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Natural regeneration and bark production in Prunus Africana (Hook.F.) Kalkman (Rosaceae) and its sustainable utilization and conservation in Kenya

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NATURAL REGENERATION AND BARK PRODUCTION IN *PRUNUS*

AFRICANA (HOOK.F.) KALKMAN (ROSACEAE) AND ITS

SUSTAINABLE UTILIZATION AND CONSERVATION IN KENYA

ELIUD KIPLIMO KIREGER

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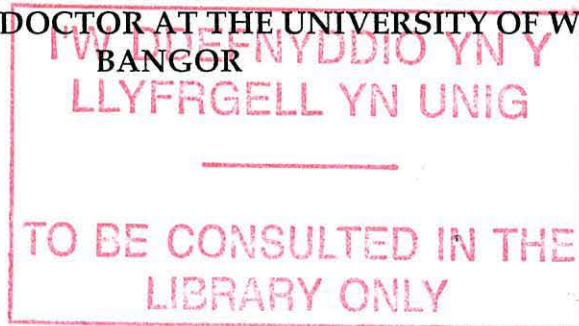
SCHOOL OF AGRICULTURE AND FOREST SCIENCES, UNIVERSITY
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APRIL 2003

DECLARATION

ABSTRACT

Studies on natural regeneration and bark production in *Prunus africana* were carried out in Kenya to provide basic information required to develop guidelines for sustainable utilization and conservation of the species. The objectives were: to analyse patterns of population structure; to develop an understanding of the effect of herbivory and disease infection on natural regeneration; and to assess available quantities of ecological sustainable bark yield per tree and characteristics that could influence it.

The results showed that the population density is relatively low and a high proportion of trees are greater than 20 cm diameter. *Prunus africana* was most abundant along forest edges and on forest patches. The average density of trees was 6 trees/ha. The spatial pattern was clumped, and linked to gap creation. Size structure suggests that *Prunus africana*'s recruitment is episodic and is dependent on canopy openings. Disease infection and herbivore damage was higher closer to parent trees where seedling density was high, and decreased with increasing distance away from the parent trees. Mortality of seedlings in *Prunus africana* is very high; the number of seedlings present at each stage decreases as the seedlings develop from one stage to another. This evidence is consistent with the Janzen-Connell model describing the spacing out of recruitment (away from parent trees) through the action of density- or distance responsive herbivores or pathogens. However, the hypothesis is too simple to determine the final recruitment pattern in *Prunus africana*.

Populations of *Prunus africana* growing in open habitats have thicker bark compared to those in closed canopy forests. The mean bark yield per tree was 75.81 kg in closed canopy forest and 73.38 kg in open farmland. Tree diameter and bark thickness are the best estimators of bark yield. However, variability in tree form between different habitats may require separate equations for accurate predictions. The ability of *Prunus africana* to withstand bark damage offers the potential for sustainable harvesting.

It is recommended that a full-scale inventory and resource assessment of *Prunus africana* be done in Kenya and harvesting regulations and quotas should be developed and enforced to achieve sustainability. To promote the recovery of *Prunus africana* populations in harvested area, interventions should include opening the canopy around, and clearing the undergrowth beneath seed bearing trees. More research work is necessary to assess the correlation between bark production and bark quality; the influence of tree-fall gaps on spatial patterns of recruitment; the best sustainable bark harvesting techniques; minimum exploitable diameter and intervals for sustainable bark harvesting in Kenya.

DEDICATION

To my wife Vivian, to my children, Jepchumba, Jepleting and Kigen who endured the pains of loneliness for prolonged periods while I was away for studies.

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My first and foremost appreciation goes to Dr. J.B. Hall, my supervisor, for his advice, guidance and supervision throughout my study period.

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Special thanks go to Moi University for granting me the leave to study under the sponsorship of Association of Commonwealth Universities; without this financial support I may not have had this opportunity.

I would like to extend my appreciation to my college colleagues, academic staff and whoever contributed in one way or another toward the completion of this thesis.

The moral support of and courage given by my colleagues at Moi University, Kenya in general makes my thanks incomplete without mentioning.

Last but not by any means least, I wish to gratefully remember the sacrifices my wife made to keep the family together while I was away in UK. My wife's understanding during my study has been without limit, and I cannot thank her enough.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANOVA   Analysis of Variance

BKR   Relative Bark Thickness

BPH   Benign Prostatic Hyperplasia

BKT   Bark Thickness

CERUT   Centre for Environment and Transformation

CITES   Convention of International Trade of Endangere Species of

             fauna and flora

DBH   Diameter at Breast Height

EU   European Union

GOK   Government of Kenya

ICRAF   International Centre for Research in Agroforestry

IUCN   International Union for Conservation of Nature

KEFRI   Kenya Forestry Research Institute

KEMRI   Kenya Medical Research Institute

KIFCON   Kenya Indigenous Forestry Conservation projec

KWS   Kenya Wildlife Service

NAS   National Academy of Sciences

PRC   Population Recruitment Curve

UNCED   United Nations Conference on Environment and Development

WHO   World Health Organization

WWF   World Wide Fund for Nature

CHAPTER I

GENERAL INTRODUCTION

This chapter provides a general background to the research reported in this thesis. It highlights problems associated with dwindling forest resources in Kenya, identifies gaps in knowledge on regeneration and exploitation of *Prunus africana* for bark and how domestication and cultivation makes a promising sustainable management system. Finally, the general research objectives of the thesis are outlined.

1.1 Background

Kenya is located on the equator in East Africa, and has a total land area of 932,230 km², which includes about 17120 km² of lake area (principally Lakes Victoria and Turkana). The land rises gradually from the Indian Ocean coast in the south-east to about 1800 m some 500 km inland where the Great Rift Valley divides the country from north to south. The Great Rift Valley is about 70 km wide and 300 m deep with precipitous walls in some parts. The land slopes gradually to the lake Victoria shore at 1070 m on the west of the Rift Valley. There are the mountain masses of Mt. Kenya (5199 m) and Aberdare Range (3964 m) to the east of the Rift Valley, and the Mau Range (3097 m), and Mt. Elgon (4321 m) to the west.

More than half of Kenya in the north and northeastern parts, and also the southern section of the Rift Valley, is composed of arid and semi-arid land. Most of the

western part of the country, and the higher land (from 1370 m to 2740 m) in the central part receive good rainfall and are fertile areas. The mountain slopes and these areas of high rainfall can support a dense natural high forests cover, some of which has been cleared for settlement and agriculture.

Kenya's indigenous forests support a wide range of species, although most recent studies have concentrated on trees and shrubs, and birds and mammals of weight over 500 g. According to KIFCON (1994), the number of higher plants in Kenya is 6000, of which approximately 200 are tree and shrub species. An estimated 50% of Kenya's woody species are found in the forests. According to IUCN there are over 100 rare woody plants (of which 36 are trees), 35 birds and 17 larger mammals that are both forest-dependent and 'threatened'.

These indigenous forests provide not only wood products, but also a wide range of non-wood products for local use and for international trade. The non-wood products extracted from the forests are diverse and have traditionally been used for subsistence; however there has been a sudden increase in the extraction of medicinal plants for cash income.

The use of plant and animal products for human and animal medicines is widespread among almost all communities. For example, in the area around Arabuko Sokoke at the Kenyan coast, up to 108 forest species are regularly used for medicinal purposes (Lukandu, 1991). Sixty-four species are used by the Mau Forest

dwellers (Lubanga, 1991). Some 58 species are exploited nationally for their bark (Kokwaro, 1976), ten of these within South West Mau (Mutangah *et al.*, 1993), for medicine, weaving basketry, beehive covers, and other uses.

The worldwide revival of interest in herbal medicine is putting intense pressure on tropical biodiversity as increasing numbers of species and individuals are harvested for their medicinal properties. *Prunus africana* (Hook.f.) Kalkman (Rosaceae); (Syn. *Pygeum africanum)* is one of these important medicinal trees.

Prunus africana is geographically widespread although restricted to Afromontane 'islands' (White, 1983) in mainland tropical Africa and mountainous outlying islands. Medicinal products using *Prunus africana* bark extract, including Tadenan (marketed in France) and Pigenil (marketed in Italy), are used in the treatment of benign prostatic hyperplasia (Bombardelli & Morazzoni, 1997; Morandola *et al.*, 1997). An annual international trade of about 220 million US dollars in the final pharmaceutical product (1997 figures: Cunningham *et al.*, 1998) is involved.
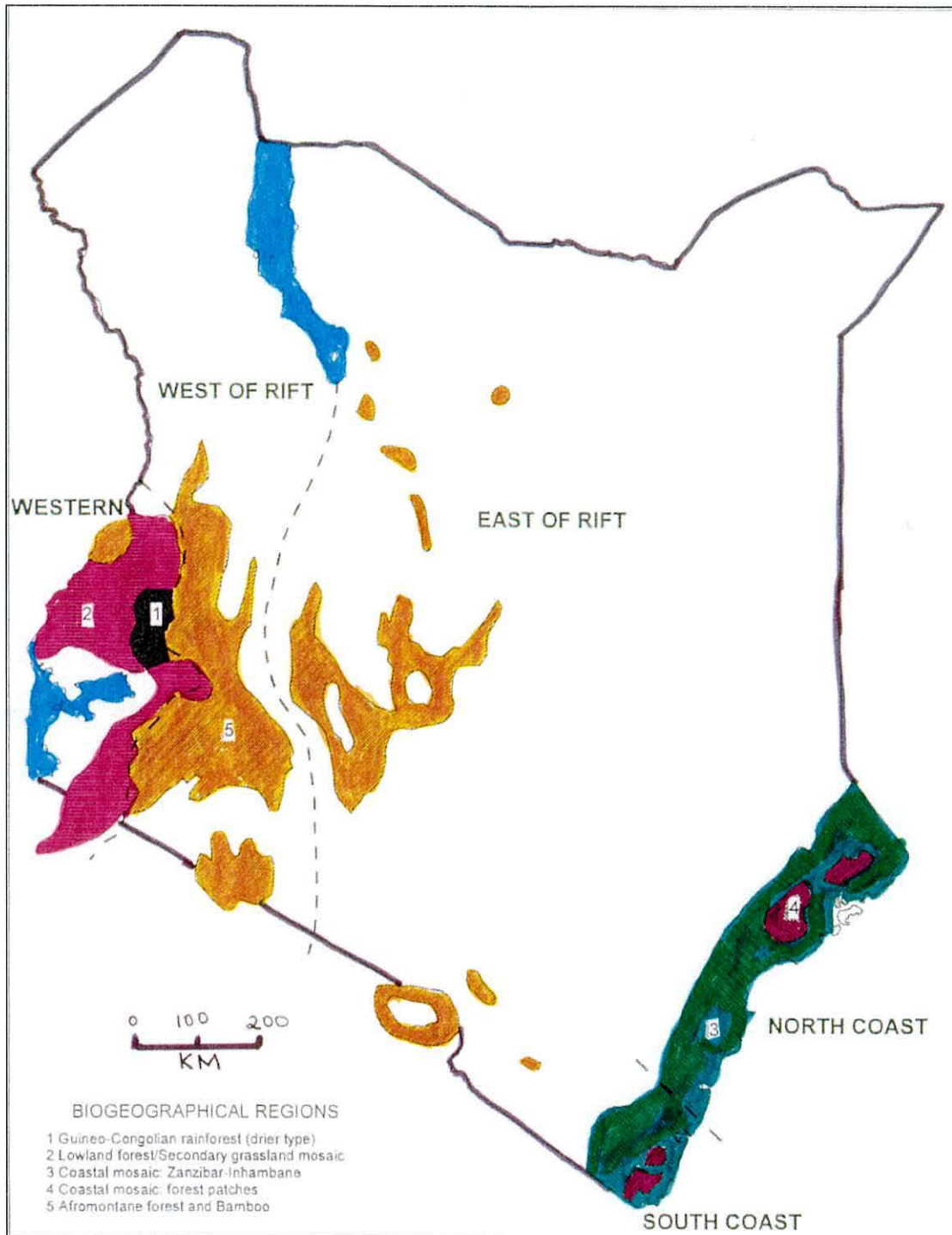
Figure 1 Map of Kenya showing distribution of Afromontane forests where *Prunus africana* is found

At least four European companies have an interest in *Prunus africana* bark for medicinal purposes, and some twenty others are involved in production and sale of herbal preparations containing *Prunus* bark extract (Cunningham *et al.*, 1997).

Marketed products generally refer to the tree as *Pygeum*, the name now relegated to synonymy.

The market for *Prunus* products is large, as is the market for alternatives. In Europe, products from *Prunus africana* and nettle root (*Urtica urens* Linn. Urticaceae) are most popular. In the United States, saw palmetto (*Serenoa repens* (Batram) small Arecaceae) fruit extract and pumpkin (*Cucurbita pepo, L Cucurbitaceae*) seeds) are most often used. It is currently anticipated that one of every two men in western countries will live beyond eighty years, and that 88% could develop histological evidence of benign prostatic hypertrophy (Cunningham, 1999). Although surgery is commonly performed and effective, it is expensive and can cause impotence. Medical therapy and phytotherapy are popular alternatives.

Prunus africana is not only a source of medicine for patients, but also an important source of income for local and national economies. The economic market for the medicine is presently ensured by the difficulty of artificial synthesis. Due to the bark's synergistic chemical composition, the medicinal activity is not completely understood and natural production offers the only source of the medicine (Andro, 1995).

The use of this medicine first came to the attention of European industry from the earlier traditional employment of the bark in warm milk in South Africa to treat

"old man's disease" (Hamilton, 1996). *Prunus africana* is, in fact, a widely used medicinal tree in many parts of Africa. Currently, bark or extracts from the bark, are exported to Europe in significant quantities from Kenya, Cameroon, Equatorial Guinea and Madagascar. To meet this demand, about 4000 tonnes of bark is collected annually by destructive felling of trees from natural stands, and awareness of this has led to concern for the long-term sustainability of harvesting and conservation of this and associated Afromontane species (Cunningham *et al.* 1998). As a result, *Prunus africana* has been listed as endangered under Appendix II of the Convention of International Trade in Endangered Species of wild fauna and flora (CITES), and alternative species of *Prunus* with similar medicinal properties are being sought (Dawson &Powell, 1999). Despite sustainable methods (removing only a narrow panel of the bark from standing trees) that allow *Prunus africana* to produce harvests of bark but continue living, the high profits and difficulty of finding the trees lead harvesters to cut down increasingly smaller trees to maximize what is collected. Destructive harvesting by felling trees and stripping all bark has become increasingly common (Plate 1). This kind of harvesting of all the mature (seed producing trees) threatens the natural regeneration process and the natural resource base in collection areas. Over-exploitation of the species, combined with the restricted distribution of the Afromontane forests where it grows, means that *Prunus africana* is officially classified as an endangered species (Dawson & Powel, 1999).

When *Prunus africana* was added to Appendix II of CITES, the Kenyan government quickly acted to ban the exploitation of the species. However, the ban was waived for the land clearance programmes approved by the government. This accounts for most of what Kenya has exported.

Plate 1. A *Prunus africana* tree that has been ring barked in Kakamega Forest, western Kenya

Data on the quantities of *Prunus africana* involved in local or national trade are very scanty. However, records from the National Agricultural Laboratories, Nairobi

indicate that 400 metric tonnes of dried *Prunus africana* bark are exported to France at a price of $2 per kilo earning $80,000 per annum. Benefits to local harvesters remain small, however, in comparison with the global market value. In late 1996, the price of *Prunus africana* extract at the Indera Spa factory in Italy was US $ 966 per kilogram (ICRAF, 1997). At present, most *Prunus africana* based products are sold within the European Union and not in the potentially large and lucrative markets of North America and Japan. Sales of *Prunus africana* bark also take place in Sweden, and Australia (Cunningham *et al.*, 1997). According to the same authors, demand for *Prunus africana* bark can be expected to increase if the Food and Drug Administration regulations of the USA and Canada are changed to favour sales of *Prunus africana* derived products, reinforcing the pressure on the species' resource base.

It is expected that with the rising incidence of prostate problems, reflecting an ageing population, and growing confidence in natural medicines, the market for *Prunus africana* remedies could double or triple in the next few years.

The sustainability of harvesting *Prunus africana* bark in Kenya is of concern, particularly with continued forest clearing and selective exploitation of the species. Conservation issues associated with *Prunus africana* collection in Kenya are:

• there is little or no published data on exploitation rates (timber and bark etc) in Kenya, and on its regeneration both natural and artificial,

- it has limited geographical range limited to the Afromontane forests and that the bark is being harvested faster than the trees can grow to supply the demand,

- that it is causing degradation and in some cases loss, of an important ecosystem (wet Afromontane forests), vital for catchment protection,

- that it is eroding genetic diversity within *Prunus africana* and even eliminating local populations.

The need for conservation, domestication and development of sustainable production systems, such as are possible through agroforestry, has been recommended if the loss of this vital resource is to be checked. Reforestation and forest enrichment with *Prunus africana* could offer an ideal combination of conservation and sustainable utilization. With appropriate management, the value of the forest could increase so that their sustainable use and conservation would become more economically valuable than their destruction (Acworth *et al.*, 1999). A few small plantations occur in Kenya. Up to 1992, 65 stands of *Prunus africana* had been established in Kenya, with a total area of 628 ha. Successful extensive planting of *Prunus africana* will require fundamental ecological information. A review of literature and unpublished knowledge and experiences in Kenya exposed that, despite the local, national and international importance of the tree, little is known about its ecology and virtually nothing on bark characteristics. Limited extensive planting of *Prunus africana* in Kenya reflects this lack of ecological information. Thousands of wildings have been taken out of the forest and potted in nurseries or transplanted only to die because of unsuitable ecological conditions.

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This study is a contribution towards the understanding of the ecology and bark characteristics of Kenyan *Prunus africana* as a basis for achieving sustainable utilization and conservation of the species. Incorporating important elements of the tree's ecological niche into nurseries and reforestation sites may allow future efforts to succeed. In addition, baseline data have been gathered on regeneration, population structure and density, as these are fundamental to understanding and monitoring of the species' status and trends.

1.2 Objectives

The overall objective of this study was to gain an understanding of bark production; the ecological characteristics playing a role in the success of seedling establishment and survival, and to establish baseline data on population status in forests in Kenya. These, is hoped, will reinforce current efforts to establish nurseries, restore depleted forests, promote domestication of the species, and offer guidance for monitoring and management.

