	-	-	-	-	-	-	+	-
Cassia singueana	-	-	-	-	-	-	-	-	+	+	+	+
Cissus quadrangularis	-	-	-	-	-	-	-	+	+	-	-	+
Combretum acleatum	-	-	-	+	-	+	-	-	-	-	-	-
Combretum ghalensis	+	+	+	+	-	+	+	-	+	+	+	-
Combretum molle	-	-	-	-	-	-	-	-	+	-	-	-
Commiphora africana	-	-	-	-	+	-	-	-	+	+	+	+
Dalbergia melanoxylon	+	+	+	-	+	+	+	+	+	+	-	-
Dichrostachys cinerea	-	+	-	+	+	+	+	-	+	+	+	+
Dodonea ungustifolia	-	+	-	-	-	-	-	-	+	+	+	+
Ehretia cymosas	-	-	-	-	-	-	-	-	-	+	-	-
Erythrina abyssinica	-	-	-	-	-	-	-	-	+	-	+	-
Euclea schimperi	-	-	-	-	-	-	-	-	+	-	-	-
Euphorbia candelabrum	-	-	-	-	-	-	-	-	+	-	+	-
Ficus glumosa	-	-	-	-	-	-	-	-	+	-	-	-
Ficus vasta	-	-	-	-	-	-	-	-	+	-	-	-
Flueggia virosa	-	-	-	-	-	-	-	-	-	-	+	-
Grewia flavescens	-	-	-	+	+	+	+	-	+	+	+	-

Grewia mollis	-	-	-	+	+	-	-	-	-	-	-	-
Grewia villosa	-	-	-	+	+	+	-	-	+	+	-	-
Hibiscus michranthus	-	-	-	-	+	+	+	-	+	+	-	-
Justica sp.	-	-	-	-	-	-	-	-	-	-	-	+
Lanea fruticosa	+	+	+	-	+	-	-	-	+	+	+	+
Maerua angolensis	-	-	-	-	-	-	-	-	+	+	-	-
Maytenus senegalensis	-	-	-	-	-	-	-	-	-	+	+	-
Maytenus undata	-	-	-	-	-	-	-	-	+	-	-	-
Olea africana	-	-	-	-	-	-	-	-	-	-	+	-
Omocarpum pubescense	-	-	-	-	-	-	+	-	+	+	+	-
Otostagia fruticosa	-	-	-	-	-	-	-	-	+	+	+	-
Otostagia integrifolia	-	-	-	-	-	-	-	-	-	-	+	-
Ozorain signis	-	-	-	-	-	+	-	-	+	+	+	+
Pterolobium stellatum	-	-	-	-	-	-	-	-	+	+	-	-
Rhus natalenisis	-	-	-	-	-	-	-	-	-	+	-	+
Solanum michranthum	-	-	-	-	+	-	-	+	+	+	+	+
Steganotaenia araliacea	-	-	-	-	-	-	-	-	-	-	+	-
Sterculia africana	+	+	+	+	+	+	-	-	+	+	+	-
Stereospermum kunthianum	-	-	-	-	-	-	-	-	+	+	-	-
Tamarindus indica	-	-	-	+	-	-	-	-	-	-	-	-
Terminalia brewnii	-	+	-	+	+	+	+	+	+	+	+	+
Vangueria madagascarensis	-	-	-	-	-	-	-	-	-	+	-	+
Ximenia americana	-	-	-	-	-	-	-	-	+	-	-	+
Ziziphus spina christi	-	-	-	+	-	-	-	-	-	-	+	-

Appendix 8 Effect of tapping intensity on flowering, seed production and seed viability (germination %) of *Boswellia papyrifera* trees in different diameter classes-at three sites in Eritrea.

location	nr of tapping points	0			6			12		
	DBH(cm)	10	20	30	10	20	30	10	20	30
Adi -Ketina	inflorescence	17.0	25.6	51.0	13.8	20.2	43.8	10.4	16.4	33.8
	fruits/inflorescence	20.0	28.6	21.8	11.9	17.7	15.2	9.4	12.1	12.6
	nr of fruits	604.8	746.8	843.0	467.4	591.6	681.2	358.0	477.8	528.2
	nr of seeds	1814.4	2240.4	2529.0	1402.2	1774.8	2043.6	1074.0	1433.4	1584.6
	seed length (mm)	22.2	22.3	22.7	21.4	21.6	21.6	19.5	19.5	19.3
	seed width (mm)	8.9	8.6	8.7	8.5	8.5	8.4	8.1	8.1	7.7
	seed mass (g)	22.8	23.9	24.7	17.5	18.8	19.7	15.4	15.7	17.9
	germination (%)	79.6	80.0	81.8	59.0	60.6	61.8	44.8	45.0	45.8
Atawen	inflorescences	19.8	24.2	51.6	15.4	18.4	45.4	12.8	15.8	30.0
	fruits/inflorescence	18.3	25.8	27.2	14.7	17.3	19.8	9.7	11.4	14.5
	nr of fruits	693.2	748.0	1306.0	491.0	634.2	1140.0	387.0	543.2	900.0
	nr of seeds	2079.6	2244.0	3918.0	1473.0	1902.6	3420.0	1161.0	1629.6	2700.0
	seed length (mm)	26.3	26.0	26.1	24.9	24.7	24.9	21.5	21.4	20.8
	seed width (mm)	8.8	8.4	8.6	7.9	8.1	8.6	7.8	7.7	7.6
	seed mass (g)	27.0	28.4	29.1	20.3	22.4	24.2	14.8	16.1	17.3
	germination (%)	92.0	92.6	93.6	60.4	61.4	63.2	38.4	39.8	40.4
Ferhen	inflorescences	11.0	19.0	28.6	7.4	13.8	20.6	7.2	13.6	21.0
	fruits/inflorescence	11.6	17.4	19.4	6.7	10.5	11.3	3.4	4.2	6.0
	nr of fruits	341.0	455.0	544.2	263.0	403.4	460.0	203.8	296.0	377.6
	nr of seeds	1023.0	1365.0	1632.6	789.0	1210.2	1380.0	611.4	888.0	1132.8
	seed length (mm)	19.7	19.6	19.6	19.1	19.2	19.1	18.6	18.8	18.8
	seed width (mm)	7.8	7.6	7.6	7.2	7.1	7.3	7.1	6.8	6.9
	seed mass (g)	15.2	16.3	17.2	13.3	14.1	15.8	12.3	13.6	14.2
	germination (%)	15.6	15.8	16.6	9.4	9.8	10.6	9.0	9.6	11.0

Appendix 9 Statistical analysis of the effects of tapping intensity and stem diameter on flowering, seed production and seed viability (germination %) at three sites in Eritrea. Two way ANOVA ns = P>0.5, * P<0.05, ** <0.001, *** p<0.001.

study area	reproductive characteristics	dbh (cm) F	dbh (cm) P	tapping F	tapping P	tapping * dbh F	tapping * dbh P	r^2
Atawen	Inflorescence/tree	850.4	***	158.6	***	27.8	***	0.98
	fruits/inflorescence	46.0	***	163.9	***	4.2	***	0.92
	number of fruits/tree	324.1	***	77.3	***	3.4	*	0.96
	seed length	0.3	ns	70.4	***	0.2	ns	0.79
	seed width	1.5	ns	25.6	***	3.3	*	0.65
	seed mass	39.8	***	751.7	***	1.7	ns	0.98
	germination	3.4	*	2133.0	***	2.0	ns	0.99
Adi-Ketina	Inflorescence/tree	954.8	***	125.0	***	11.1	***	0.98
	fruits/inflorescence	27.1	***	129.2	***	4.3	***	0.90
	number of fruits/tree	85.2	***	149.4	***	1.0	ns	0.92
	seed length	0.2	ns	73.8	***	0.5	ns	0.80
	seed width	2.3	ns	30.9	***	0.8	ns	0.66
	seed mass	14.8	***	180.4	***	6.0	ns	0.91
	germination	2.6	ns	813.0	***	0.2	ns	0.98
Ferhen	inflorescence/tree	316.6	***	60.0	***	2.8	*	0.95
	fruits/inflorescence	57.7	***	295.8	***	6.6	***	0.95
	number of fruits/tree	187.0	***	120.6	***	1.3	ns	0.95
	seed length	0.2	ns	37.2	***	0.4	ns	0.67
	seed width	2.8	ns	59.3	***	1.3	ns	0.78
	seed mass	28.8	***	55.3	***	0.6	ns	0.82
	germination	3.3	*	78.3	***	0.2	ns	0.82

Appendix 10 Long–term perspectives for the development of *Boswellia papyrifera* in Eritrea

What should be done to alleviate regeneration constraints?

In areas with adequate supply of viable seeds, grazing is the main factor limiting regeneration of *Boswellia papyrifera*. In view of the slow seedling growth, long-term measures are needed to protect germinants, seedlings, and probably saplings, from grazing. Establishment of enclosures in many ways is a promising approach towards that end provided grazing is strictly implemented over a long period. The length of this period has still to be determined. In view of the observed high mortality of germinants during the first growing season, additional measures are also needed to improve the regeneration sites. Such measures include the construction of soil and water conservation structures on hillsides to reduce erosion and conserve moisture into the soil.