CHAPTER II

A REVIEW OF THE CURRENT STATE OF KNOWLEDGE OF *PRUNUS AFRICANA* IN EASTERN AFRICA WITH EMPHASIS ON KENYA

The aim of this review is to provide the current state of knowledge of *Prunus africana* that may influence its regeneration, bark production and conservation in Kenya. Thus the chapter reviews geographic distribution of the species, climatic requirements, reproductive biology, pests and diseases, population statistics, economic importance and management. The chapter also presents an overview of trade in medicinal plants, and specifically in *Prunus africana*, conservation issues relating to trade in medicinal plants in general and *Prunus africana* in particular, and domestication of *Prunus africana*.

2.1 Description and distribution of the species

2.1.1 Description of the species

Prunus africana (Hook.f.) Kalkman, Rosaceae (Syn.*Pygeum africana* Hook.f.,) is a long lived tree which may grow to a height of more than 40 m and a diameter exceeding 1 m (Cunningham *et al.*, 1998). It is indigenous to Africa and Madagascar. Fichtl & Adi, (1994), describe *Prunus africana* as a tall evergreen forest tree with cylindrical, very straight and clean bole (Plate 2.1a). The bark is rough, dark brown, sometimes scaling irregularly into squares, branches are brown and corky, branchlets dotted with prominent lencticels. (Plate 2.1b). Leaves are

glaborous, glossy green, elleptic to oblong and 5 to 15 cm long with toothed margins, and they have a slight but distinct smell of bitter almonds (Plate 2.1c). Flowers are small, creamy white, and fragrant, arranged in racemes in clusters in the leaf axils. Its fruit is a drupe, round, and up to 1 cm in diameter, dark red when ripe, extremely bitter and contains one or two seeds (Plate 2.1d).

2.1.2 Geographic distribution

Prunus africana is characteristic of the Afromontane forests of tropical Africa. However the range extends beyond the Tropic of Capricorn almost to the southern limit of the continent. At these higher latitudes the species is present in evergreen forest at low altitudes (<500 m). The distribution pattern is extremely fragmented, with occurrence in 'islands' in highlands of eastern, central and southern Africa from Ethiopia to South Africa and with western outliers in Cameroon, Nigeria, Angola, Sao Tome and Equatorial Guinea (Bioko). It is also present on the mountains of Madagascar and Grand Comore (Cunningham & Mbenkun, 1993).

Plates 2.1a-d. A *Prunus africana* tree; the bark of *P. africana* tree; three year-old *P. africana* seedlings; and freshly harvested *P. africana* seeds respectively, all in Nandi district, Kenya

Plate 2.1a.

Plate 2.1b.

Plate 2.1c.
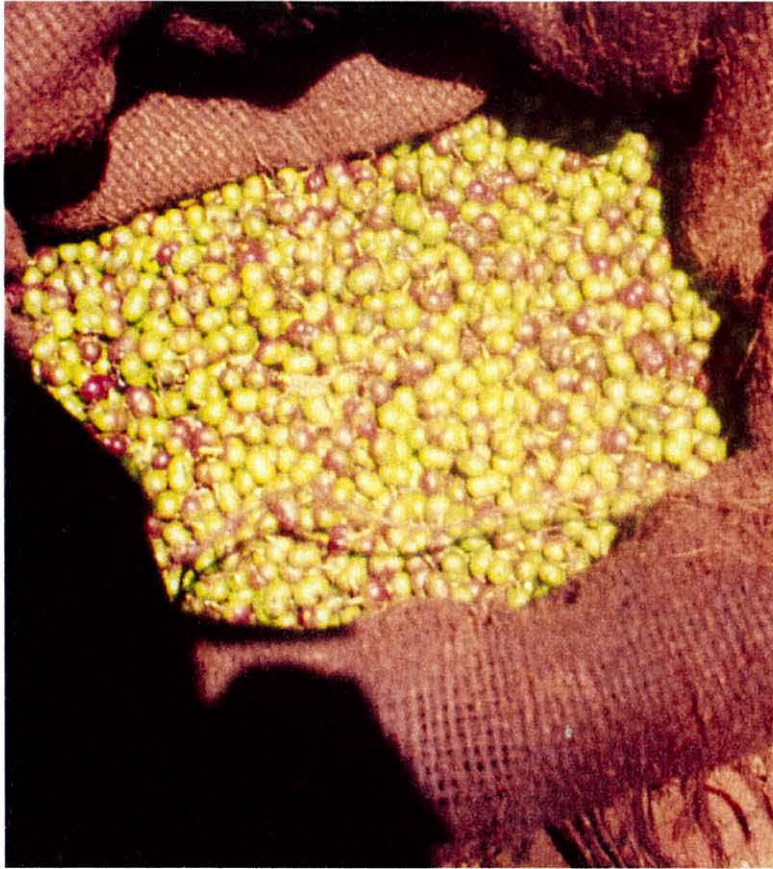
Plate2 .1d.

In eastern Africa *Prunus africana* occurs in Kenya, Uganda, Tanzania, Ethiopia, Sudan, Rwanda, Burundi and Democratic Republic of Congo (Figure 2.1).

In Kenya *Prunus africana* occurs in the highland forests of Mt. Kenya, the Aberdare Range, Tugen hills, Mau Range, Timboroa forest, Cherangani hills, Mt. Elgon, Kakamega and Nandi forests (Schaefer, 1990). In the drier areas, it grows on isolated moist hills in Taita hills, Chyulu hills, Mt. Kulal. Mt. Nyiru, Mathews Range and Marsabit. It also grows well in riparian forests and in clumps or as isolated trees in the grasslands of the Kenyan highlands. Isolated trees are also found in live fences on farms in western Kenya and in the Kenyan highlands (Plate 2.1a).

Prunus africana is light demanding and often associated with the forest edge. Geldenhuys, (1981) concluded it was an early secondary successional species in the Bloukrans River Gorge, Southern Cape forests of South Africa. Seedling establishment in the wild in Mount Cameroon is excellent in areas of forest where there is good light penetration to the floor (Ndam, 1998), and fertile well-drained soil (Iversen, 1993). Form varies- in forest, the high foliage is open and the branches are often pendulous, but in grassland habitats the crown is more rounded and compact (Mbuya *et al.* 1994).

Reported early growth, early flowering and association with disturbance (Eggeling, 1940, Geldenhuys, 1981) are consistent with White's (1983a) listing as a "nomad". A combination of nomadic behaviour and extended longevity explains why *Prunus africana* so often occurs as sparsely distributed large individuals in closed forest communities (Hall *et al.*, 2003).

In its natural habitat, the species is associated with a large variety of species. For example in Kenya, it is associated with *Podocarpus falcatus* (Thunb.) Mirb. Podocapaceae, *Polyscias kikuyuensis* summerhayes Araliaceae, *Cassipourea molasana* Alston Rhizophoraceae, *Celtis africana* Burm.f Urticaeae, *Albizia gummifera* C.A. Smith Leguminosae, *Aningeria spp.* Sapotaceae among others (Albrecht, 1993).
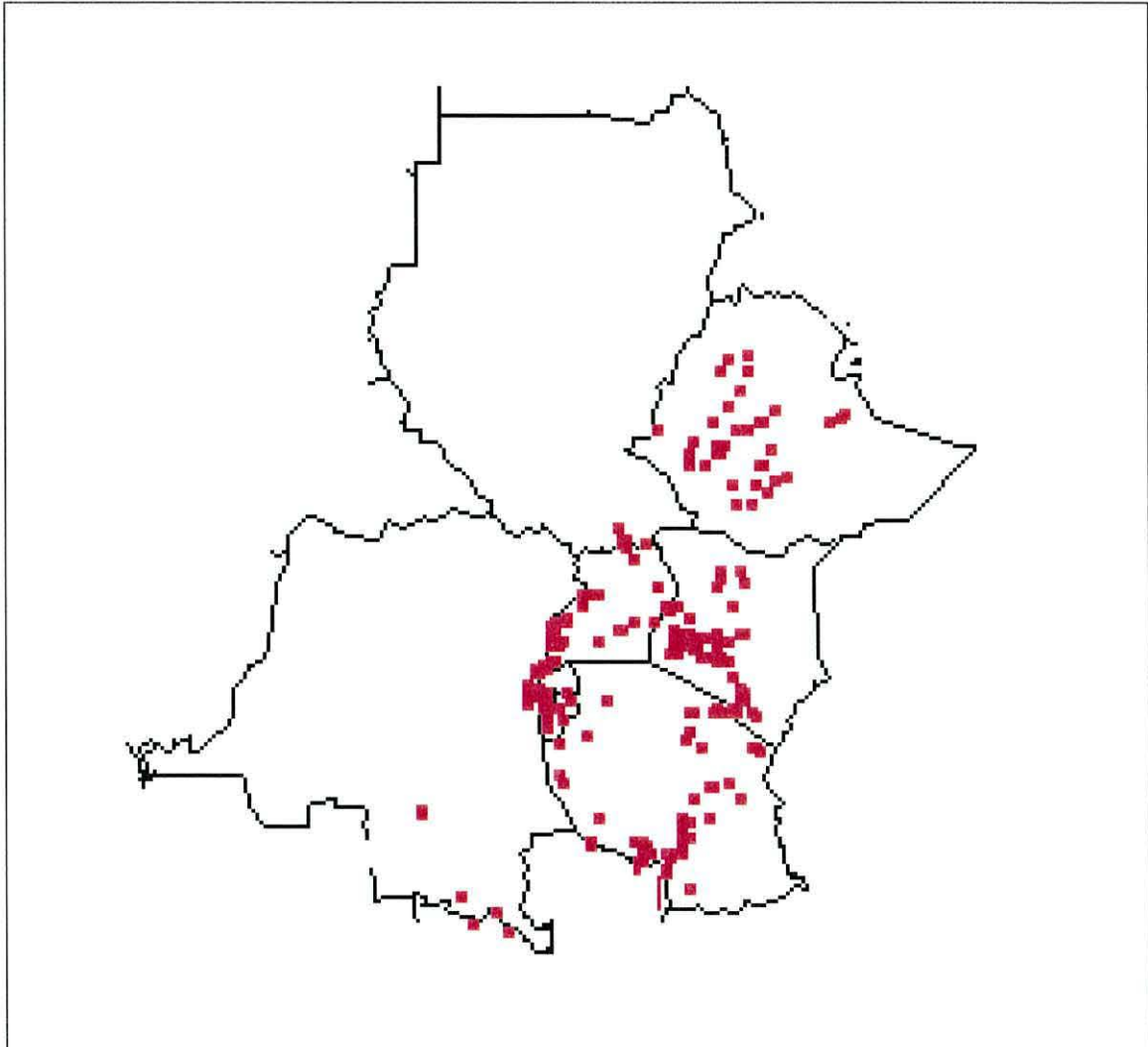
Figure 2.1 Distribution of *Prunus africana* in Eastern Africa

Source of data – collection localities noted on voucher specimens held in various herbaria, supplemented by specimen localities noted in literature.

2.1 .3 Climate

2.1.3.1 Elevation

The natural distribution of *Prunus africana* in the afro-montane forests of Africa is mainly from 900-3000 m (Graham, 1960; White, 1983) but elevations as low as 600m have been reported (Geldenhuys, 1981) in Bloukrans River Gorge, South Africa. In eastern Africa it is recorded from as low as 915 m, at Kibwezi forest (2°27′S, 37°55′ E), to 3100 m on Mt. Kenya, (0°00- 0°32′S, 37°21′-37°50′E) Table 2. 1.

2.1.3.2 Rainfall and Potential Evapotranspiration

Prunus africana is reported to usually occur in high rainfall areas (mean annual rainfall ≥900 mm). In eastern Africa *Prunus africana* occurs in high rainfall montane forests receiving as high as 2550 mm, and its distribution extends to hilltops in dry areas with mean annual rainfall as low as 600 mm. The greater part of the natural range in Kenya coincides with the highlands west of Rift Valley, with mean annual rainfall 1000-1800 mm, in a single long rainy season (February to November, with peaks in April- May and September-November). The relationship between rainfall and altitude in areas were *Prunus africana* occurs is presented in figure 2.2., while the relationship between rainfall and temperature is presented in figure 2.4. Precipitation, potential evapotranspiration and number of dry months (≤25 mm of rainfall) for the various locations where *Prunus africana* occurs in Kenya are indicated in Table 2.2.

Table 2.1 Reported elevations of *Prunus africana* in Kenya, in order of decreasing altitude

	Altitude (m)	Forest	Co-ordinates	Specimen citation (all in EA)
1.	1525-3100	Mount Kenya	0º00'-0º32'S, 37 º 21'- 37 º 50'E	Holyoak 720, Honore 661
2	2600-3070	Mount Elgon	1 º 08'N, 34 º 40'E	Jackson 349
3	2775	Londiani	0 º 07'S, 35 º 43'E	Perdue & Kibuwa 9154
4	2745	Timboroa	0 º 05'N, 35 º 32'E	Gardener 1505
5	2651	Enesambulia	0 º 49'S, 36 º 07'E	Greenway & Kanuri 9154
6	2560	Nasambolai Valley	1 º 00'S, 36 º 09'E	Greenway & Kanuri 14846
7	2500	Mount Nyiro	2 º 07'N, 36 º 50'E	Adamson 1779
8	2380-2439	Aberdares Range	0 º 59'S, 36 º 39'E	Anstey 570
9	2100-2256	Subukia	0 º 02'S, 36 º 09'E	Birch 61/68
10	2200	Kijabe hill	0 º 56'S, 36 º 35'E	Humbert 158
11	2195	Mau forest	0 º 23'S, 35 º 23'E	Kerfoot 156
12	1982-2140	Mount Kulal	2 º 43'N, 36 º 56'E	Adamson 10
13	1970-2135	Nandi forests	0 º 05'-0 º 10'N, 34 º 57'-35 º 23E'	Siemens 432, Dale 144
14	2135	Elgeyo forests	0 º 20'N, 34 º 59'E	Moon 145
15	2070	(Cherangani hills)	0 º 45'N, 35 º 30'E	Kenya FD EAH 1346
16	1980	Marsabit	2 º 45N, 37 º 50'E	Faden 68/647
17	1830	Chyulu hills	0 º 18'-37 º 40'S, 0 º 50'-38 º 00'E	Bally 268
18	1830	Oldonyo sabuk	1 º 08'S, 37 º 15'E	Faden et al. 74/1310
19	1725	Ngangao forest		
		(Taita Hills)	3 º 21'S, 31 º 28'E	Faden et al. 72/201
20	1700	Yala river	0 º 10'N, 34 º 57'E	Gillett 1675
21	1680	Kakamega forest	0 º 14'S, 34 º 52'E	Perdue& Kibuwa 9413
22	1585	Kisii	0 º 4'1S, 34 º 46'E	Nattrass 1773)
23	1534	Mbooni hills	1 º 0'S, 37 º 27'E	Nicholson 44
24	1070	Mathews Range	1 º 12'N, 37 º 22'E	Adamson 65
25	915	Kibwezi forest	2 º 25'S ,37º58'E	Makin 21

Table 2.2 Rainfall and potential evapotranspiration for localities where *Prunus africana* occurs in Kenya, in order of decreasing mean annual precipitation, MAR - Mean annual rainfall, Pot.EvaT. - Mean annual potential evapotranspiration

	Forest	MAR (mm)	Pot. EvaT. (mm)	No. dry months	Specimen citation (all in EA)
1	Mount Kenya	800-2550	1251	6	Holyoak 720
2	Kakamega	1905	-	-	Machin 792
3	Nandi forests	1063-1828	1251-1445	6-7	Moon 1256
4	Mau forest	1450	1251	6	Perdue & Kibuwa 9154
5	Mount Elgon	1309	1174	6	Jackson 349,427, 3499
6	Cherangani hills	1241	1402	6	Okwaro wamuhoya 67
7	Timboroa	1222	1292	6	Gardener 1505
8	Olokurto	1174	1158	6	Glover *et al.*1023
9	Aberdares	991-1142	900-1297	8-9	Schmitt 1991
10	Subukia	1066	1210	8	Birch 61/50
11	Elgeyo forests	1063	1445	7	Moon 1256
12	Kijabe hill	991	1287	9	Humbert 922
13	Oldonyo Sabuk	908	1360	9	Faden *et al.* 74/1310
14	Chyulu hills	870	1360	9	Bally 268, 7653
15	Mbooni hills	900	1360	9	Nicholson 44
16	Marsabit	817	1292	8	Faden, 68/67
17	Kibwezi	611	1470	10	Makin 21
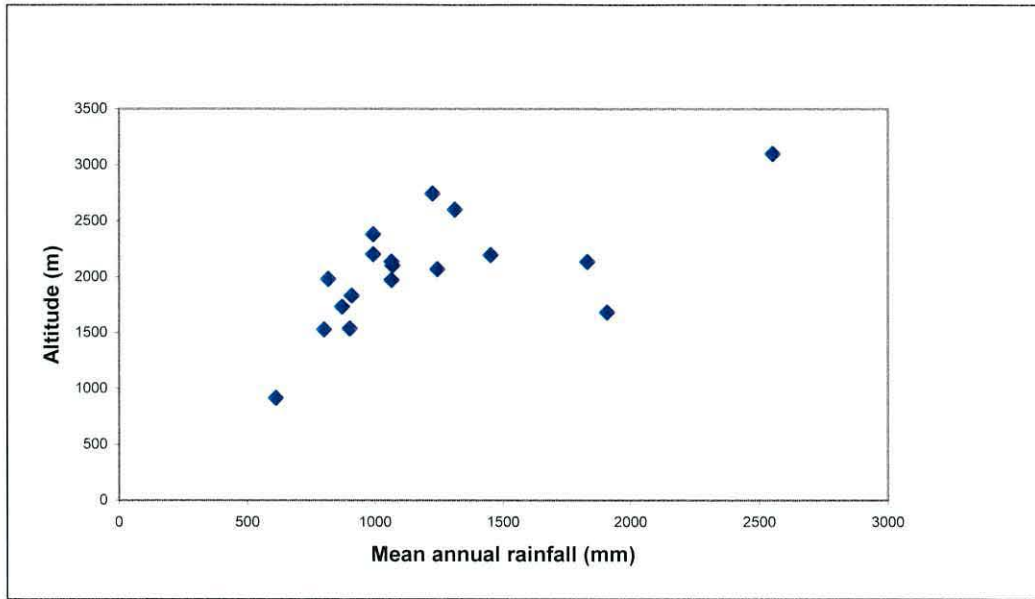
Figure 2.2 The relationship between altitude and rainfall in distribution of *Prunus africana*