In areas unaffected by livestock grazing, lack of viable seeds due to tapping is the major cause for lack of recruitment. Tapping through its effects on the various reproductive characteristics of *Boswellia papyrifera* trees disrupts the regeneration process at the seed production stage. The mechanism by which tapping affects the seed production is not yet understood. The physiological basis should be further investigated.

Given the economic and social importance of the tree and its potential for watershed protection in an area where erosion is severe, *Boswellia papyrifera* is a candidate not only for conservation but also for afforestation. So far, no attempt has been made to domesticate the species. All the frankincense harvest comes entirely from naturally growing trees. This study has demonstrated that there are sufficient indications that the species might go extinct at local level. If the present exploitation continues, it is likely that the species will soon disappear even from the remaining Boswellia stands.

In order to avoid this undesirable situation from happening, there is a dire need for intervention. In this respect, four major areas where intervention are proposed:

- restoration of the woodland from areas where it has disappeared,
- rehabilitation of existing *Boswellia papyrifera* stands through spontaneous regeneration,
- integration of *Boswellia papyrifera* in the farming systems, and
- security of land and tree tenure.

a. Restoration of the original Boswellia woodland

In areas where isolated trees and stands still exist measures are need to be taken to restore the original *Boswellia papyrifera* woodland by taking these stands as nucleus for expansion. In order for the vegetation succession to proceed, these areas should be protected against livestock grazing. Moreover, the local environment should be improved by constructing soil and water conservation structures in the hills so as to reduce runoff and enhance the infiltration of water in the soil. Since the restoration of the original vegetation take many years before tangible economic benefits could be obtained, this strategy should be taken as a long-term project aiming at biodiversity and environmental protection.

b. Rehabilitation of Existing *Boswellia papyrifera* woodlands

In most cases, the natural regeneration of indigenous vegetation is enhanced if the remaining forests of an area are conserved and massive efforts are made to rehabilitate the degraded vegetation (Teketay 1996, Haile et al. 1998). The success of such regeneration strategy largely depends on our understanding of the underlying ecological factors that affect the regeneration process of the species concerned. In many cases, the exclusions of all forms of biotic pressure from an area have proven successful in restoring the natural plant succession and subsequent establishments of plant cover (Prasad and Pandey 1989). Area closure from livestock has positive effects on the rehabilitation of degraded lands through plant succession and natural regeneration. The physical, chemical and biological properties of the soil in enclosed area is improved and provides a favourable growing conditions for plants growing there (Namdeo et al. 1989, Bendz 1990).

Area closure alone does not necessarily bring a successful regeneration of Boswellia stands. Even if the remaining stands are enclosed, lack of viable seeds caused by intensive tapping still remains a serious problem. Hence, area closure in combination with a less intensive tapping practices should be introduced. Area closure is a straightforward action, the regulation of the tapping regimes, however, is more complex. This is because of difficulties arising over the control of tapping intensity for every plant. To be able to control the present tapping practices reasonably, a rotation tapping should be introduced. The length of the tapping cycle and also the number of tapping points per tree should be further investigated. In any event, over-tapping should be prohibited. The control over the current tapping practice should be able to allow trees produce viable seeds to compensate for the loss incurred during the tapping period.

The problem of migrant workers in tapping trees should be re-considered. The conflicting interest between migrant workers and the local community should be addressed seriously. The desire by the migrant workers to maximise gum collection without considering the well being of the Boswellia trees on one hand and the reluctant attitude of local communities towards the species (because of lack of incentive) calls for a new tree tenure arrangement and change in the collection and the commercialisation of frankincense as a whole.

c. Integration of *Boswellia papyrifera* in the farming systems

Since the abundance and distribution of Boswellia stands in Eritrea is declining, it is difficult to maintain the current supply of frankincense for local consumption and export. If the current exploitation continues, it is likely that the species would even disappear. In this respect an alternative measure i.e. agroforestry intervention is needed so as to integrate the species into the farming system. This means a gradual domestication of the species. According to Simons (1997), the idea of domestication is to identify and improve agroforestry trees species according to farmers and market demands and to make the planting material available to farmers.

The development of any crop for domestic or commercial purpose and especially for the latter ultimately depends on its market potential (Booth and Wickens 1988, Leakey and Newton 1994, Simons 1994, 1997). The fact that *Boswellia papyrifera* is already a cash generating tree is a sufficient ground to justify for its integration in the farming system. What in general trigger domestication is not clearly known. In most cases, it is argued that increased commercialisation of non-timber forest product leads to depletion, which may promote domestication or deforestation (Godoy et al. 1993). This is true for products with no tenurial right of indigenous communities (Homma 1992). Godoy et al. (1993) underlines that in areas with high population pressure, even the traditional harvesting techniques of non-timber products could deplete forest resources. Generally goods extracted for export and sale outside the village are more likely to be depleted than good extracted for local consumption (Godoy et al. 1993). Some gum is locally consumed as frankincense, most of the product is exported

To complement to the naturally growing Boswellia trees and through to enhance the domestication process, Boswellia tree planting at farm level should be initiated. This could be done at various places (1) on the edge of agricultural areas, (2) on land less suitable for cultivation. This intervention has both economic and environmental benefits. Economically, the extraction and prudent marketing of the plants increases the income of rural communities (Godoy et al. 1993) through the sale of frankincense and provision of nectar for bees during dry season. Environmentally, appropriate and well-managed agroforestry systems have the potential to: control runoff and erosion, maintain soil organic matter and physical properties; and promote nutrient cycling and efficient nutrient use (Baumer 1990, Young 1997).

Boswellia papyrifera is a multipurpose perennial tree species that has already the above stated qualities. Its present economic benefits generated from the sale of frankincense makes it attractive to farmers for its integration in the farming system. It grows in dry and marginal areas that are less suitable for arable crop production and avoids the competition for arable land. To this end, there is adequate information on its germination requirements and early seedling growth and development. These silvicultural knowledge should be used to raise seedlings needed for planting.

d. Security of land and tree tenure

The various traditional land tenure systems in Eritrea all have detrimental effects on the conservation of the natural forests in general and of Boswellia woodland in particular. In these land tenure systems, the tree tenure is not explicitly indicated. In all cases, trees within a holding belong to the land holder but that is not the case for the exploitation of Boswellia trees. The problem of land tenure and ownership of trees is a fundamental one for agro forestry intervention (Baumer 1990, Zeeuw 1995).

Land re-distribution every 5-7 years (dessa system) discourages the landholder to make long-term investment such as planting of trees. Increasing population pressure in most areas with this kind of land tenure system has lead to unscrupulous cutting of the vegetation. The new land law that has been promulgated in 1994 provides lifelong ownership of land and in principle, it is expected to replace the old land tenure systems.

Baumer (1990) noted that, if the tree in a field automatically belongs to the owner of that field, there is no problem. But in most cases ownership of trees is complex and poses a serious setbacks to the integration of trees in the farming systems. In the case of *Boswellia papyrifera* tree ownership, land ownership itself does not allow farmers to exploit gum from Boswellia trees even within their holdings. This is mainly because Boswellia trees are legally owned and exploited by licensed concessionaires. In this respect, the land tenure reform and the existing *Boswellia papyrifera* tree tenure system should be re-evaluated in such a way that ensures a sustainable exploitation of the species. Ideally, the old tree tenure should be replaced by a new one that guarantees individuals or community based ownership of trees. The transfer of Boswellia tree ownership from a concession system to individual or household based tenure, is a positive step towards a sustainable management. If local communities are expected to participate in the conservation and eventual integration in the farming system, the communities residing in the vicinity of Boswellia woodlands should be beneficiaries of the species. It is believed that this would bring a change in attitude of the local communities towards the species.

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Summary

Boswellia papyrifera is a deciduous, gum producing multipurpose tree species, that grows in a savanna belt that stretches from northern Nigeria eastwards till it reaches the highlands of Ethiopia and Eritrea. The trees are tapped on the stem for an oleo-gum called olibanum (true frankincense). Despite its economic importance *Boswellia papyrifera* is a threatened species in Eritrea. The natural Boswellia woodlands are converted into agricultural fields while unregulated grazing hinders the natural regeneration. In part this happens because the local population has no interest in protecting trees which under the prevailing regulations may only be tapped by concessionaires. It goes without saying that before effective measures can be taken to prevent the species from disappearance, information will be needed on its present distribution and ecological requirements, population structure and natural regeneration, and on the factors and processes leading to the decline of the Boswellia population. The research presented in this paper was undertaken to provide this information.