Source of data – collection localities noted on voucher specimens held in various herbaria, supplemented by specimen localities noted in literature.
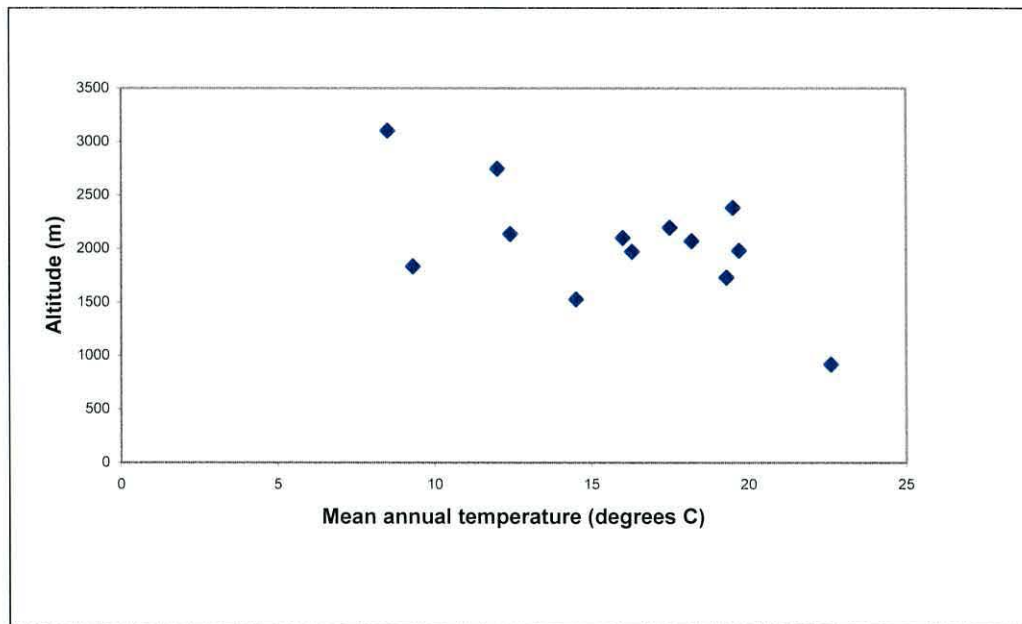
Figure 2.3 The relationship between altitude and temperature in areas of occurrence of *Prunus africana* in Kenya

Source of data – collection localities noted on voucher specimens held in various herbaria, supplemented by specimen localities noted in literature.

2.1.3.3 Temperature

Prunus africana's occurrence at high altitudes implies low temperatures, but in eastern Africa, temperatures vary widely across its natural range. In Kenya for example, mean annual minimum temperatures vary from 7.9°C to 16.5°C; mean annual maximum from 18.3°C to 28.7°C; and mean annual temperature from 13.1°C to 22.6°C. The relationship between temperature and altitude in areas were *Prunus africana* occurs is presented in figure 2.3. The coldest conditions are found at Timboroa, Londiani, Mt. Kenya and Aberdares, while hotter conditions occur in Kibwezi, Marsabit and Mt. Kulal. Table 2.3.

Table 2.3 Temperatures at areas of occurrence of *Prunus africana* in Kenya.

Mean ann. – Mean annual, Mean max. - Mean maximum, Mean min. – Mean minimum.

	Forest	Mean ann.	Mean max.	Mean min.	Specimen citation
1	Kibwezi	22.6	28.7	16.5	Makin 21
2	Marsabit	19.7	24.4	15.1	Faden 68/67
3	Oldonyo sabuk	9.3	24.9	13.5	Faden *et al.* 74/1310
4	Chyulu hills	19.3	24.9	13.5	Bally 268, 7653
5	Taita hills	19.0	24.9	13.5	Faden *et al.* 72/201
6	Cherangani hills	18.2	25.4	11.1	Okwaro wamukoya, 67
7	Mau forest	17.5	23.9	11.1	Perdue & Kibuwa 9154
8	Nandi forests	16.6	3.5	9.5	Moon 1256
9	Mount Elgon	16.3	21.1	9.7	Jackson 427
10	Subukia	16.0	23.2	9.5	Birch 61/50
11	Aberdares	15.9	20.9	10.8	Schmitt1991
12	Mount Kenya	8.5	19.0	10.0	Holyoak 720
13	Londiani	13.1	18.3	7.9	Gardener 1505
14	Timboroa	12.0	18.3	7.9	Perdue & Kibuwa 9154
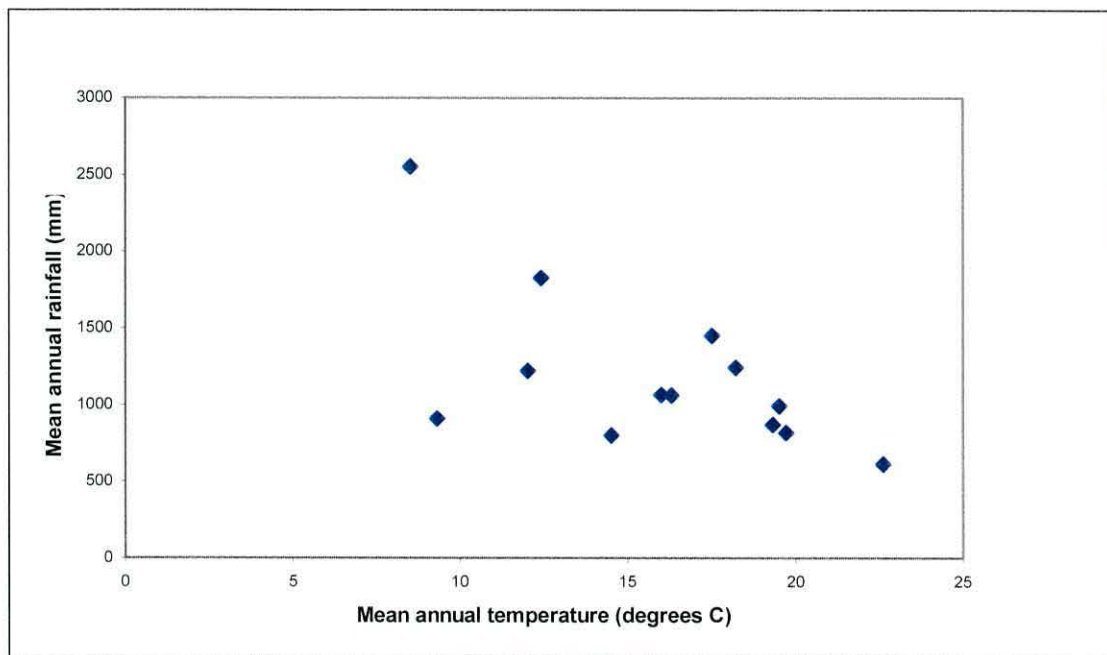
Figure 2.4 Relationship between rainfall and temperature in areas of occurrence of *Prunus africana* in Kenya

Source of data – collection localities noted on voucher specimens held in various herbaria, supplemented by specimen localities noted in literature.

2.1.4 Flowering, fruit development and seed dispersal

Within eastern Africa there is wide variation in flowering time in *Prunus africana*, considered a reflection of the strong flowering seasonality of the equatorial climate pattern (Hall *et al.*, 2003). However, flowering in most parts of Kenya for example seem to correspond with the wet season (April - September), when lowest

temperatures are also experienced. (Table 2.4). Fruiting period seems to be 2-3 months following flowering and is usually associated with rainfall. Flowering and seed set of *Prunus africana* is cyclic with good flowering occurring at 2 to 3 – year intervals (Munjuga *et al.*, in press). Large variation in timing of fruiting within years is reported to be common.

Despite its wide distribution in Africa, there is little published information on the seed dispersal process. In Kenya, Munjuga *et al.* (in press) noted greenbuls (*Andropadus graciliorstris, Andropadus latirostis, Andropadus nigriceps kikuyuensis*) and mousebirds *Colius striatus* as birds feeding on *Prunus africana* fruits and potentially dispersing the seeds. Three primates, *Cercopethicus mitis* WOLFF, *Cercopethicus nicitans* (L) and *Colobus abyssinicus* (OKEN) are also known to feed on *Prunus africana* in Kakamega forest and could contribute to seed dispersal too.

Table 2. 4 Flowering period of *Prunus africana* in Kenya

Period	Forest	Co-ordinates	Specimen citation
January	Mount Elgon	1°08'N, 34° 33'E	Gardener 60
February	Mount Elgon	1°08'N, 34° 33'E	Gardener 60
February	Mount Kulal	2° 43'N, 36° 55'E	Adamson 64
March			
April			
May	Nandi forests	0° 05'-0° 10'N, 34° 57'-35° 23E'	Moon 2003
	Elgeyo forests	0° 20'N, 34° 59'E	Moon 2003
	Taita Hills	3° 21'S, 38° 2'E	Faden 164
June	Marsabit forest	2° 18'N, 3° 58'E	Field 425
July			
August	Kakamega forest	0° 14'S, 34° 52'E	Holyoak 2000
	Chyulu Range	0° 18'-37° 40'S, 0° 50'-38° 00'E	Gibbons 155
	Kijabe hill	0° 56'S, 36° 35'E	Humbert 155
	Oldonyo sabuk	1° 08'S, 37° 15'E	Faden & Ngweno 159
September			
October			
November	Londiani forest	0° 07'S, 35° 4'E	Perdue & Kibuwa 426
December	Mau forest complex	0° 23'S, 35° 23'E	Kerkoof 156
	Mathews Range	1° 12'N, 37° 22'E	Cooper 2012

2.1.5 Pests and diseases

A potential limiting factor of plantation establishment and other intensive cultivation in the natural range of a species is the presence of obligate and associate pests and diseases. Observations have indicated that *Prunus africana* may be affected by a number of natural and possibly debilitating pests and diseases, although their effects have yet to be fully quantified (Sunderland & Nkefor, 1997). The leaves were found to have been extensively eaten by a Lepidopteran caterpillar (Plate 2.2), which then pupates on the plant itself as observed by Arap sang (1988).

Attack by coleopterous stem borers, whose presence is indicated by localised resin exudation through small bore-holes has been observed in Kakamega and Nandi forests (Authors, pers.obs.). The vigour of the trees themselves does not seem to be compromised, however the presence of stem borers may have significant implications for bark production and recovery. Pathogenic fungi have been reported from nursery and seedling studies, Tsingalia, 1989; Mwanza *et al.* 1999)

Plate 2..2 Leaves of a *Prunus africana* tree that have been extensively eaten by Lepidopteran caterpillars in Kakamega forest, Kenya

2.1.6 Population statistics

Natural populations of *Prunus africana* are characterised by low and patchy stocking levels (general level, 1-2 ha^{-1}, high, 5 ha $^{-1}$) and the frequent and under-representation of small individuals (Ndam *et al.* 2000). Most reports of density based on large areas ($\geq$10 ha) indicate few trees ha^{-1} of $\geq$30 cm DBH, (Geldenhuys,

1981, ONADEF, 1997, CERUT, 1999) and attention has been drawn to this unbalanced distribution of *Prunus africana* trees among diameter classes (Cunningham & Mbenkun, 1993; Sunderland & Tako, 1999). Even in populations that have not been reduced by harvesting recruitment of *Prunus africana* into the productive size classes is limited.

2.1.7 Economic importance

Prunus africana tree has multiple uses, as a timber it is used for heavy flooring, window and door-frames and furniture. In construction it has been used in the past for lorry bodywork and as bridge decking, and for railway sleepers. It is also used for poles, fuelwood (Plate 2.3a & 2.3b), charcoal, mortars, bee-forage (Plate 2.4), mulch, green manure and wind breaks (Kokwaro, 1976; Noad & Bernie, 1989; ICRAF 1992; Albrecht, 1993; Cunningham & Mbenkun, 1993). The bark, leaves and fruit of *Prunus africana* are part of the pharmacopoeia of wild medicines used by traditional healers in Africa. Commercial use of the species by the pharmaceutical industry began in the 1970s with the manufacture and marketing of the bark extract as an effective treatment of Benign Prostatic Hyperplasia (Cunningham & Mbenkun, 1993).
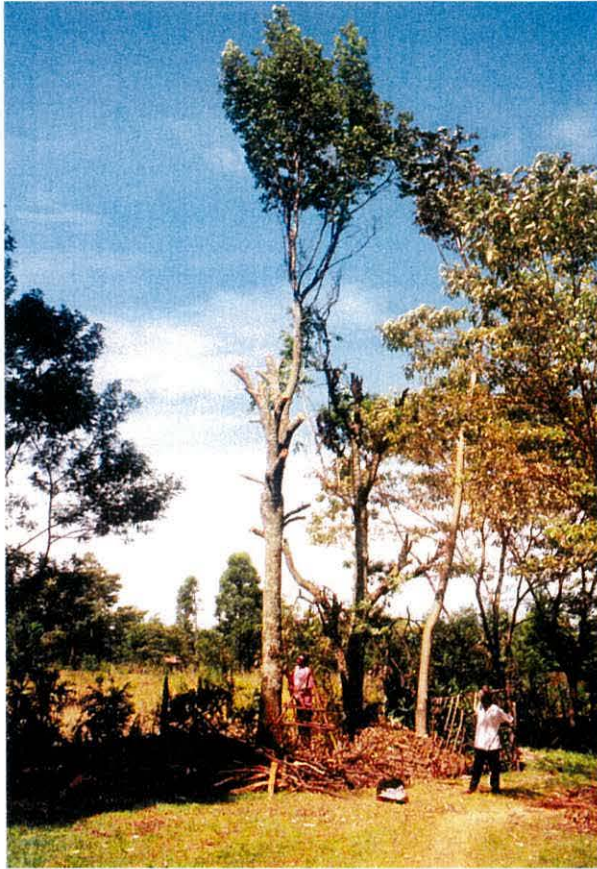
Plate 2.3a A *Prunus africana* tree that has been lopped by a farmer for fuelwood in Nandi district, Kenya

Plate 2.3b Firewood obtained from one *Prunus africana* tree in Nandi District, Kenya

Plate 2..4 *Prunus africana* tree that is being used as bee-forage by a farmer in Nandi district, Kenya

2.1.8 Bark yield

Available information on bark yield per tree is variable and to some extent conflicting. Macleod (1986) presents a figure of 55 kg tree^{-1} and a range of 38-128.2 kg, assuming harvesting with sustainability, CERUT (1999) presents figures suggesting 27.8 kg tree^{-1}, while Walter & Rakotonirina (1995) estimated yields from

felling and complete striping in Madagascar at 50-200 kg per tree[-1] depending on size.

2.1.9 Forest management and *Prunus africana*

Management of the forest resources in Kenya is guided by the National Forest Policy and supported by the Forest Act (KIFCON, 1994). The policy, first published in 1957 and subsequently revised in 1968, is now being redrafted to reflect the changes that have taken place in Kenya over the past 30 years. The new policy, building on the conventional forest management guidelines of the previous policies, will include specific reference to conservation of biodiversity and recognition that many forest areas have been over-exploited and will need to be left to regenerate. There is less emphasis on government control of forest and a widening of the institutional base for forest management, including community participation. The forest act will also be revised to reflect the changes in the policy.

The Forestry Department, under the Ministry of Environment and Natural Resources, is responsible for the management of the gazetted forest areas. The department has been restricted in its capacity to fulfil these responsibilities, largely due to inadequate resources. In 1991, the Forest Department and the Kenya Wildlife Service (KWS) signed a Memorandum of Understanding for the joint management of selected forests. These forests include all major gazetted areas of importance to conservation. Joint management plans have been drawn up, and

Forest tourism is being developed by KWS. Revenues generated are re-invested in forest conservation.

Exploitation of indigenous timber was banned in the 1980s, and a special permit is required for the exploitation of Prunus *africana* and other indigenous medicinal trees. Unfortunately illegal felling of *Prunus africana* trees for both bark and timber continues. Management activities by the Forest Department within indigenous forests have been effectively restricted to the active management of plantations, law enforcement to curb illegal extraction, which is rampant, and licensing the extraction of forest produce such as firewood. Recently tourism has been promoted by KWS in a number of areas, involving the development and maintenance of infrastructure and the licensing of private lodges operating within forest reserves and parks.

2.2 Medicinal plants and conservation
2.2.1 Plants in medicine

Plants are an important source of medicine- plant derivatives are key ingredients in everything from aspirin to contraceptive pills making them the foundation of health care systems all over the world. For example, up to 80 % of people in Africa consult traditional medicine doctors, who often administer extracts of local plants (WWF, 1996). Some plants are known virtually by everyone in a community and are grown in home gardens or within farms, others are only known to specialists.

In many industrialised countries, interest in traditional medicine is rising. In 1990, people in Canada, France, Germany, Italy, Japan, UK and USA spent more than US $ 3.3 billion on over-the-counter herbal medicines annually (WWF, 1996). In richer countries, herbal medicine is rapidly gaining in popularity because of dissatisfaction with the effectiveness of modern medicines and their side effects. As pathogenic organisms develop resistance to pharmaceutical medicines, companies mount urgent efforts to uncover more secrets of the plant world and new cures for diseases.

The first pure substance derived from a plant was morphine, extracted from the opium poppy at the turn of the 19th century (Hollman, 1991). Today, much modern medicine is based on the use of pure chemical substances, marketed as pharmaceutical drugs. Chemicals are also extracted from plants and then altered to produce drugs: an example is diosgenin, derived from various species of yam (*Dioscorea spp*) and other plants and used to manufacture progesterone, a basis of the oral contraceptive pill (Hamilton, 1992).