The distribution of *Boswellia papyrifera* was investigated both at macro and micro level. The macro-level study showed that the geographical distribution of *Boswellia papyrifera* is limited to areas in the southwestern and southern part of the country. Here it is found in areas between 800 and 1850 m a.s.l., with a mean annual rainfall between 375 and 750 mm and a dependable length of growing period (DLGP) of 45 – 100 days. The mean annual maximum and mean minimum temperatures corresponding with the higher altitude limit are about 25 and 14°C respectively and with the lower altitude limit about 32 and 20°C. Based on a survey including 113 villages it was found that the probability of the occurrence of *Boswellia papyrifera* increases to a value of 1 when mean annual maximum and minimum temperatures reach values higher than 30 and 18°C respectively, the annual rainfall is at least 500 mm. and the DLGP exceeds 60 days. The above mentioned climatic limits are subject to the prevailing conditions in south western Eritrea. They explain why *Boswellia papyrifera* has not spread into and across the central highlands (too low minimum temperatures) and into the arid lowlands (lack of rainfall), but they cannot be considered as absolute limits. The macro distribution study has confirmed the general idea that the Boswellia area has decreased over the last 50 years. Especially in the transition zone between the moist and arid lowland agroecological zone, the species has probably disappeared as a result of a combination of population pressure and recurrent droughts.

The micro distribution study was conducted at three highland sites (altitude between 1600 and 2000 m) and two lowland sites (altitude between 800 and 1600 m) with Boswellia woodlands. To cover the whole altitude range, at each site 20 x 20 m sample plots were placed at 100 m altitude intervals parallel to the contour lines. Results from observations on 144 plots indicated that the main environmental factors locally affecting the distribution and

abundance of the species are in order of importance altitude, land use intensity, soil organic matter content and slope angle and to a lesser extent also silt content and pH of the soil. At the three highland sites, the abundance decreased with altitude while the reverse trend was observed at the lowland sites. At all sites, the abundance decreased with increasing land use intensity. As land use is linked with local topographic features the abundance of Boswellia increased with slope angle and from valley bottoms to hill and mountain tops, which are unsuitable for crop production and not accessible to livestock. Soil organic matter and silt content had positive effects on population density and pH (mainly ranging from 8.5 to 7.0) had a negative effect.

After the studies on the occurrence and abundance of *Boswellia papyrifera* at regional and site level, tree growth and population structure were studied in different environments. As a general trend it was found that at earlier stages of development *Boswellia papyrifera* invests more of its biomass in height and crown depth and at a later stage in stem diameter growth. This can be considered as a strategy to shorten the time that the species might be subject to livestock browsing. The observations on mature trees showed that growth is strongly affected by altitude. The maximum tree height at the lowland sites was twice the value found at the highland sites. Furthermore, a strong negative linear relationship was found between mean tree height and crown depth and altitude. This suggests that the species grows better in the warm moist lowlands than in the moist highlands.

The most important outcome of the population study is the lack of natural regeneration of *Boswellia papyrifera.* In almost all stands of the five study-areas seedlings and saplings were absent and only larger trees were found. Only at two sites with untapped trees recruitment was found in plots not accessible for or closed to livestock. This prompted further research on the effects of grazing and tapping on regeneration.

The effect of grazing is well illustrated by the observations that at one of the research sites 280 germinants per ha were found in the non-grazed plots versus 12 in the grazed plots. Detailed population studies revealed that also in the non-grazed plots about 60 % of the seedlings died during the first year. Tree mortality was found to decrease with increasing basal diameter, and found to be substantially reduced when a diameter of 3 cm is reached. Three years of field observations revealed that most seedlings remained in the same basal diameter class during this period, illustrating that it will take several years before seedlings reach the low mortality stage.

The tapping studies at stand level clearly showed that tapped trees hardly produced viable seeds. Most seeds were empty and most of the filled ones failed to germinate. Observations on individual trees indicated that tapping resulted in a reduction in inflorescence, the number of fruits, seed mass and seed viability. When tapping was resumed after a resting period this effect was directly apparent. The germination percentage

immediately dropped from over 90 % in the control trees to about 60 % in trees tapped at six points and to 40 % in trees tapped at 12 points. These percentages are still high enough to produce recruitment. Annually tapped trees, however, produced hardly any viable seeds. With germination rates of about five percent and a high seedling mortality, tapped trees apparently cannot provide recruitment. How tapping affects flowering, fruit and seed production and seed viability is not yet known. It is likely that competition for assimilates for gum production and for generative growth and seed filling is involved. The favourable effect of non-tapping periods suggests, however, that tapping regimes can be developed in which acceptable levels of gum and viable-seed production can be combined. A practical solution for the lack of viable-seed production in the existing stands could be to retain untapped mother trees as a seed source for recruitment.

The main conclusions are that:

- Because of climatic conditions the occurrence of *Boswellia papyrifera* is restricted to the southwestern and southern part of Eritrea. Within this region a more or less continuous area of Boswellia woodland exists in the moist lowland- and moist highland agroecological zones. In addition a small, isolated Boswellia area exists further north in the arid highland zone, while the species has disappeared from the transition zone between the moist lowlands and arid highlands.

- The future existence of the natural Boswellia woodlands is threatened for two reasons: (1) a reduction in area as a result of land clearing for agriculture, a process which under the present concession-based exploitation system leads to complete removal of Boswellia trees, (2) a lack of natural regeneration in the remaining Boswellia stands. The present system of intensive annual tapping throughout the dry season, leads to low production of mainly non-viable seeds and where viable seeds are produced, seedlings and saplings usually are destroyed by livestock.

- Establishment of enclosures in which no tapping and grazing is allowed was found to be an effective measure to reintroduce and promote natural regeneration in existing Boswellia woodlands.

Based on these conclusions the following recommendations were made:

- As the land clearing problem and its underlying causes can not be solved in the near future, practical measures and research efforts should be directed towards solving the regeneration problem. Given the promising results of the enclosure system further research is needed to make this system operational in terms of the required length and frequency of the non-tapping period and the duration of the non-grazing period.

- At the same time has to be investigated whether or not retention of untapped mother trees as permanent seed source for recruitment and the introduction of a cut and carry grass harvesting system are feasible and acceptable alternatives for a comprehensive ban on tapping and grazing.
- As a second priority attention should be paid to the replanting of former Boswellia areas. This requires, amongst others, identification of high gum-yielding mother trees for seed supply and selection of suitable replanting areas.
- Given the urgency of the Boswellia problem and the size of the research programme, the establishment of a special Boswellia research and development unit is strongly recommended

Samenvatting

Boswellia papyrifera is een bladverliezende boomsoort, voorkomend in de savannegordel, die van Noord Nigeria tot aan de hooglanden van Ethiopië en Eritrea loopt. De stam van de boom wordt getapt voor een gom, die wierook levert. Ondanks het grote economische belang van de gomproductie, is *Boswellia papyrifera* een bedreigde boomsoort: de natuurlijke Boswellia vegetatie moet plaats maken voor landbouwgewassen, terwijl begrazing de natuurlijke verjonging verhindert. Ten dele komt dit doordat alleen concessiehouders de bomen mogen tappen en de boeren er derhalve geen belang bij hebben om de bomen te beschermen. Alvorens maatregelen kunnen worden genomen om het verdwijnen van Boswellia tegen te gaan, zal inzicht moeten worden verkregen in de verspreiding en de ecologische niche van *Boswellia papyrifera*, in de populatie-opbouw en de verjonging van de natuurlijke vegetatie en de processen die tot de achteruitgang ervan leiden. Het onderzoek dat in deze publicatie is vastgelegd, had ten doel om deze kennis te verschaffen.

De verspreiding van *Boswellia papyrifera* werd op macro- en op microschaal bestudeerd. Op macroniveau werd geconstateerd dat de geografische verspreiding van de soort beperkt is tot gebieden in het zuidwesten en het zuiden van het land. Hier komt Boswellia voor in gebieden op 800 – 1850 m. boven zeeniveau, met een gemiddelde jaarlijkse regenval tussen 350 en 750 mm en een betrouwbaar groeiseizoen van 45 tot 100 dagen. De gemiddelde jaarlijkse maximum- en minimum temperaturen die met de boven- en benedengrens van de hoogteligging overeenkomen, bedragen respectievelijk 32 en 20 °C. Een onderzoek waarin 113 dorpen in drie provinciën werden bezocht, liet zien dat de waarschijnlijkheid van het voorkomen van *Boswellia papyrifera* de waarde 1 haalde wanneer de gemiddelde jaarlijkse maximum- en minimum temperaturen respectievelijk boven de 30 en 18 °C lagen en de gemiddelde jaarlijkse regenval minimaal 500 mm en de lengte van het groeiseizoen minimaal 60 dagen bedroeg. Deze klimaatsgrenzen weerspiegelen de omstandigheden in Eritrea. Ze laten zien waarom *Boswellia papyrifera* zich niet in en over het hoogland heen (te lage minimum temperaturen) oostwaarts heeft kunnen uitbreiden en ook niet in noordelijke richting (vanwege te lage regenval), maar zij kunnen niet als absolute grenzen worden opgevat. De macrostudie heeft voorts bevestigd dat het Boswellia areaal de laatste 50 jaar sterk is afgenomen en dat Boswellia vrijwel geheel verdwenen is in het overgangsgebied tussen de "moist lowland" en "arid lowland" agro-ecologische zone.