In Kenya the bark of fifty eight plant species including *Prunus africana, Warburgia salutaris* Bertlof. F. Chiov, *W. stuhlmanni* Engl, *W. ugandensis* Sprague (Canellaceae) is used for treatment of various ailments (Kokwaro, 1976). The red and black fruits of *Afzelia quanzensis* Welw. Leguminosae are also widely used traditionally. The

white lignotubers of *Synaptolepis kirkii* Gilg (Thymeliaeaceae) and leaves and twigs of the resurrection plant *Myrothamnus flabellifolious* Welw (Hamamelidaceae)are similarly used(WWF, 1996). In Kenya records have been made of use of herbal medicines by numerous societies, including the Maasai, Kipsigis, Marakwet, Turkana , Akamba and people living around Arabuko Sokoke forest. Records of medicinal plant use for the entire East African region, compiled from East African herbarium records and personal research have been published by Kokwaro (1976), but few quantitative ethnobotanical studies have been done of medicinal plant use in Kenya. However, the Kenya Medical Research Institute (KEMRI) has an active programme analysing active ingredients of medicinal plants. KEMRI has also developed a medicinal plant database at the KEMRI Traditional Medicine and Drugs Research Centre, Nairobi. KEMRI also has a programme studying active ingredients of medicinal plants and developing commercial products, including anti-malarials from *Azadirachta indica* A Juss. Meliaceae (Barus. Pers. Comm. 2002).

2.2.2 Trade in medicinal plants

There is large-scale international trade in medicinal plants, used both for herbal medicine and for the manufacture of pharmaceutical drugs. There is also growing interest in obtaining samples of plants used, to explore new commercial medicinal products. The scale of international trade in medicinal plants is difficult to assess because of lack of reliable statistics and trade secrecy, but it is estimate to be growing at a rate of 10% per annum in US and Europe (WWF, 1996).

It is estimated that 35000-70000 species of plants have been used at one time or another for medicinal purposes (Farnsworth & Soerjarto, 1991). By far the greater number of species is employed in herbal medicine and used in unrefined or semi-processed form, often in mixture with non-plant ingredients. The herbal sector is growing fast, increasing by 12-15% by value per year in the UK, USA, and Italy (Abrahams, 1992). According to McAlpine & Warrier (1992), there are more than 2000 herbal medical companies in Europe and more than 220 in the USA. The McAlpine & Warrier report also states that Germany is the largest market in the world for herbal medicines, with annual sales of US$ 1.2 billion representing nearly 25% of the international pharmaceutical market.

Published data on Kenyan medicinal plants used in local or international trade is very scanty. Exceptions are records of trade on oleoresins from *Aloe secundiflora*, which indicate that as much as 73 tonnes per annum are exported to Europe (Anon., 1998), and *Prunus africana* bark trade with France whereby one individual trader is reported to export 400 tonnes per annum at a price of US $2 per kilo (Achieng, 1998). The need for research in this area cannot be overemphasised.

Far less obvious than the export trade in medicinal plants, is the informal sector trade in medicinal plants. The economic value of this trade is also far more difficult to assess, yet it is important at household level and at national scale. Trade in medicinal plants occurs in rural areas throughout Kenya. Sales commonly take

place at roadside stalls, cattle auctions, bus stops, markets, and medicinal plant clinics.

Prunus africana has the potential to enhance the economies of farmers in the Kenyan highlands, especially if some form of processing is done before export. Since all bark is collected from the `wild', one possible way of enhancing the welfare of smallholder farmers would be domestication of the species by improving bark traits, and the marketing and processing of the bark, to expand the trade and provide farmers with greater economic opportunities.

2.2.3 Trade in *Prunus africana*
2.2.3.1. Trends in the trade

Both benign prostatic hyperplasia (BPH) and prostate gland hypertrophy commonly affect older men. They are expected to become more common amongst the ageing male population of Western Europe and the USA (Cunningham *et al.* 1997). Treatments for this disorder include surgery, balloon dilation, hypertherinia (using urethral probes), phytotherapy and pharmaceuticals containing anti-androgens and 5-alpha reductase inhibitors. Although surgery is commonly practised and effective, it is expensive and is potentially dangerous, (ANON, 1992). For this reason, medical therapy such as use of *Serenoa repens* extract, pumpkin seed (*Cucurbita pepo*) and *Prunus africana* extract are popular alternatives. Therefore as prostate gland hypertrophy and BPH become more common among men in Western Europe and the USA, so will the market demand for treatment of this

problem rise. This includes the demand for herbal preparations. At present, most *Prunus africana* based products are sold within the European Union (EU) and not in the potentially large and lucrative markets of North America and Japan. Sales of *Prunus africana* also take place within Sweden, where it is normally registered as a pharmaceutical speciality (De Smet *et al.*, 1993) and Australia (Commonwealth of Australia, 1995).

2.2.3.2 Structure of international trade in *Prunus africana*

The lucrative market for *Prunus africana* bark extracts used medicinally to treat prostate problems is the major reason for international trade. Current international export demand for *Prunus africana* bark, primarily to Europe, is about 4000 tons per year. About ten percent of this is harvested in Kenya (Figure 2.5 & 2.6). *Prunus africana* products are traded as:

* unprocessed, dried bark;

* bark extract;

* brand-name capsules in final form;

* a component of hair-tonic (in Japan) and

* timber and furniture from wood in local trade.

The *Prunus africana* timber trade being local, rather than international, emphasis here is on the trade in *Prunus africana* bark extracts and medicinal herbal preparations.

While all bark exported from Kenya is unprocessed, most bark exploited in Cameroon and Madagascar is processed locally to produce the extract which is then exported to Italy and France.
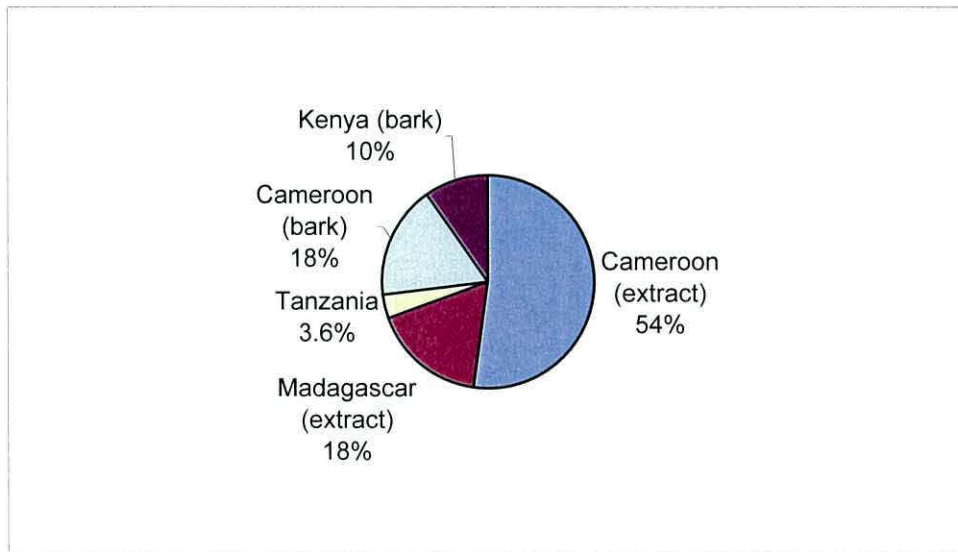
Figure 2.5 Annual world trade of *Prunus africana* bark in 1997 by source countries. Although the proportion *Prunus africana* bark in international trade varies between countries from year to year, Cameroon is consistently the major source of supply, followed by Madagascar and Kenya. (Data from Cunningham & Mbenkun, 1997).
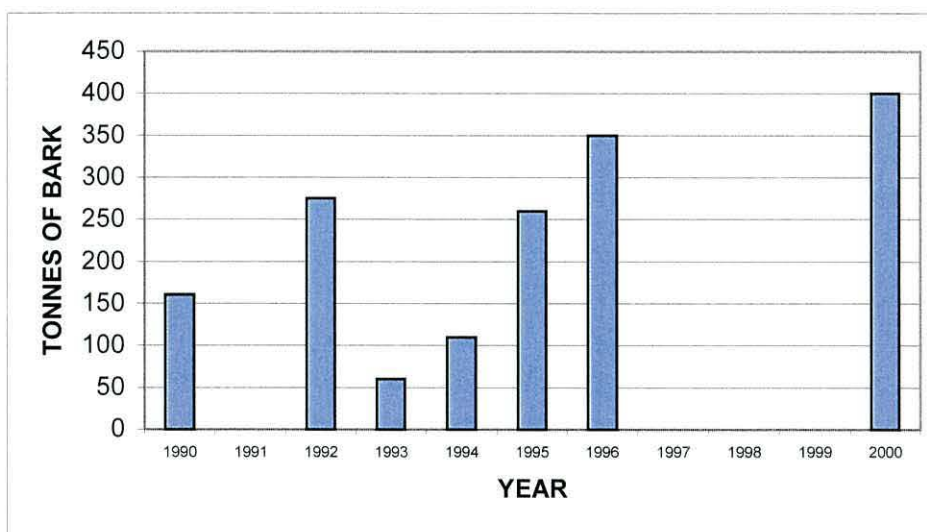
Figure 2.6 Histogram showing total quantity of unprocessed bark exported from Kenya over the period 1990-2000. Data were obtained from records of the National Agricultural Research Laboratories (NARL), Kabete, Kenya.

A wide variety of brand names in a range of dosages are available and marketed in Europe (Table 2.1), including the Scandinavian countries and Australia. In the USA, marketing of *Prunus africana* extract is mixed with other ingredients (including Saw Palmetto, *Serenoa repens*, fruit extract and pumpkin *Cucurbita pepo*, seeds), such as 'Urinozonic' takes place by mail order or through the Internet. The retail cost of *Prunus africana* herbal preparations is high. In November 1996 in Paris, France, a box of 30 'Tadenan' capsules (50 mg) costed FrF 105.90 (US$ 20.7, 16.14 Euro) and 60 capsules FrF 200.20 (US$ 39.17, 30.52 Euro). In Switzerland, a box of 30 "Prostatonin" capsules (25 mg) costed Sfr 31.30 (US$ 25.30, 21.45 Euro).

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Table 2.5 Brand names, quantity, form, company and country of origin of *Prunus africana* herbal preparations sold within Europe, South America and USA. In USA *Prunus africana* herbal preparations are sold as health foods.

Brand Name	Quantity	Form	Company	Country
Acubiron	30 mg	Capsules	Laboratories Bohn	Spain
Bidrolar	25 mg	Capsules	Spyfarma	Spain
Catiz drags	25 mg	Capsules	Laboratorios Volpino	Argentina
Foudaril	30 mg	Capsules	Gap	Greece
Gernide	25 mg	Capsules	Vita	Spain
Normobrost	30 mg	Capsules	Spedrog Caillon SAIC	Venezuella
Pigenil	25 mg	Capsules	Inverni della Beffa Inverni della Beffa	Italy
Pigenil	50 mg	Capsules	Millet Roux	Italy
Prolitrol	25 mg	Capsules	Infofarma	Brazil
Prohitrol	25 mg	Capsules	Nature's Way	Spain
Prosactive	100 mg	---------	Prodes	USA
Prostamal	25 mg	Capsules	BoerihngerIngelheim, Basel	Brazil
Prostatonin	25 mg	Capsules	Baldaci	
			Baldaci	Switzerland
Prostem	25 mg	Capsules	Sarget	Brazil
Rostem	50 mg	Capsules		Brazil
Pyrafricum	25 mg	Capsules	Solaray	Spain
Pygeum africanum extract			Krauterpfarrer Kunzle	
Kunzle	50 mg	---------	Uni-Pharm	USA
Rotamat	25 mg	Capsules	Diethelm, Zurich	Switzerland
Tadenan	25 mg	Tablets	Laboratoire Debat	Greece
Tadenan	25 mg	Capsules	Diamant	Switzerland
Tadenan	25 mg	Capsules	Boerhinger Mannheim, Vienna Boerhinger Mannheim	France
Tadenan	25 mg	Capsules	Rousel	Portugal
	25 mg	Capsules	Lek	
Tadenan			Carulla Vekar	Austria
	50 mg	Capsules		
Tadenan				Austria
Trianol	50 mg	Capsules		Italy
Tuzanil	25 mg	Capsules		Yugoslavia
	25 mg	Capsules		Spain

Source: Cunningham *et al.* 1997

2.2.3.3 Internal Trade in *Prunus africana* in Kenya

Prunus africana is widespread in the highlands of Kenya. For most of the time that exports have been occurring from Kenya, bark has been harvested from the forests of the Mau, Kakamega, Aberdares, Mt. Kenya and Karura-Ngong areas. (Cunningham *et al.*1997). Some parts of these forests were degazetted by the government for new tea plantations, settlement, or agriculture allowing bark harvest as a by-product of land clearance. Further destructive harvesting through felling also took place on farmlands elsewhere in Kenyan highlands (Authors pers.obs., 1998)

Once harvested, bark is bought and transported to the home of the only licensed exporter, near Lake Baringo, where it is dried, and packed into shipping containers. CITES regulations for export permit applications are followed. Once these are granted, the container is transported by road to Mombasa for shipping to Prosynthese (France), a subsidiary of Groupe Fournier. In 1992, price paid to the Kenyan exporter was 11 FrF/kg (*ca* US$ 2, 1.68 Euro). Recent details of Kenyan trade are scanty because of a standing ban on exploitation of indigenous tree species, but are estimated at about 400 metric tonnes annually. Monopoly control over the export of *Prunus africana* bark has to some extent limited illegal harvesting.

2.2.4 Conservation issues relating to trade in medicinal plants

The vast and expanding market for medicinal plants is putting unbearable pressure on tropical forest resources as increasing numbers of trees and herbs are harvested for their medicinal properties (Hamilton, 1992). Unlike the relatively few species of generally cultivated plants used in the manufacture of pharmaceutical drugs, most species used in herbal preparations are collected from the wild (Akerele *et al.*, 1991). When harvesting is for local use, there is little over-collection, but the scale of modern commercial pressures on medicinal plants is resulting in widespread depletion. A good example is the highly prized medicinal tree *Warburgia salutaris* that has become extinct in Zimbabwe through over-harvesting (Hamilton, 1992).

Concern for conservation of medicinal plants is surfacing at local, national and international levels. Guidelines for conservation of medicinal plants have been published by World Health Organisation (WHO), the World Conservation Union (IUCN), and the World Wide Fund for Nature (WWF).

Conservation issues in international trade in medicinal plants for existing products mainly concern those plants which are harvested from the `wild', and whether their trade threatens conservation of biodiversity or is not sustainable, (the case for the great majority of the species). Biodiversity may be threatened if the trade

endangers survival of the species, erodes its genetic diversity or causes loss or degradation of important natural or semi-natural ecosystems (Hamilton, 1992).

The majority of conservation problems that result from existing trade in medicinal plants arise because the plants are collected from the `wild', as opposed to being cultivated. Lewington (1992a) reports that it is very difficult to determine the precise origin of medicinal plants currently imported into Europe, and that it is complicated by the fact that some species which are cultivated are also collected from the `wild'. Only a few species, required in large quantities, are cultivated to any extent (Lewington 1992a, Akerele *et al.*, 1991).

Cultivation (domestication) of threatened species can be a useful measure to take pressure off `wild' populations, especially if accompanied by steps to protect the wild plants better.

2.2.5 Conservation of *Prunus africana*

Conservation of tropical trees and forests is a subject that has received considerable attention since the United Nations Conference on the Environment and Development (UNCED), yet the term often remains undefined (Leakey & Izac, 1996). From a species point of view, conservation can seek to:

• preserve the habitats where the species inhabits

• prevent the species from going extinct

• preserve all possible gene or genotypes of the species

• preserve all genetic variation of high utility value.

These four are considered simply as conservation, and confusion can arise as to specific objectives of conservation efforts (Leakey & Izac, 1996).

There is no doubt that tree species are best conserved *in-situ* within natural forest habitats. Recognition of the difficulties of this approach for species of important human use such as *Prunus africana* has led to calls for conservation through utilisation. This means linking conservation of the species to expansion of its cultivation. By so doing, farmers adjacent to Afromontane forests can reduce pressure on natural stocks and thus conserve *Prunus africana* genetic resources by cultivation. In this way, the 'wild' germplasm can be protected in the natural ecosystem while the germplasm of greatest utility value can be conserved and promoted through cultivation and domestication of trees on farms.

It is desirable to promote the cultivation and domestication of *Prunus africana* as its integration into agroforestry systems would benefit the welfare of the local people, the environment, and the economy of the producing countries. By sustaining the industry, supplies of the drug will be ensured for the treatment of prostrate gland disorders. It must be remembered, however, that the successful conservation of *Prunus africana* requires knowledge of its ecology and biology that can be applied in the management and sustainable utilisation of the species.

2.2.6 Domestication of *Prunus africana*

The need to domesticate *Prunus africana* is evident from the current high levels of demand for its products (primarily bark and timber). As discussed earlier, the levels of demand cannot be met in the long-term from wild populations. With legal harvesting banned in Kenya and natural bark stocks dwindling in Cameroon and Madagascar (the major suppliers to the international trade), to continue harvesting from wild populations at existing rates will not be sustainable. Furthermore, much of the present supply of bark is harvested using techniques that are un-sustainable (felling and/or complete stripping) which usually kill the tree. However, given the economic benefits that the farmers stand to gain if they plant the species, cultivation of *Prunus africana* potentially promises a sustained product supply. Development of sustainable harvesting techniques and intervals for sustainable harvesting will act as incentives for farmers to plant. Domestication of *Prunus africana* thus has an important role in ensuring its sustainable and beneficial exploitation while significantly reducing the threat of depletion and extinction of wild populations.

2.2.6.1 Propagation of *Prunus africana*

The seeds of *Prunus africana* are considered recalcitrant and unless carefully stored only a negligible proportion remains viable after as short a period as three weeks (Sunderland & Nkefor, 1997). Therefore one major constraint to the domestication of *Prunus africana* is the availability of viable seed in sufficient quantities. However, vegetative propagation through cuttings from juvenile plants of *Prunus africana* has

been achieved with varying degrees of success in Kenya, Madagascar and Cameroon (Nzilani, 1999; Tchoundjeu *et al.*, 1999a, 1999b). Experimental work in Kenya has indicated that air-layering is also possible, (Nzilani, 1999).

2.2.6.2 Planting of *Prunus africana* in Kenya

A few small plantations of *Prunus af*ricana occur in Kenya. Simons *et al.* (1998) reports a planted block of *Prunus africana* 0.4 ha in extent, at Ngong, as the first attempt at its cultivation. This stand was planted in 1913 as a timber stand. Other pure and mixed plantations were planted in the 1950's in Meru, Ragati, Kimondi and Kakamega forests. Up to 1992, 65 stands of *Prunus africana* had been established in Kenya, with a total area of 628 ha. The last of these plantings (16.2 ha) was carried out in the Nyeri Hill Forest in 1992. A management trial was established at Muguga in 1997 using wildings from South Nandi.

Domestication and cultivation of *Prunus africana* in plantations or agroforestry systems has tremendous potential, both for sustainable bark production and generating cash income. A study of the basic biology of the species is necessary to enhance it domestication, cultivation and to demonstrate how to integrate into agroforestry systems.

CHAPTER III

PRUNUS AFRICANA POPULATIONS IN KENYAN FORESTS

In this chapter, the diameter class structures of *Prunus africana* populations in four stands in Afromontane Kenyan forests are analysed and discussed. As a relevant background, the chapter starts with a review covering forest stand regeneration dynamics in the tropics, patterns of tree size distribution, population demographic structure and conservation, and methods for modelling forest structure.

3.1 Introduction, Literature Review and Objectives of the study

3.1.1 Introduction

Foresters have long been interested in size structure of forest stands and recruitment of trees into the next size class (Hartshorn, 1975). The use of size classes is usually adopted in preference to age classes especially when the stages of a population are easily recognizable, for example in trees (Usher, 1966). In mature forests, the range of ages in a size class may be extreme due to differential growth responses resulting from succession, suppression, competition, and the like. The difficulty of determining the ages of tropical wet forest trees from increment cores complicates the use of age classes. However, most trees can be assigned to stages with relative ease.

Recognition of the steady-state condition in forest communities is commonly based on the analysis of the population structure of the dominant species, either directly or indirectly through the interpretation of size class structure (Daubenmire, 1968).

Size class structure refers to the numerical distribution of differently sized individuals of tree species in a given stand (Mueller-Dombos & Ellenberg, 1974). Where a consistently positive relationship between age and size of trees exists, the analysis of stand structure is a time-specific method of studying long-term forest dynamics. Continuously regenerating species must be reproducing in the shade of the forest canopy; thus seedlings and saplings of these species must be present in the undergrowth. Where the accordance of young trees in the undergrowth with the dominants in the canopy is complete, tree species have all aged population structure as reflected in a characteristic reverse J-curve of age or size distribution (Daubinmire, 1968; Whittaker, 1974). Characterization of species as continuously regenerating is usually based on the visual assessment of frequency distribution in size classes; the degree of departure from an ideal distribution may also be quantitatively assessed.

Diameter at breast height (DBH) is a fundamental measurement in the quantitative inventory of forests. It is also the easiest measurement to make, since it is made directly, without use of distance estimates or optical tools. DBH is the primary measured parameter for quantitative tree ecology and forestry, being used in studies to compare cross-sectional area, dominance, ground cover, and biomass, and in dynamic long-term studies to measure increment rates.

3.1.2 Forest stand regeneration at the community level

3.1.2.1 Regeneration dynamics of forest tree species

Regeneration dynamics of forest tree species can be related to the scale of disturbance. In the absence of large-scale catastrophic disturbances, regeneration dynamics is strongly influenced by endogenous factors (vegetation structure and species interactions), which operate at scales of thousands of square metres or less (Grau, 1999). One of the factors controlling regeneration dynamics at this scale is the tree fall gap. Species differ in their response to canopy gaps. This variation in response is one of the factors contributing to reduced competitive exclusion at the community scale and has been hypothesised as one of the factors contributing to the maintenance of biodiversity in species-rich tropical forests (Connell, 1971, 1978; Denslow, 1987; Houston, 1994; Janzen 1970).

Tree fall gaps are canopy openings produced by the death of one or a few canopy trees. Tree falls generate gaps at scales that depend on the height and canopy projected area of the adult trees. In most tropical forests, tree fall gaps range between 100-400 m² (Denslow, 1987). The main ecological effect of tree fall gaps is the increase in resource availability (light and soil nutrients), which promotes seed germination and the growth and release of suppressed juveniles (Brokaw, 1985; Denslow, 1987; Veblen, 1992). A gap phase regeneration mode (Veblen, 1992) is characterised by recruitment mostly in tree fall gaps. Since tree fall gaps are frequent disturbances typical of mature forests, species having a gap-phase

regeneration mode should have a size distribution reflecting continuous regeneration i.e (negative exponential) at spatial scales that include several tree falls. Mature mixed forests can be maintained by frequent small disturbances, less frequent large disturbances or by long-term cyclic forest dynamics dominated by multi-cohort structure (Sano, 1997).

3.1.2.2 Gap dynamics in tropical rainforests

Forests can be considered dynamic mosaics of vegetation patches of different ages produced by disturbances and influenced by different abiotic and biotic conditions (Matinez-Ramos *et al.*, 1989). Three main phases (gap, building and mature) have been recognized in the forest regeneration cycle since initial work by Watt (1947), Whitmore (1975, 1982, 1989), and Swaine & Whitmore (1988) have placed tropical trees in categories defined by their light requirement for germination and establishment, suggesting two routes by which trees may attain maturity in the forest mosaic. Light-demanding pioneer species, germinate establish and grow to maturity in gaps, while non-pioneer (climax) species germinate and establish primarily in the shade, but often attain maturity when juveniles are released from suppression.

Whitmore's framework restricts species to one route to maturity and defines this route in terms of light requirements early in the cycle. It is the composite of all the successful and unsuccessful routes to maturity that eventually determine the growth rate of a population, which in turn defines its local persistence or extinction.

3.1.2.3 General patterns of size distribution over time

As cohorts of seedlings in a population age and grow larger, their size distribution tends to spread out. Initially the members of the cohort are nearly identical in size (e.g. seedlings emerging from a single years seed crop) but with time some will grow rapidly into larger size categories, while others will remain practically the same year after year. Thus their size distribution, initially sharply peaked, will tend to become lower, wider and flatter with time.

3.1.3 Population demographic structure and conservation

A central issue in conservation is maintenance of genetic variability needed in populations to ensure viability (stability) of a species, in particular that of endangered species like *Prunus africana*. It is thought that loss of genetic variation may increase susceptibility of a population to pests and disease (Beardmore, 1983).

The demographic structure of a population or species may reflect whether or not sufficient recruitment is occurring in the population or species to maintain genetic diversity or simply preserve an adequate number of breeding individuals (Menges, 1991). Habitat fragmentation has affected *Prunus africana* population demography over large areas. Throughout their range, most populations are in a critical state because of continuing destruction of their habitats and extraction for commercial purposes (Achieng, 1998).

The change in numbers, which a tree population exhibits over time, is a direct result of recruitment and mortality processes. The population grows when recruitment of new individuals exceeds the number of deaths, and it declines when mortality is greater than recruitment. Population stability is achieved when the recruitment rate is exactly balanced by death rate. These simple demographic relationships determine the sustainability of forest resource exploitation.

Detailed ecological information, however, is lacking for most tropical species. In consequence, the exploitation of most tropical forest resources has become a purely extractive activity with little consideration for the continued regeneration of species. Unfortunately, overexploitation, high mortality and low recruitment inevitably lead to population extinction.

3.1.4 Predicting population trends from size distributions

Size distribution is often used to indicate the stability of a tree population, and examining the diameter distributions of a species is often used towards this end (Lorimer, 1980; Knowles & Grant, 1983; Ogden, 1985; Hart *et al.*, 1989; Franklin *et al.*, 1993, Read *et al.*, 1995). There are few records of long-term population trends in most tropical tree species. In the absence of direct estimates of population size through time, this seems a reasonable alternative.

The presence of a large number of juveniles relative to adults is taken to indicate that a population is stable, perhaps growing, but few juveniles can be seen as a

warning that population is in decline. It is argued that species in the process of being eliminated from the forest during succession fail to reproduce and thus lack sufficient advanced regeneration. The lack of congruence between adult and juvenile population densities in a stand is an indicator of change, and is a major concern for conservation (Foster et al, 1996). Diameter distributions have been used to project population trends in the tropics, and early studies suggest that some dominant canopy species in tropical forests do not produce juveniles in the immediate area. This lead to the cyclical succession, or the mosaic theory of regeneration (Aubreville, 1938; Richards, 1952).

The underlying assumption that species with low juvenile density are in decline has not been explicitly tested. However, other factors being equal, increasing populations should have a relatively higher proportion of juveniles than decreasing populations. In general terms, this justifies the assumption that population sustainability correlates with size distribution.

The size distribution of trees in a given forest stand is the crucial factor affecting the fate of trees, and size structure shifts in time from stand to stand in a whole forest, reflecting the regeneration process triggered by gap formation (Kohyama, 1993). Kohyama (1991) proposed a size structured model of rainforest trees in which established individuals shades and suppresses the growth of smaller trees and the recruitment of seedlings. Simulation with the model led to the convergence to a stationary tree-size distribution.

3.1.7 Methods for modelling the heterogeneity of forest structure

The structure of forests is an important factor in the analysis and management of forest ecosystems. Structural characteristics have been used to define spatial heterogeneity and temporal dynamics of understory vegetation, to investigate patterns of regeneration and gap dynamics, to explain micro-climatic variation, and to predict timber production (e.g Whittaker 1966; Spies & Franklin, 1989; Ong & Smith, 1992; Buongiorno *et al.*, 1994 and Chen & Franklin, 1995).

The measurement of structural heterogeneity, complexity, or diversity is, however not as simple as might be expected. Forest structure has been described, in the most general terms, as the distribution of biomass in space, that is a vertical and horizontal spatial arrangement of plant species, plant sizes or age distributions (Crow *et al.*, 1994) characterized by variation in species and age classes, arrangement of species into different canopy layers, and distribution of individuals into diameter classes (Smith, 1986). While these definitions recognize the 3-dimensionality of forest structure, quantitative, ecologically relevant measures of the full three dimensions of structural complexity that allow comparisons among forest stands are, however, still lacking.

Several 1-dimensional structural variables have been taken to represent forest structure, including stem density, basal area, canopy cover, the number of canopy layers and the mean and variation in tree sizes (Diameter and height) measure by coefficient of variation etc. (see Spies & Franklin, 1991). Such conventional stand

descriptors do not incorporate directly the vertical and horizontal spatial arrangement of the plants, and largely ignore the spatial character of forest structure.

Recently, researchers have begun to investigate 2-dimensional horizontal point patterns (x, y) of stem-mapped data with nearest neighbour analyses using Ripley' K-function or other tools (Kuuluvainen et al., 1996). The horizontal pattern of tree locations, which are typically classified into regular, random, and clustered patterns (Mouer, 1993) are thus incorporated into the description of forest structure. Observed spatial patterns have been linked to processes (tree mortality, competitive interaction, regeneration and gap creation, Pretzsch, 1997) believed to be responsible for the observed pattern and have enabled tests of several hypotheses (random mortality hypothesis, Kenkel, 1988).

3.1.8 Objective

The objective of the current study was to analyse the population structure of *Prunus africana* in relation to regenerational patterns. Inferences about past successional changes and predicted population trends could be provisionally drawn. Population structure data when employed for successional interpretation offers information on the potential changes that could occur in the forest.

The hypothesis tested was that *Prunus africana* has a gap-phase regeneration mode (*sensu* Veblen, 1992) which implies that an inverse J- shaped curve in diameter

distribution, growth release is due to canopy openings and that trees are clumped at the spatial scale of tree-fall gaps.

3.2 Methodology

The minimum DBH for inclusion in an inventory defines the sample size and therefore the completeness of the survey. Smaller DBH's yield more information per unit area of forest, but usually limit the overall geographical sample size. Larger DBH's sample fewer juvenile trees, but enable a larger area to be sampled. A compromise was sort by using a minimum DBH of 10 cm as recommended by Campbell (1989).

Sampling and measurement where undertaken in four forests (Table 3.1 and figure 3.1) where the forest had not been logged, burned or otherwise significantly altered by direct or indirect human activities. The forests represent a range of environmental conditions (altitude, rainfall, temperature) where *Prunus africana* occurs in Kenya. One stand within each forest was selected that had densities of *Prunus africana* representative of the given forests (about 4 trees per ha or more).

In order to assess the population structure and density of *Prunus africana*, in each study stand, sample plots were laid at each site, following a modification of the Plotless Sampling method of Cottam and Cutis (1956). In this method one *Prunus africana* tree (≥10 cm DBH) located approximately in the centre of the forest stand was used as a starting point, and a complete search carried out moving out in all directions until 50 *Prunus africana* trees were identified and measured. Trees were

numbered serially as they were identified and measured. For the 50 trees recorded, distances from one tree to the nearest conspecific neighbour, and diameter at breast height (DBH) of trees were measured. The area that was occupied by the 50 sampled trees in each forest was then determined. The number of saplings (trees <10 cm DBH and ≥ 1 m tall) in the same area were also counted. All trees were latter classified into 10 cm diameter classes. The frequencies of these categories were scored in each population and were used to determine the population structure of each individual stand.

Table 3.1 Study sites in order of altitude

Forest	Co-ordinates	Altitude (m)	Mean annual rainfall (mm)	Mean annual temperature (degrees C)
Timboroa	0°05'N, 35° 32'E	2745	1222	13.1
Elgeyo	0°20'N', 34° 59'E	2135	1063	15.0
Kinale	0°59'S, 36° 39'E	2380	1050	15.9
Kakamega	0°14'S, 34,° 52' E	1680	1905	17.0

3.3 Data analysis

Knowledge about population structure is useful for interpreting succession. To estimate population structure, seven 10 cm DBH size classes were arbitrarily established. The total numbers of individuals in each size class in each stand were divided by the total number of individuals, thus giving relative density of each size class for each stand. These relative frequency data for each size class provided an estimate of population structure and were used for evaluating the successional status of each forest stand. The analysis was then made on the basis of the

frequencies of individuals in each DBH class at each individual stand and of the combined data of all stands. Whereas age structure better reflects the history of recruitment, size structure may be a better predictor of short-term future composition of the forest (Veblen, 1992). Under constant conditions, negative exponential decline in number of individuals with increasing size can be interpreted as evidence of continuous recruitment and probable persistence of the species population (Veblen, 1992).
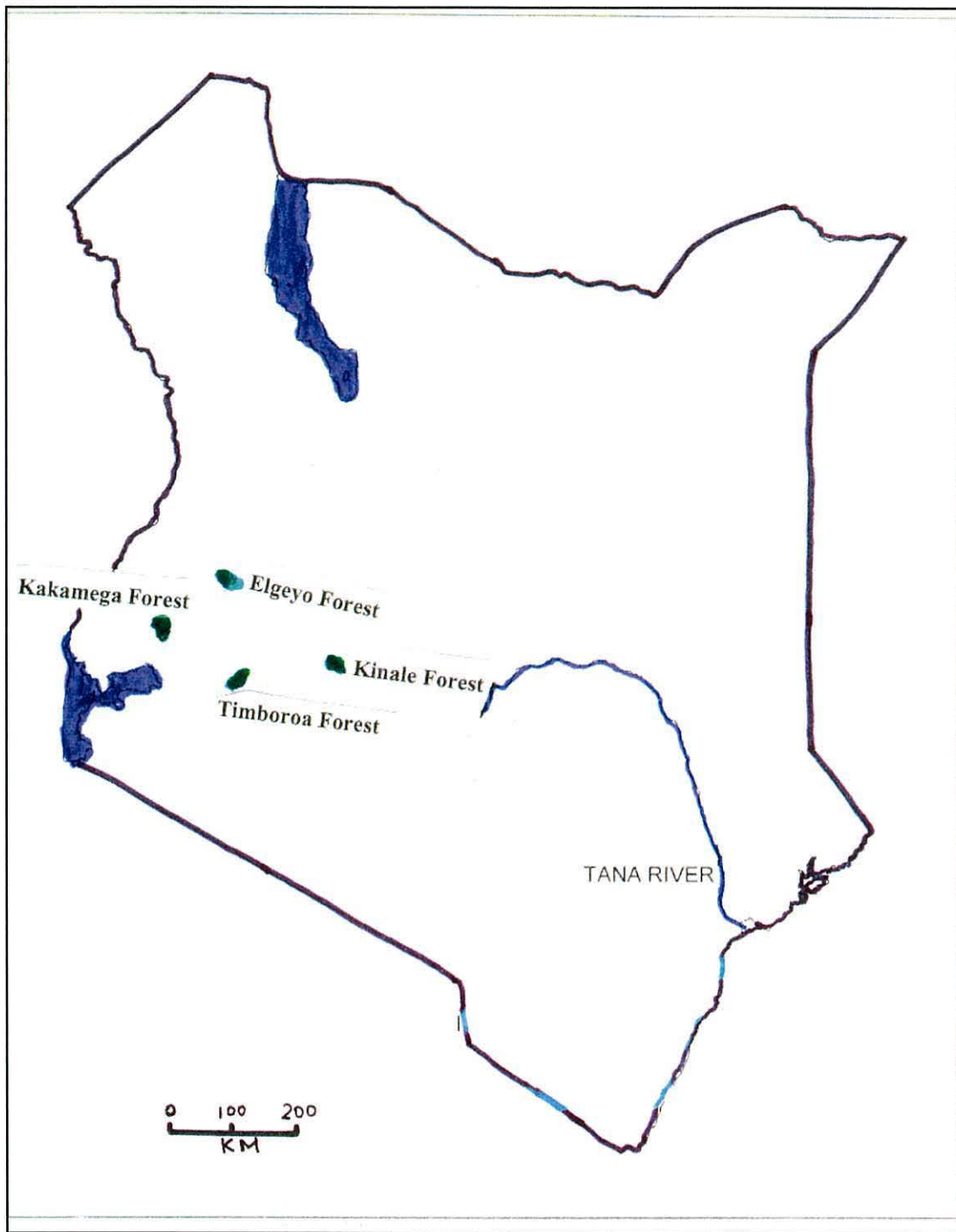
Figure 3.1 Study sites

3.4 Results

3.4.1 Population structure

A total of 200 individuals of *Prunus africana* were sampled in the four study sites (50 in each study site), ranging from 10 cm to 169 cm DBH (Figs. 3.2a-d) Kakamega site had peaks between 20 - 39 cm DBH while Elgeyo and Timboroa had peaks between 30 - 39 cm DBH and Kinale site had peaks between 40- 49 cm DBH (Table 3.2).