De studie over de verspreiding op microniveau werd uitgevoerd op vijf locaties met Boswellia vegetatie, drie in het hoogland (gelegen tussen 1600 en 2000 m boven zeeniveau) en twee in het laagland (gelegen tussen 800 en 1600 m boven zeeniveau)Om per locatie het gehele hoogtetraject in het onderzoek te betrekken, werden per 100 meter hoogteverschil, evenwijdig aan de hoogtelijnen bemonsteringsvelden van 20 x 20 m gemarkeerd. De resultaten van 144 velden lieten zien dat op lokaal niveau de verspreiding van Boswellia in volgorde van belangrijkheid bepaald wordt door de hoogteligging, het landgebruik, het organische-stofgehalte van de bovengrond, en de hellingshoek van het terrein en in zekere mate ook door de textuur en de zuurgraad van de bodem. Op de hooglandlocaties nam het aantal Boswellia bomen af met de hoogteligging terwijl het omgekeerde het geval was op de laaglandlocaties. Op alle locaties nam het aantal Boswellia bomen af met toenemende intensiteit van het landgebruik. Aangezien het landgebruik verband houdt met de topografie was het aantal Boswellia bomen het grootst op steile hellingen en op heuvel- en bergtoppen, die ongeschikt zijn voor landbouw en onbereikbaar voor vee. Het organische-stofgehalte en het siltgehalte van de bovengrond had een positief effect en de pH (binnen het traject van 8.5 – 7.0) een negatief effect op het aantal Boswellia bomen.

Na de studies over het voorkomen en de dichtheid van *Boswellia papyrifera* op regionaal en plaatselijk niveau, werd op de reeds genoemde locaties de groei en ontwikkeling van Boswellia bomen bestudeerd. Hierbij werd gevonden dat aanvankelijk vooral lengtegroei en verticale kroonontwikkeling plaatsvindt en pas in een later stadium de diktegroei van de stam. De maximale boomhoogte was op de laaglandlocaties twee keer zo groot als op de hooglandlocaties. Voorts werd een uitgesproken, significante negatieve lineaire relatie gevonden tussen de hoogte en kroondiepte van de bomen en de hoogteligging. Dit wijst er op dat de bomen beter in het warme, vochtige laagland groeien dan in het koele hoogland.

De belangrijkste uitkomst van het onderzoek naar de populatieopbouw van de natuurlijke Boswellia vegetatie was het ontbreken van natuurlijke verjonging. Op de vijf locaties werden alleen grote bomen maar geen zaailingen aangetroffen. Slechts op twee locaties werd op plaatsen, waar de bomen niet getapt werden en waar het vee niet kon doordringen, natuurlijke verjonging gevonden. Deze constatering was de aanleiding om de invloed van begrazing en van tappen op het regeneratieproces nader te onderzoeken.

Begrazing bleek een sterke negatieve invloed te hebben op de natuurlijke verjonging. Zo werden op één van de onderzoekslocaties in niet-begraasde terreinen 280 zaailingen per ha aangetroffen tegenover 12 op begraasde velden. Gedetailleerde populatiestudies toonden aan dat ook bij afwezigheid van begrazing meer dan 60 procent van de zaailingen in het eerste levensjaar dood gingen. De zaailingensterfte nam daarna af en was vrijwel verdwenen wanneer de stamdiameter 3 cm bedroeg. Veldwaarnemingen over een periode van drie jaar lieten zien dat het enige jaren duurt voordat dit stadium wordt bereikt.