Table 3. 2a Diameter at breast height (DBH) and nearest conspecific neighbour distances for *Prunus africana* trees in Timboroa forest.

Area sampled = 4.6 ha

Tree density = 10.9 trees/ha, Sapling density = 2.4 saplings/ha

Tree Number	DBH (cm)	Neighbour distance (m)	Tree Number	DBH (cm)	Neighbour distance (m)
1	31	-	26	53	59
2	42	38	27	54	61
3	44	42	28	51	28
4	30	28	29	44	36
5	42	37	30	36	49
6	45	45	31	10	45
7	54	51	32	58	52
8	10	43	33	45	36
9	41	67	34	60	29
10	42	21	35	61	15
11	46	26	36	53	31
12	30	41	37	51	23
13	31	36	38	12	41
14	30	51	39	10	28
15	33	45	40	21	39
16	11	41	41	26	43
17	32	32	42	12	36
18	35	36	43	19	8
19	37	59	44	18	51
20	30	48	45	38	56
21	51	72	46	35	10
22	60	51	47	25	61
23	60	43	48	31	38
24	32	47	49	53	42
25	59	48	50	36	41

Table 3.2b Diameter at breast height (DBH) and nearest conspecific neighbour distances for *Prunus africana* trees in Elgeyo forest.

Area sampled = 12.3 ha

Tree density = 4.1 trees/ha, Sapling density = 0.7 saplings/ha

Tree Number	DBH (cm)	Neighbour distance (m)		Tree Number	DBH (cm)	Neighbour distance (m)
1	38	-		26	14	33
2	29	57		27	10	49
3	50	63		28	36	52
4	40	48		29	41	55
5	127	81		30	15	47
6	10	52		31	52	41
7	75	45		32	30	46
8	169	42		33	16	37
9	64	37		34	25	29
10	12	48		35	18	45
11	24	51		36	11	36
12	21	19		37	31	23
13	35	37		38	47	51
14	25	51		39	39	67
15	37	43		40	43	38
16	22	36		41	36	42
17	24	43		42	46	58
18	27	41		43	33	88
19	62	52		44	55	72
20	162	68		45	59	76
21	90	51		46	66	61
22	70	44		47	34	36
23	11	36		48	77	53
24	14	23		49	84	52
25	27	47		50	86	56

Table 3.2c Diameter at breast height (DBH) and nearest conspecific neighbour distances for *Prunus africana* trees in Kinale forest.

Area sampled= 5.7 ha

Tree density = 8.8 trees/ha, Sapling density = 1.1 saplings/ha

Tree Number	DBH (cm)	Neighbour distance (m)	Tree Number	DBH (cm)	Neighbour distance (m)
1	60	-	26	35	37
2	54	37	27	46	33
3	50	33	28	11	23
4	60	29	29	48	30
5	46	56	30	32	28
6	36	28	31	58	35
7	45	33	32	48	28
8	37	12	33	59	36
9	58	19	34	58	22
10	34	28	35	60	23
11	58	37	36	36	28
12	10	29	37	41	46
13	41	47	38	63	23
14	38	36	39	61	38
15	39	35	40	43	37
16	58	23	41	47	33
17	37	27	42	45	21
18	34	38	43	43	61
19	60	18	44	40	23
20	58	41	45	46	22
21	60	28	46	15	28
22	42	39	47	25	32
23	61	21	48	21	23
24	44	28	49	55	18
25	59	23	50	28	30

Table3.2d Diameter at breast height (DBH) and nearest conspecific neighbour distances for *Prunus africana* trees in Kakamega forest.

Area sampled = 8.2 ha

Tree density = 6.2 trees/ha, Sapling density = 1.0 saplings/ha

Tree Number	DBH (cm)	Neighbour distance (m)	Tree Number	DBH (cm)	Neighbour distance (m)
1	41	-	26	57	41
2	34	37	27	60	43
3	44	33	28	32	32
4	42	51	29	65	25
5	48	28	30	26	33
6	50	32	31	14	25
7	33	25	32	20	33
8	46	23	33	35	51
9	10	30	34	47	40
10	58	31	35	64	51
11	52	35	36	28	26
12	61	33	37	31	28
13	55	38	38	32	32
14	53	41	39	28	37
15	49	45	40	23	39
16	35	20	41	47	27
17	23	51	42	44	18
18	22	36	43	19	9
19	32	25	44	10	36
20	29	26	45	60	27
21	24	37	46	17	23
22	25	28	47	36	31
23	38	57	48	14	27
24	25	56	49	27	21
25	21	45	50	35	24

Table 3.3 Descriptive Statistics of diameter at breast height (DBH) (cm) in the four study sites

Site	Area (ha)	N	Mean	Median	StDev	SE Mean	Minimum	Maximum	Q1	Q3
Timboroa	4.6	50	37.44	36.50	15.17	2.15	10	61	30.00	51.00
Elgeyo	12.3	50	45.24	36.00	35.17	4.97	10	169	23.50	59.75
Kinale	5.7	50	44.8	45.5	13.79	1.95	10	63	36.75	58.00
Kakamega	8.2	50	35.90	34.5	15.75	2.23	10	65	24.75	48.25

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Elgeyo forest also had a high number of trees >70 cm DBH (Tables 3. 2b, 3.3 and Fig 3.2b). Examining diameter size classes in each of the four study sites identified the general patterns of population structure. *Prunus africana* populations in the four study sites are represented almost entirely by larger trees (Figures 3.2a-e and Table 3.4).

Table 3.4 Diameter frequency distribution of trees in the four study sites

DBH Classes (cm)	Study Sites and areas sampled (ha) respectively					
	Timboroa (4.6)	Elgeyo (12.3)	Kinale (5.7)	Kakamega (8.2)	Total (30.8)	Percentage
10 - 19	8	10	3	8	29	14.5
20 -29	3	9	3	11	26	13
30 - 39	16	10	10	11	47	23.5
40 - 49	9	5	15	9	38	19
50 - 59	10	4	11	6	31	15.5
60 - 69	4	3	8	5	20	10
≥70	0	9	0	0	9	4.5

The most abundant classes are the intermediate ones, with fewer larger and smaller individuals. The size structure distribution showed similar patterns in the four sites (Figures 3.2a-d), and appear to be typical for the species, as they now exist in the forests in Kenya.

A - Timboroa forest

B - Elgeyo forest

C - Kinale forest

D - Kakamega forest

E - All forest stands combined
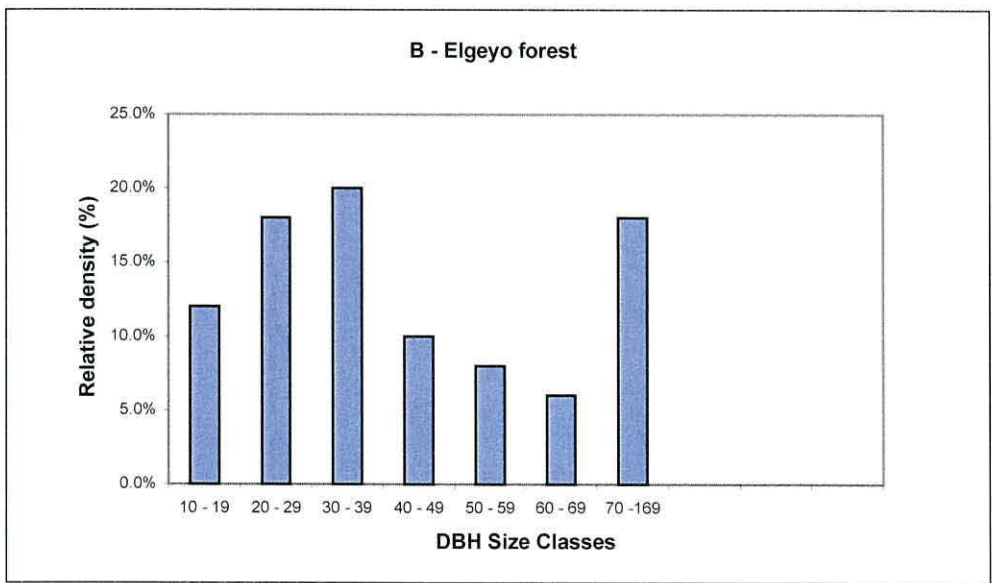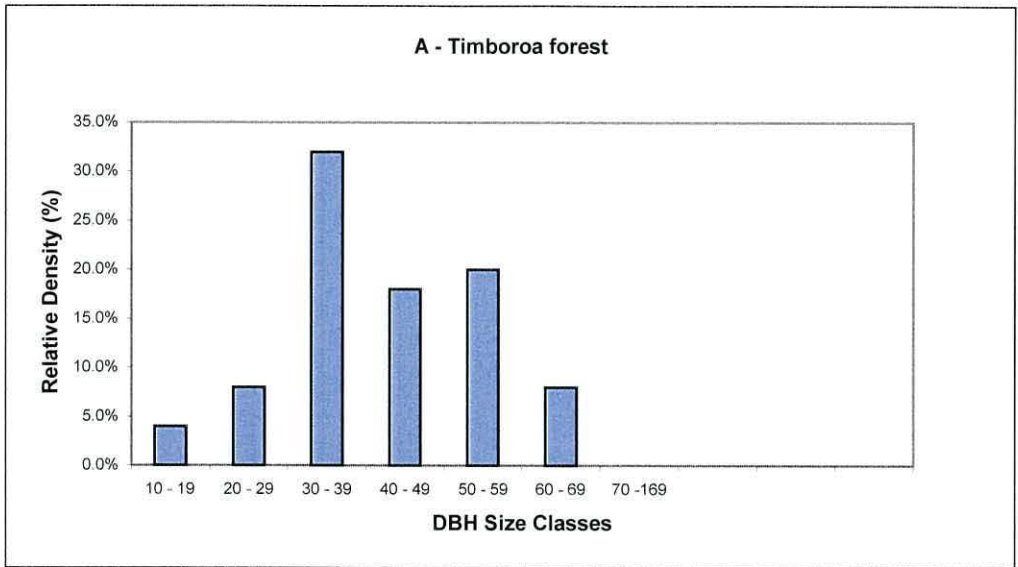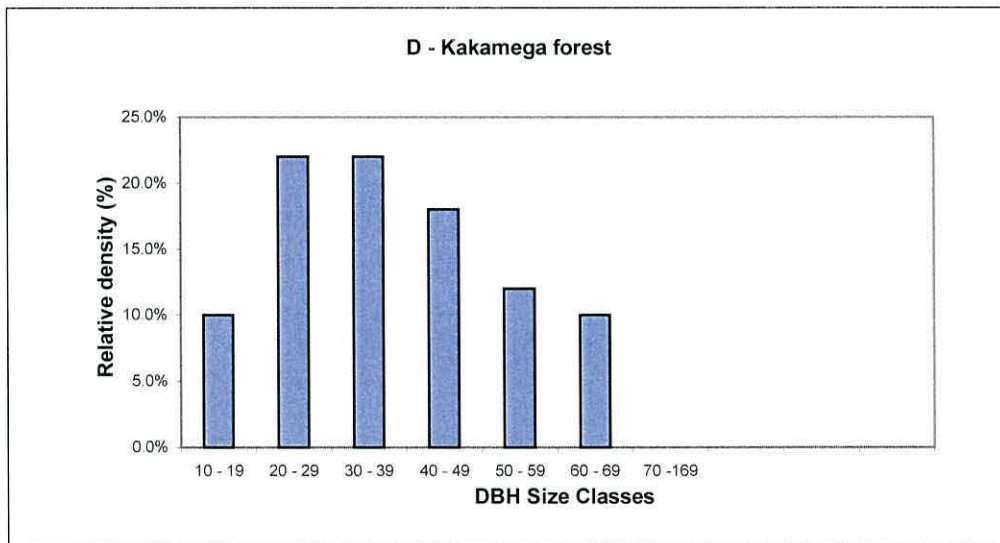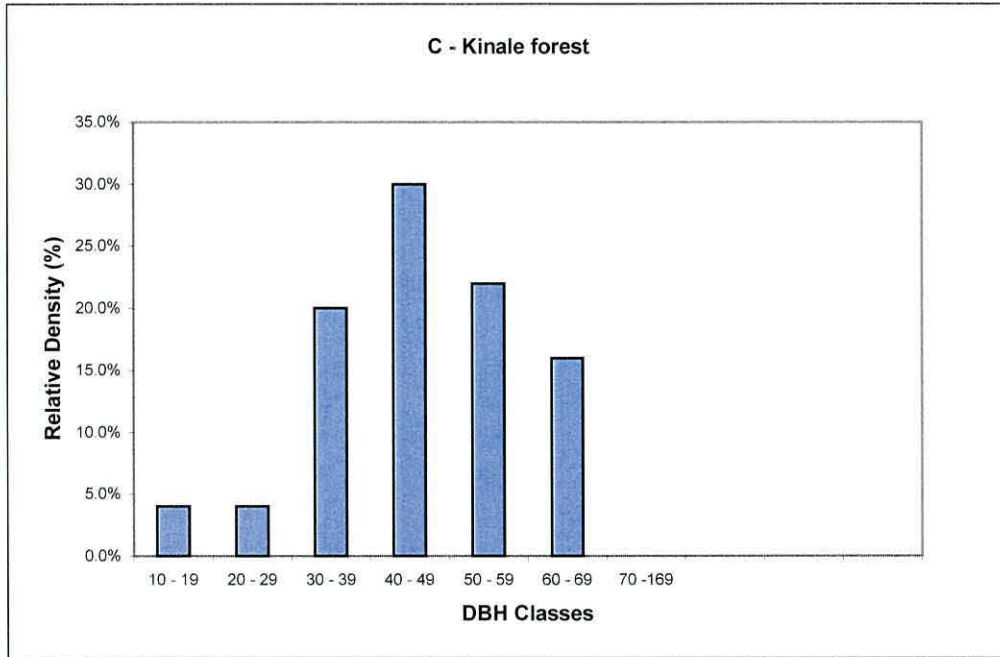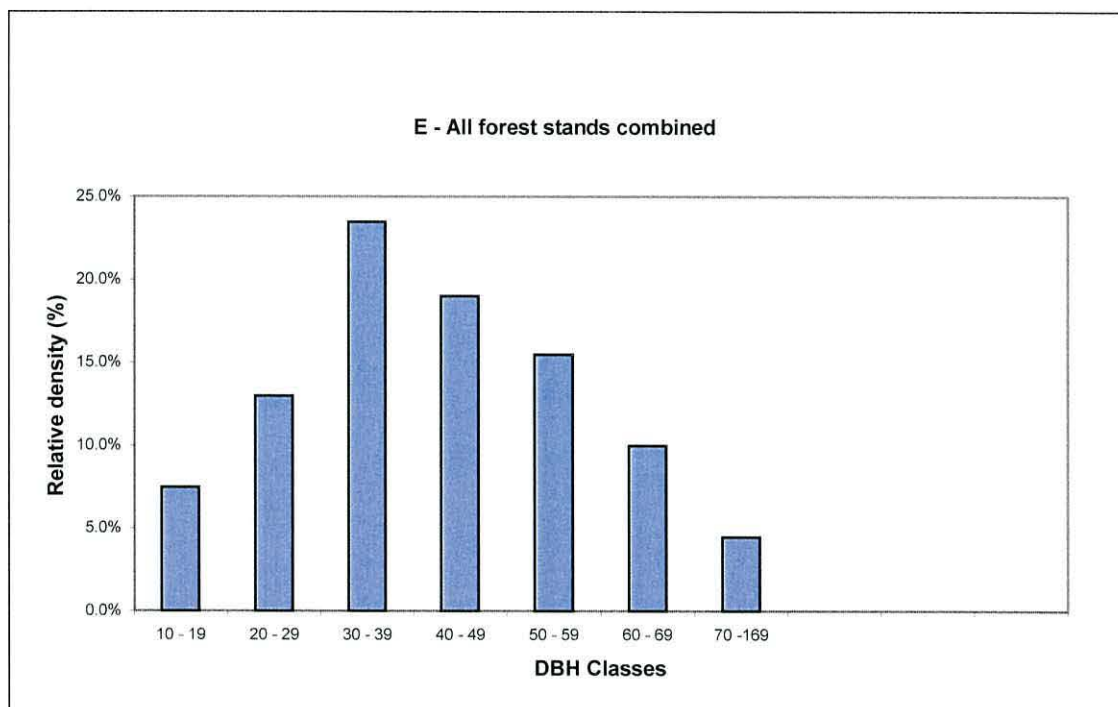
Figures 3.2A-E Population structure of *Prunus africana* in the four study stands. Combined (Fig 3.2E) represents pooled data from all the four stands

3.4.2 Tree density and distances to nearest conspecific neighbour

In the four study sites, the areas sampled ranged from 4.6 ha in Timboroa to 12.3 ha in Elgeyo (Table 3.5). The variability in sampling area was due to variation in distances between trees, and the requirement to sample 50 trees more than 10 cm DBH. A total of 17.67 hectares was sampled overall. The mean distances between trees were, 30.7, 33.5, 40.9 and 48.1 m for Kinale, Kakamega, Timboroa and Elgeyo respectively (Table 3.5). The mean area per tree ranged from 942.5 m² in Kinale to 2313 m² in Elgeyo. Tree density per hectare ranged from 4.3 stems/ha in Elgeyo

site to 10.6 stems/ha in Kinale, while sapling density ranged from 0.7 saplings/ha

in Elgeyo site to 2.4 saplings/ha in Timboroa.