Getapte bomen bleken bijna geen kiemkrachtige zaden te produceren. De meeste zaden bleken leeg te zijn, terwijl de gevulde zaden niet kiemden. Waarnemingen aan individuele bomen toonden aan dat tappen leidde tot aanleg van minder bloeiwijzen, een geringer aantal vruchten, tot lichtere zaden en afname van de kiemkracht. Ook wanneer bomen na een rustperiode opnieuw getapt werden, trad dit verschijnsel op. Na het op nieuw in tap nemen, liep het kiemingspercentage, dat bij zaden van niet getapte bomen boven de 90 % lag, terug tot 60 % bij bomen die op zes punten en tot 40 % bij bomen die op 12 punten werden aangesneden. Deze percentages zijn waarschijnlijk voldoende om verjonging mogelijk te maken, maar dit is niet het geval bij bomen die jaarlijks worden getapt. Deze produceerden weinig zaden waarvan slechts ongeveer 5 % kiemkrachtig was, terwijl onder veldomstandigheden de overlevingskans van zaailingen minder dan 40 % bleek te zijn. Hoe tappen de bloei, de zaadproductie en de kiemkracht beïnvloedt is nog niet bekend. Waarschijnlijk is er sprake van concurrentie tussen gomproductie enerzijds en generatieve groei en zaadvulling anderzijds. Het gunstige effect van taprust lijkt er te wijzen dat tapsystemen kunnen worden ontwikkeld waarbij de productie van gom en van kiemkrachtige zaden in evenwicht zijn. Het aanhouden van een voldoende aantal niet-getapte bomen voor zaadproductie zou een andere mogelijkheid kunnen zijn om het regeneratievraagstuk op te lossen.

De belangrijkste conclusies van het onderzoek zijn de volgende:

- Klimatologische omstandigheden beperken het voorkomen van *Boswellia papyrifera* tot het zuidwesten en zuiden van Eritrea. In het gebied, dat tot het vochtig laagland en het vochtig hoogland gerekend wordt, ligt een min of meer continue Boswellia vegetatiezone. Verder noordwaarts ligt in het droge hoogland een klein Boswellia gebied, dat geisoleerd is geraakt van de zuidelijke zone, doordat Boswellia in het overgangsgebied van het vochtige- naar het droge laagland verdwenen is.

- De toekomst van de natuurlijke Boswellia vegetatie wordt bedreigd door het oprukkende landbouwfront en door het ontbreken van natuurlijke verjonging. Dit laatste komt omdat intensief getapte bomen geen kiemkrachtige zaden leveren en de zaailingen onder niet-getapte bomen door het grazende vee gedood of beschadigd worden.

- Het instellen van z.g. gesloten gebieden, waarin niet getapt mag worden en geen vee mag grazen, blijkt een effectieve maatregel te zijn om de natuurlijke verjonging te herstellen.

Op grond van deze conclusies worden de volgende aanbevelingen gedaan:

- Aangezien op korte termijn geen oplossing kan worden gevonden voor het verdwijnen van Boswellia tengevolge van landontginning, zal het onderzoek zich allereerst moeten richten op het verjongingsvraagstuk. Gezien het succes van het instellen van gesloten gebieden moet nagegaan worden hoe lang de taprust en de daarop volgende tapperiode moet zijn om de zaadproductie op peil te houden. Voorts moet bepaald worden hoe lang het graasverbod moet gelden.
- Tegelijkertijd moet onderzocht worden of het aanhouden van enkele niet getapte bomen voor zaadproductie en het invoeren van een "cut and carry" gras-oogstsysteem een algeheel tap- en graasverbod kunnen vervangen.
- Als tweede prioriteit zal aandacht besteed moeten worden aan de herbeplanting van vroegere Boswellia velden. Dit houdt o.a. in: selectie van moederbomen voor zaadproductie en het uitzoeken van terreinen die geschikt zijn voor herbeplanting.
- Gezien de urgentie en de veelzijdigheid van het Boswellia vraagstuk, wordt tenslotte aanbevolen om een speciale Boswellia onderzoekseenheid in het leven te roepen.

Curriculum Vitae

Woldeselassie Ogbazghi Temnewo was born on 12 August 1958 in Ropto, Eritrea. He received his primary education in his home village, and his secondary education at Keren and Asmara (1973-1981). In 1981, he was admitted to the University of Asmara. After graduation in 1985, he worked as a graduate assistant and later as an assistant lecturer in the same University (1985-1987). In 1988-1989 he completed his Diplôme d'Etude Approfondi (DEA) in Tropical Plant Biology at the University of Pierre Marie Curie (Paris VI), France.

From January 1990-1995, he was a lecturer and head of the department of Soil and Water Conservation, College of Agriculture and Aquatic Sciences of the University of Asmara. During this period, he participated in various professional ad-hoc committees of the University. In 1993 he attended a course on irrigation and soil management in Bet-Dagan, Israel and in 1995 a course on a remote sensing at the University of Stockholm.

From 1994-1996, he was a member of a research team on rehabilitation of degraded lands in Eritrea sponsored by IDRC, Canada. From September 1996 to September 2000 he investigated the distribution and regeneration of *Boswellia papyrifera*. The results of this research are given in this thesis.

Woldeselassie Ogbazghi Temnewo is married and father of two sons and two daughters.