Table 3.5 Area sampled, mean distances to nearest conspecific neighbour, tree and sapling densities and number of saplings for each study site and for combined data of all sites

Study Site	Area sampled (ha)	Mean distance (m)	Density Trees/ha	Density Sapling s/ha
Timboroa	4.6	40.9	10.9	2.4
Elgeyo	12.3	48.1	4.1	0.7
Kinale	5.7	30.7	8.8	1.1
Kakamega	8.1	33.5	6.2	0.9
Total	30.7	-	-	-
Mean	7.7	38.3	6	1.3/ha

Table 3.6 Descriptive Statistics of distances to nearest conspecific neighbour (m) in the four study sites

Site	N	Mean	Median	StDev	SE Mean	Minimum	Maximum	Q1	Q3
Timboroa	49	40.94	41.00	13.51	1.93	8.00	72.00	34.00	50.00
Elgeyo	49	48.12	47.00	14.14	2.02	19.00	88.00	37.50	54.00
Kinale	49	30.67	29.00	9.2	1.35	12.00	61.00	23.00	36.50
Kakamega	49	33.51	32.00	10.24	1.46	9.00	57.00	26.00	39.50

3.5 Discussion

The study shows that the density of *Prunus africana* is relatively low and a high

proportion (85.5%, Table 3.4) of trees is >20 cm DBH (n=200) within all sample

plots. It was observed that *Prunus africana* is most abundant along forest edges and on forest patches. In this study, the average density of trees >10cm DBH ranged from 4.1 stems/ha to 10.9 stems/ha and the mean is 6 trees/ha. The spatial pattern of sapling locations in *Prunus africana* was observed to be clumped, and could be linked to gap creation. Seedlings were arranged in clumps, with wide spacing between clumps. The spatial pattern trees, which might have resulted from gap recruitment, may have been affected by logging disturbances, tree falls or both. These types of disturbances usually result in patchwork patterns, which create the perfect environment for clumps of seedling recruitment.

Prunus africana populations in the four sites are represented almost entirely by larger trees (Figures 3.2a–d and Table 3.3), apparently because they have difficulty recruiting in the understory environment. The smaller size classes are missing (10-20 cm DBH) meaning sporadic or no recruitment during some past period. Under this scenario, the bias towards adult rather than sapling or pole abundance indicates an episodic recruitment whereby successful recruitment is followed by disappearance of conditions that permit establishment and survival of young juveniles.

Three of the four sites showed peaks of recruitment in the size classes between 30 and 39 cm DBH. Kinale site showed peaks of recruitment at diameter classes between 40-49 cm. Peaks in establishment may be attributed to climatic conditions

controlling seed or seedling ecophysiology, fluctuations in seed production, seed predation, herbivory, or increased canopy disturbances during that period.

Seedlings germinate in thousands under *Prunus africana* adult trees, but the species will probably become less common since very few individuals less than 10 cm DBH were encountered. This species could gradually be replaced in the forest by the abundant shade tolerant trees, unless gaps occur frequently enough to allow the recruitment.

The results of this study suggest either that *Prunus africana* is not reproducing as well as in the past [which is not the case since thousands of seedlings were counted in the next study (chapter 4 of this thesis)] or that individuals grow rapidly from seedling cohorts whenever a gap is created. The second possibility seems more likely for a light demanding species like *Prunus africana*, but data on growth rates would be essential for interpreting this pattern, if it is in fact true. Since exploitation of indigenous trees was banned seventeen years ago, there is no indication that seed sources are being lost through felling of mature trees; therefore lack of gaps created annually per hectare might be a possibility.

It appears therefore that chance plays an important role in recruitment of *Prunus africana* to larger diameter classes. After the seedling stage, the pattern that develops is determinate in its response to recognizable environmental

discontinuities, but probabilistic within these on a finer scale, thus producing irregularity in diameter class distribution. Recruitment therefore results in a variety of cohort combinations at any given site. If seedlings were included, a U- shaped population structure pattern could have resulted. This kind of species can be referred to as an 'infrequent' recruiter. Due to the great longevity (100 years and more) of *Prunus africana*, infrequent recruitment may be sufficient to maintain the current low density.

The heterogenous population structure of the shade-intolerant *Prunus africana*, in which tree groups of different diameter sizes are found in different forest stands, could be correlated with ages of gaps. This could explain a significant proportion of the variation in diameter distribution between different forest stands. Variation in light levels within gaps may affect the survivorship and growth rates of *Prunus africana* seedlings and saplings.

Adult *Prunus africana* trees flower profusely, seed production is high per tree, and seeds germinate readily under the canopy, but disease infection and herbivory of young seedlings is one of the major factors contributing to low recruitment. On the other hand sparse recruitment is not a rare phenomenon in tropical tree species, in some species recruitment events may be separated by gaps of more than 10 years without any perceptible change in overall population structure.

A stable population of any species displays a typical J-shaped, curve that represents relatively high numbers in smaller size classes and lower numbers with increasing age and size class through mortality. However, the populations of *Prunus africana* in the four study sites are in decline. There are fewer individuals in the lower size classes than in the mid-range-size classes.

3.6 Conclusions

Size structure suggests that *Prunus africana* recruitment into large size classes is episodic and may be dependent on fine-scale canopy openings, and therefore the species can be characterised as having a gap-phase regeneration mode. Selective logging of mature associated timber tree species is likely to produce canopy openings that can improve recruitment of *Prunus africana* juveniles

Although the pattern of diameter distribution in *Prunus africana* in natural closed canopy forests is unbalanced, there is a potential for sustainable management based on small scale gaps (tree-fall size) and spatial dynamics at stand scale need to be considered to ensure the regeneration of mature trees. Gap–based approaches (Coates & Burton, 1997) may provide a conceptual basis for sustainable management of this species in natural forests. This study and the study on patterns of seedling regeneration (Chapter 4 of this thesis) suggest that tree-fall gaps and density-dependent mortality may influence spatial patterns of recruitment. Consequently, the interactions between these two factors need to be better understood in order to explain and manage species regeneration.

CHAPTER IV

SEEDLING REGENERATION IN *PRUNUS AFRICANA* IN KAKAMEGA

FOREST, AND THE EFFECT OF DISEASE INFECTION AND HERBIVORY.

The first part of the chapter introduces the subject area, reviews key concepts relating to seedling regeneration and herbivory and disease infection in tree seedlings. The second part reports two studies, one conducted between August 2000 and January 2001 and another conducted between November 2001 and January 2002 in Kakamega Forest, Kenya. The first study examines the spatial pattern of seedling distribution relative to parent trees and how herbivory and disease incidence in seedlings varies with distances from parent trees. The second study analyses how herbivory and disease incidence vary among seedling stages and among trees. In the first study, surveys on the number of seedlings damaged by herbivores and pathogens were carried out in ten *Prunus africana* trees adopting a line transect method. In the second study a modification of the Adaptive Cluster Sampling method was used to assess the variation in herbivory and disease infection among four seedling stages in five *Prunus africana* trees.

4.1 Background information and objectives of the present study

4.1.1 Herbivory and its effects on plants

A complex of factors influences the successful regeneration of a tropical forest tree from seed to maturity. Studies on factors such as patterns of herbivore and

pathogen attack, or seed dispersal mechanisms, can reveal much about the variables determining success at different life phases and dispersal distances.

For most tree species, mortality rates are highest in the seedling stages. The processes causing early mortality can be critical determinants of adult abundance and distribution. Factors that affect offspring survival in relation to parent trees have been assumed important for the determination of the spatial pattern of trees. Species studies on factors that affect seedling survival and distribution in natural forest ecosystems are necessary to enhance understanding of spatial distribution of adult trees and processes shaping forest communities.

Herbivory is the term applied to the animal consumption of any plant material, and it ranges from 0% up to 100% leaf surface area removed (defoliation at this level of severity), but it is a common convention to use herbivory to indicate folivory (Lowman, 1997). Insects are the most abundant herbivores although birds and mammals also play important roles (Lowman, 1997). There are a number of insect guilds that feed on plants, including leaf chewers; leaf miners; gall formers; shoot, bud, twig, stem and root borers; sap suckers, and fruit and seed feeders (Hunter, 1997). Phytophagous insect species, excluding the mining and gall-forming guild, may be classified into defoliators and non-defoliators or suckers (Brown, 1982). Thus insect herbivores damage plants in a variety of ways, some being more obvious than others (Day & Leather, 1997).

Herbivory plays an important role in organisation of plant communities as well as being a selective force in the evolution of plant secondary chemicals and plant morphology (Hunter, 1997). Several workers (Brown, 1982, 1985; Brown *et al.* 1987) have experimentally shown that natural levels of insect herbivory can have substantial effects on species richness, plant cover and seedling establishment as well as influencing the growth, survival and reproduction of individual species. However, the effect of herbivory on host plants depends on a number of factors, including the herbivore species, type and amount of tissue removed and timing of defoliation, as well as host plant characteristics such as age, size and vigour (Crawley, 1997). Moreover, herbivore damage may be enhanced by abiotic factors such as inadequate moisture, light, and/or soil nutrients. These factors acting singly or in combination can significantly reduce plant growth and survival (Wright *et al.*, 1989) by reducing resistance (ability to avoid damage) and tolerance (ability to compensate for damage) to pests (Schroth *et al.*, 2000).

The number and type of insect herbivore greatly influence their impact on plants. Most of the serious damage to plants is caused when pests reach high densities; although some species cause considerable damage even when relatively few are present (Walter & Parry, 1994). Conway (1978) pointed out that few stem borers and sometimes-just one, may be sufficient to kill a tree. Whereas leaf-chewing herbivores may simply remove photosynthetic tissue, a sap-sucking herbivore or a long-lived pathogen will continuously drain carbon, nitrogen and other nutrients from the host (Ayres, 1992).

Different species of plants exhibit enormous variability in response to herbivory, with physiological and chemical defence attributes obviously contributing to these differences (Lowman, 1997). Brown *et al.* (1987) showed that under natural levels of insect herbivory *Vicia sativa* Linn. (Leguminosae) produced more leaves and *V. hirsuta* S.F.Gray (Leguminosae) fewer leaves than when herbivory was reduced. The authors further noted that in *V. sativa,* herbivory caused a reduction in the number of pods per plant and the number of seeds per pod, but no effect on individual seed weight while in *V. hirsuta* herbivory had no effect on pod or seed number but caused a reduction in seed weight. Similarly, in Australian dry sclerophyll forest, herbivore damage levels showed substantial differences with *Eucalyptus nova-anglica* Deane & Maiden (Myrtaceae) losing up to 300% leaf surface area a year, and *E. blakelyi* Maiden (Myrtaceae) as little as 4-10% (Lowman & Heatwole, 1992).

The physiological mechanisms of plant response to herbivory are complex and poorly understood (McNaughton, 1983; Wilson, 1988). Three broadly contrasting positions have apparently been hypothesised about the effects of herbivores on host plant fitness. The first, which dominates the literature on plant-herbivore interactions, is the hypothesis that herbivory is always detrimental to the host plant (McNaughton, 1983) (Position 1). A second hypothesis is that host plants can compensate for low levels of herbivory, so that there is no net change in fitness until some level of herbivory is reached that leads to a lower fitness (Position 2). A

third and relatively minority viewpoint (McNaughton, 1983) is that moderate levels of herbivory may result in overcompensation by the host plant, due to intrinsic or extrinsic consequences of herbivory, so that plant fitness is increased by low levels of herbivory (Prins & Verkaar, 1992) (Position 3). These views are in line with earlier findings by Mattson & Addy (1975) that insect herbivory can have a positive, negative, or neutral effect on plant growth in forest ecosystems. I therefore intend to see which of these three hypotheses best explains *Prunus africana* data.

Many researchers (Piene & Percy, 1984; Ericsson *et al.* 1985; Haukioja *et al.*, 1990) have established that herbivory affects the synthesis, transport, allocation and conversion of essential plant growth factors. Herbivores remove parts of the mineral capital of the plant, part of its carbon reserves and photosynthetic machinery that would have captured more energy and carbon and, indirectly nutrients (Ericsson *et al.* 1985, Haukioja & Honkanen, 1997). Herbivory may also simultaneously damage tissues that are elements of the hormonal control system by which plants regulate intake and allocation of resources (Haukioja *et al.*, 1990) thus disrupting the physiological events associated with hormonal controls. Plant hormones such as auxins occur in high concentrations in stem tips, young leaves, and flowers and are very important in cell elongation in shoots and stimulate cambial activity and root primordia formation (Barbosa & Wagner, 1989). Destruction of buds and lack of photosynthetic activity in defoliated species can thus result in decreased availability of carbohydrates and the hormones that are translocated with them (Bassman & Dickmann, 1985; Barbosa &Wagner, 1989).

Therefore any feeding that impairs or destroys one part of a plant can have complex and far-reaching effects on both neighbouring and distant parts of the plant. Reichie *et al.* (1973) noted that damage to foliage might reduce apical growth, activate dormant buds, cause twig death, or significantly increase the leaching of nutrients to the understory. Defoliation may thus compromise plants' ability to cope with environmental stress. A compromised plant may have a shorter stem, causing it to be increasingly shaded by neighbours, or shallower root system, making it more prone to drought (Ayres, 1992). The continuum of plant responses to herbivory illustrates the importance of identifying conditions under which plants response differently to herbivory.

4.1.2 Disease in plants

Disease is a disturbance in the normal physiological functioning of a plant, has many causes, and exhibits an array of appearances and results (Manion, 1981). Any agent that causes disease is a pathogen and may either be biotic such as fungi or abiotic such as air pollution. Some pathogens are parasites, but not all parasites are pathogens. Any organism that lives on and derives nutrients from another organism is a parasite, but only those parasites that cause a disruption in the normal physiological function of the host are classified as pathogens (Manion, 1981). Biotic diseases, because infectious agents cause them, usually show a clumped distribution pattern of diseased individuals (Horsfall & Cowling, 1977). Inoculum produced by diseased individuals is most concentrated around the

diseased individuals, thereby contributing to a higher incidence of disease in localized areas. Only with initial infection caused by inoculum dispersed from a distance does the distribution of disease approach randomness (Manion, 1981). Topographic features that produce moisture or temperature conditions favourable for inoculum production, dispersal and infection may contribute to the clumped disease distribution patterns typical of biotic diseases. Abiotic diseases are usually random in a population except when the agent is distributed in a non-random manner.

The importance of damping-off organisms and other plant pathogens to tree seedlings in natural forest has received little attention, but may be a common cause of death in small seedlings. Damping-off is a frequent cause of mortality in newly germinated seedlings, and is caused by soil-borne fungi. Newly germinated seedlings of *Platypodium elegans* (Pittier) H.C. Lima (Leguminosae) suffered density and distance-dependent mortality from damping-off on Barro Colorado island (Augspurger & Kelly, 1984). Seeds were sown at two densities in shade houses imitating small gaps and understory conditions. Light was found to be more important than density in determining the likelihood of damping-off, with most mortality in deep shade.

4.1.3 Seedling dispersal and diversity of tropical forests

To explain high species diversity in tropical forests, Janzen (1970) and Connell (1971) hypothesised disproportionately high seed and seedling mortality close to adult conspecifics {("distance hypothesis") (Hypothesis A)} or in sites of greater juvenile conspecific density {("density hypothesis") (Hypothesis B)}. They proposed that seedling predators, herbivores, or pathogens caused the high mortality. One expected outcome of the increased mortality in adult proximity is a spatial pattern characterised by the lack of juvenile individuals in the vicinity of adults (Clark & Clark, 1984; Sterner et al. 1986; Condit et al. 199; Itoh et al. 1997; and Okuda et al. 1997). Because of higher mortality close to adults, Janzen and Connell predicted that maximum population recruitment should occur at some (unspecified) distance from the parent tree {("spacing hypothesis") (Hypothesis C)}. Distance-dependent mortality should also decrease the clumping of progeny around adults compared to that in the initial seed shadow (Janzen, 1970). The lower recruitment probability near adult conspecifics increases the probability of establishment of non-conspecifics, and thereby maintains high species diversity. Howe & Smallwood (1982) combined hypotheses A and B into an "escape hypothesis" (Hypothesis D) since progeny density is correlated with proximity to adult conspecifics.

Janzen and Connell proposed that species-specific predators inflict more mortality on seeds and seedlings near adults than at greater distances. This might be due to the high density of seeds or seedlings close to adults or abundance on the foliage of

adults and subsequent discovery the seedlings nearby. This hypothesis has been expanded to include other lethal agents of seeds and seedlings, notably parasites and pathogens (Augspurger 1983a, 1983b; Kitajima & Augspurger 1989).

The more general model {("compensatory hypothesis") (Hypothesis E)} of Connell (1978) and Connell *et al.* (1984) embraces the preceding distance and density hypotheses. This hypothesis states that at any site, rare species are favoured over common ones. For more abundant species the rates of recruitment, growth, or survival are lower than those for rare species. The conspecifics of commoner species are nearer than those of rare species, and the close proximity between them could cause attacks by natural enemies (predators, herbivores, pathogens), interference, or competition. Thus compensatory mechanisms should increase the abundances of rare species at the expense of more common ones, and species diversity would be maintained.

4.1.4 Factors influencing seedling distribution

Regeneration of tree species can be characterised by the scale of disturbances and environmental heterogeneity to which the species responds, and by the spatial relationships between adults and juveniles (Grau, 1999). In the absence of large-scale catastrophic disturbances, regeneration dynamics is strongly influenced by endogenous factors. These factors include:

• tree fall gaps

•density-dependent mortality of seed and seedlings due to pathogens, herbivores and predators

•short distance dispersal, allelopathy, competition between offspring and parents or between siblings for resources

•local heterogeneity of the physical environment (Kozlowski, 1949; Harper, 1977; Auspurger, 1984; Grubb, 1986; Veblen, 1992; Willson 1993; Forget 1994).

Studies on such individual factors can reveal much about the variables determining success at different levels.

Reviews of literature on factors controlling tropical seedling distribution have interpreted the body of articles on the Janzen-Connell hypothesis in different ways. Lieberman (1996) argues that community-wide analyses reveal a general absence of compensatory mechanisms caused by nearness to adult conspecifics and that species that show density-dependence appear to be the exception. Coley & Barone (1996) state that 63 % of the tree species studied in 36 studies where found to have some degree of higher mortality or damage near conspecific adults. On the other hand, Burkey (1994) found that an abundant species, *Brosimum alicastrum* SW (Urticaceae), seems to override the Janzen-Connell effect by producing very large amounts of fruits, satiating predators and herbivores. Nichols *et al.* (1999) argue that, if a herbivore has equal probability of finding and attacking a seedling throughout a forest block, then distance to conspecific adults may not be of significance, whereas a high density clump of seedlings, which might be found in a large gap, may be subject to destruction by herbivores regardless of its location in relation to adult trees.

Hypotheses A-E have theoretical merit, each can account for the coexistence of a large number of species, but data are not presently available to determine which are in force in a particular forest (Condit *et al.* 1992).

Forest species composition and diversity vary in broadly predictable ways in relation to environment and biogeography. However, we still know relatively little about the population-level processes, which produce these patterns. We do not know the extent to which local abundance of a tropical tree species like *Prunus africana* is constrained by the fecundity of parent trees, by availability of suitable germination sites, or by early survivorship in the face of seed predation, herbivory, pathogens, competition and access to resources.

4.1.5 Parent-offspring spatial relationship in trees

The seed shadow of a plant is a gradient where seed density decreases monotonically from parents (Harper, 1977). Seed dispersal generates seedling spatial patterns that depend on the height and canopy projected area of the adult trees. In the absence of seed predation, and everything else being equal, seedling density will decrease in the same proportion as seed density. If seedling predators are density-responsive, they will concentrate their foraging near parent plants. If seedling consumption is intense near parents, seedling density will increase with distance; but if seedling predators are inversely-density responsive, they will concentrate their foraging on the tail of the seed shadow and seedling density will

decrease with distance. On the other hand, if seedling predators are insensitive to seedling density, no relationship between seedling predation and seedling density is expected.

Models advanced to predict parent-offspring spatial relationships in plants often assume that parent plants generate a leptokurtic seed shadow (Willson, 1992, 1993), which in turn affects seed predators. If seed predators are density or distance responsive, seed survival probability will be low near parents. Consequently, the population recruitment curve (PRC) – evaluated as seedling abundance - will yield a peak away from the parents (Janzen, 1970). Alternative population recruitment curves have been derived considering: satiation of predators (Hubell, 1980); canopy gaps as recruitment foci for seedlings (Becker *et al.* 1985); and seed deposition patterns of frugivores (Howe, 1989).

Changes in the number of individuals and their spatial pattern during the transition from seeds to saplings have important implications for the fitness of the parent, the size and the genetic and spatial structure of populations and ultimately, species diversity and pattern within the community.

The location where offspring are successfully recruited depends upon both the number of seeds dispersed to any distance from the parent and the probability of their survival (Janzen, 1970). Dispersal is generally viewed as an adaptation to increase the probability of survival of offspring, although the dispersal distance

required to maximize any increase is generally unknown (Augspurger, 1983). Dispersal also increases the survival probability by moving offspring to new or vacant sites, (Hamilton & May, 1977) or to more suitable habitat, (Gadgil, 1971) or both. Increased dispersal distance also increases the probability of encountering a light gap.

4.1.6 General Objectives of the studies

The general objectives of the studies 4.3 and 4.4 were to develop an understanding of the relative roles of herbivory and disease on regeneration of *Prunus africana* seedlings in a natural forest.

4.2 Study site

4.2.1 Introduction

Kakamega Forest (Plate 4.1) is generally considered to be the easternmost limit in today's climate of the lowland Guineo Congolean rainforest of central Africa (White, 1983) that in the past millenium stretched across the entire expanse of central to eastern Africa (IUCN, 1995). Faunally and florally, Kakamega is dominated by central African lowland species, but due to its elevation (1,400-2,300 meters (4,000-7,000 ft.) and proximity to the formerly contiguous Nandi Forests it also contains well-represented highland elements and is thus unique (Zimmermann, 1972). Thus, Kakamega Forest is a significant island of biodiversity

that has developed along its own unique evolutionary course for thousands of years and which shows a high level of endemism (IUCN, 1995).
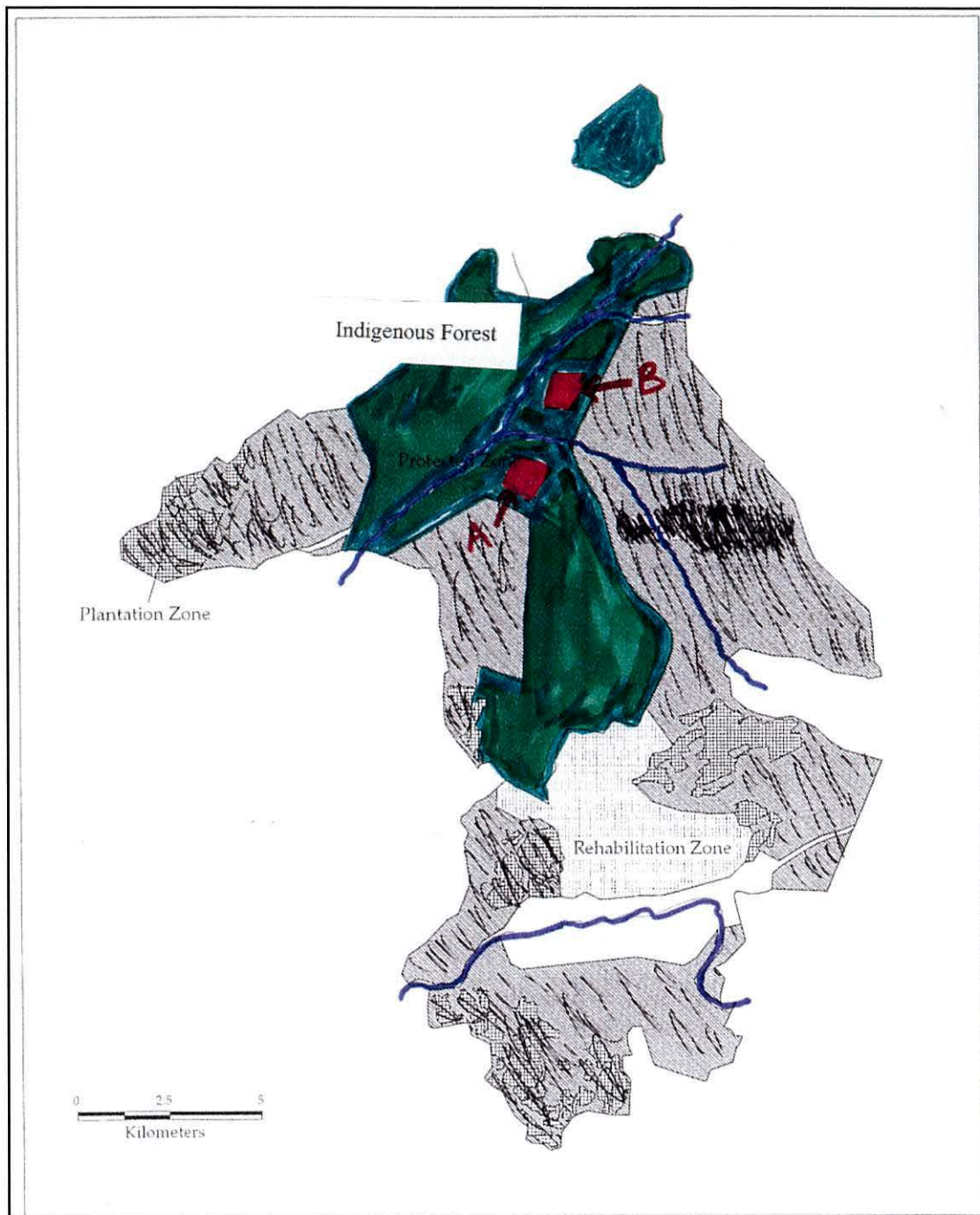
Figure 4.1 Map of Kakamega forest showing the location of the study sites

The forest gazetted area is 238 Km^2, but less than half of this is still indigenous forest, and the indigenous forest has been extensively disturbed.

Throughout the forest are grassy glades (Plate 4.1), from about 1 ha to 50 ha in area, with a few still larger. The origin of these glades is uncertain. Some are certainly recent clearings, but others, which predate existing records, may have originated from past human activity such as cattle grazing or may be the result of movements by large herbivores, such as buffalo and elephants. Up to 20% of all Kenyan plant and animal species occur only here. Plants, and especially orchids, are found in extremely high diversity. Over 380 plant species have been identified in Kakamega Forest. This enormous diversity has not been fully studied. Opportunities for scientific studies are abundant in Kakamega and are of crucial importance to the conservation of its unique ecosystem and the flora and fauna.

Plate 4.1 a section of Kakamega forest, arrow showing the sampling area

Kakamega Forest was ranked as the third highest priority for conservation (after Arabuko sokoke and Shimba hills, both at the coast) among forests in Kenya by the International Union of Conservation of Nature (IUCN) in 1995. This was due to both species richness and habitat rarity, which are both high priorities for conservation in Kakamega Forest. The great pressure of harvesting on the forest threatens species. Kakamega Forest is severely over-exploited due to its small size and its location in a densely populated agricultural area (600 people per square km). Legal (and illegal) collection of fuel wood is hastening the deterioration of the forest, along with over-harvesting of various plants for local medicinal use, poles for construction of new homes, and fibre for ropes. These activities are severely depleting the forested land.

Illegal harvesting along with poor but legal logging management has resulted in alarming rates of deforestation. Over 50% of the forest has been lost in the last 25 years (IUCN, 1995). Not only is the forest growing smaller, but also it is being fragmented into islands of indigenous growth separated by clear cuts and forest plantations.

4.2.2 Geology

Basalt, phenolites, and ancient gneisses underlie Kakamega Forest and are covered by a layer of clay-loam soil (GOK, 1994a). Most of these rocks have been weathered to form moderately fertile clay soils (GOK, 1994a, KIFCON, 1994a). These soils are dependent on the decomposition and reincorporation of dead

organic matter. Fertility of the soils has dropped as illegal loggers and local families have increasingly removed wood.

4.2.3 Climate

The annual rainfall amounts vary between 1000 mm and 2400mm with a long-term mean of 2109 mm (GOK, 1994a, KIFCON 1994a). Rainfall is heaviest in April and May (during the "long rains"), with a slightly drier June and a second peak of rain roughly in September to November (the "short rains"). January and February are the driest months. The temperature is fairly constant through the year, with an annual mean daily minimum temperature of 11^0 C and an annual mean maximum of about 26^0 C.

4.2.4 Plant Communities

Kakamega forest corresponds to White's (1983) Transitional rain forest in the Guineo-Congolian biogeographical region. In addition to areas classified as "virgin" rain forest, the forest can be classified into various other categories including: colonizing forest, disturbed forest, clearings made for pit-sawing and charcoal burning, plantation areas, natural glades, swamps, and riparian forest (KIFCON, 1994a). Like rainforests elsewhere, the physical structure of Kakamega Forest is complex, consisting of multiple layers of vegetation. The trees are usually well buttressed at the base. Though a variety of hypotheses have been proposed, it is most likely that buttresses have the obvious function of supporting shallowly

rooted trees. Also like other rainforests, diversity is high. There are over 150 documented species of woody trees, shrubs and vines, and 170 species of herbs of which 60 are orchids. Nine of these orchids are only found in Kakamega rainforest. In addition, there are 62 species of ferns (KIFCON, 1994b). All totalled there are over 380 documented plant species. Gaps in the forest canopy are frequent, which allows for succession and the maintenance of species diversity. Some of the commercially important tree species found in Kakamega forest include the following: *Afromontanum* sp., *Albizia gummifera*, *Aningeria altissima*, *Antiaris toxicaria*, *Bersama* sp., *Brillantasia cicatroza*, *Chrysophyllum albidum*, *Cordia abyssinica*, *Croton megalocarpus*, *Dracaena* sp., *Fagara mildbraedii*, *Harungana* sp., *Impatiens stuhlmannii.*, *Maesopsis* sp., *Markhamia lutea.*, Milicia excelsa, *Olea capensis*, *Polyscias* sp., *Prunus africana*, *Trema* sp. (KIFCON, 1994b).

4.2.5 Current management and use

Kakamega forest has been managed for tourist attraction as well for woody and non-wood products as the only tropical rainforest in Kenya. Before 1960's, the demand for forest products was low especially for indigenous hardwoods. Only selective felling of indigenous species was carried out in selected compartments in the forest (Wachihi pers.comm. 2000).

Increased demand for timber and other forest products in the recent past has led to indigenous species being illegally exploited in the forest. Exotic species are being

exploited legally. Demand for settlement and agricultural land has led to the excision of some parts of the forest, thereby reducing its area.

4.3 Spatial pattern of natural regeneration relative to parent trees in *Prunus africana*

The specific objectives of this study were:

• to determine the spatial pattern of seedling distribution relative to parent trees

•to examine how herbivory and disease incidence vary among trees and with distance from parent trees.

An understanding of spatial pattern of seedling regeneration in trees and the effect of herbivores and pathogens require information on parameters such as the number of seedlings of a given age or size and proportions of seedlings infected by disease and those attacked by herbivores at various distances from the parent tree.

4.3.1 Materials and methods

This study was carried out in a natural forest stand in Kakamega forest reserve (Fig 4.1, point A), and it took place between August 2000 and January 2001. A natural stand in this case is defined as a natural forest where most of the species present where not planted except for limited enrichment planting. In Kakamega the peak flowering season of *Prunus africana* occurs in the months of June to August, although sporadic flowering occurs all year round. Based on information obtained from the forest office, a natural stand was identified where *Prunus africana* was abundant because the species density is generally very low. Once the stand was identified as shown in figure 4.1, a random point was chosen in the centre of the stand. A point-centred quarter sampling approach was adopted (Bullock, 1996). Two perpendicular straight lines, which cross each other on the sample point, were

measured out. This created four sampling units (quarters). In each quarter, and starting from the random point, the nearest mature and seeding *Prunus africana* tree was identified. Thereafter, a second tree nearest to the first one but at least fifty meters from the first one and within the quarter was identified. The same procedure was used in the other quarters until ten trees were identified in total, at least two from each quarter. For a tree to qualify to be selected it had to be seeding and at least fifty meters from the last sampled tree. For each tree, DBH, height and general information of the microenvironment in which the tree was growing was recorded, and is presented on table 4.1.

Table 4.1 General information associated with each parent tree

Tree No.	DBH (cm)	Height (m)	Location within forest	Other information
1	39	29	Edge	Open – no undergrowth
2	35	27	Inside	Average density undergrowth
3	42	30	Inside	Average density undergrowth
4	36	31	Inside	Dense undergrowth
5	38	28	Edge	Open – no undergrowth
6	41	33	Inside	Average density undergrowth
7	40	29	Inside	Average density undergrowth
8	45	34	Inside	Average density undergrowth
9	40	30	Inside	Average density undergrowth
10	43	31	Inside	Average density undergrowth

Key. 1. Open – (no undergrowth) – less than 10% undergrowth per unit area

2. Average density undergrowth – 10-50% undergrowth per unit area

3. Dense undergrowth – more than 50% undergrowth per unit area

To assess the pattern of natural regeneration relative to the parent trees, four transects, measuring 20m each from the base of the parent tree were established. 0.5x0.5m quadrat size was deemed most convenient for sampling in this study, and was used to sample along the transects at two meter intervals from the parent tree up to 20 m. In each quadrat seedlings were identified, counted and the health status recorded. Recorded seedlings were marked to ensure that nothing was counted more than once and nothing was missed. *Prunus africana* seedlings undergo four distinct stages that can be recognized on the basis of the fixed number of leaves present at each stage (Tsingalia, 1989). Two stages of seedling development were studied. The stage of development of each seedling was recorded as:

• Young seedlings ≤ 25 cm in height (stage 1) with two or less green leaves without an apparent meristem (Clark & Clark, 1985). Most of the seedlings in this category would be about one year old or less.

• Old seedlings > 25 ≤ 100 cm in height (stage 2) with four or more leaves and a distinct meristem. Most of the seedlings in this category would be more than one year old.

For each seedling the health status was recorded as:

(i) damaged by herbivory (seedlings with parts of their foliage missing or with holes in their foliage)

(ii) diseased (seedlings that had lost its original colour through decay, had brown patches or had signs of rotting)

(iii) healthy – seedlings with no sign of herbivory or disease.

4.3.2 Data analysis

To test whether herbivory, disease incidence and seedling abundance were related to distance from parent trees; one-way ANOVA tests where carried out to decide whether the prevalence of seedling attack by disease or herbivores was correlated with distance from parent tree. Seedling abundance, disease incidence and herbivory were analysed by comparing ten different distances from the parent tree. Number of seedlings per given distance for the tree concerned (as a percentage of the total seedling count for that tree) was used to compare seedling abundance at various distances. Disease incidence and herbivory as percentages of the total count of seedlings for the distance and tree concerned was used to asses variation in disease incidence and herbivory. The data was regressed against distances from parent tree. Percentages of disease incidence and herbivory were arcsine transformed before ANOVA to normalize the data.

4.3.3 Results

4.3.3.1. Seedling abundance

The original data set as recorded in the field is presented in appendices 1a-i.

Table 4.2. shows total count of seedlings at each distance interval in the ten study trees. 43.4% of all seedlings where disease infected, 39.0 had been attacked by herbivores and 17.5% where healthy (Fig. 4.2). Seedling abundance along transects decreased with increasing distance from the parent trees (Fig. 4.3). Statistically

significant (ANOVA, P<0.001) variation in seedling abundance occurred between distances from parent trees; among trees and between the stages of seedling development (Tab. 4.3). The highest abundance occurred two to four meters from the parent trees (mean distance 3 meters) (Fig. 4.3), and was statistically significant (Table 4.4), variation among trees (Table 4.5) and between stages (Table 4.6) was also statistically significant. Seedling abundance was positively correlated with disease infection, and inversely related to distance from parent trees (r = 0.363 and - 0.381 Resp.) (Tab. 4.7) and was statistically significant. The relationship between herbivory and seedling abundance was not statistically significant. Herbivory was positively correlated with disease incidence (r=0.408) and inversely correlated to distance from parent tree (r= 0.538).

Table 4.2 Total count of all identifiable individual seedlings ≤ 100 cm tall at each distance of the ten study trees.

	Distance from parent tree (m)											
	1	3	5	7	9	11	13	15	17	19	Total	Total area
Area (m²)→	1	1	1	1	1	1	1	1	1	1	10	
Tree↓												
1	442	397	355	275	352	268	221	177	86	0	2573	10
2	88	180	126	133	102	46	0	0	0	0	675	10
3	220	253	225	228	172	135	85	38	34	0	1390	10
4	43	77	52	44	54	5	0	0	0	0	282	10
5	49	132	103	94	51	2	0	0	0	15	442	10
6	569	660	794	440	481	440	364	309	73	0	4129	10
7	134	202	174	180	143	95	41	0	0	0	985	10
8	490	484	447	391	400	312	263	221	47	0	3056	10
9	263	308	266	261	219	184	139	91	32	0	1763	10
10	310	355	304	310	308	220	172	133	52	0	2164	10
Total	2608	3047	2846	2356	2282	1707	1285	969	324	15	17459	100
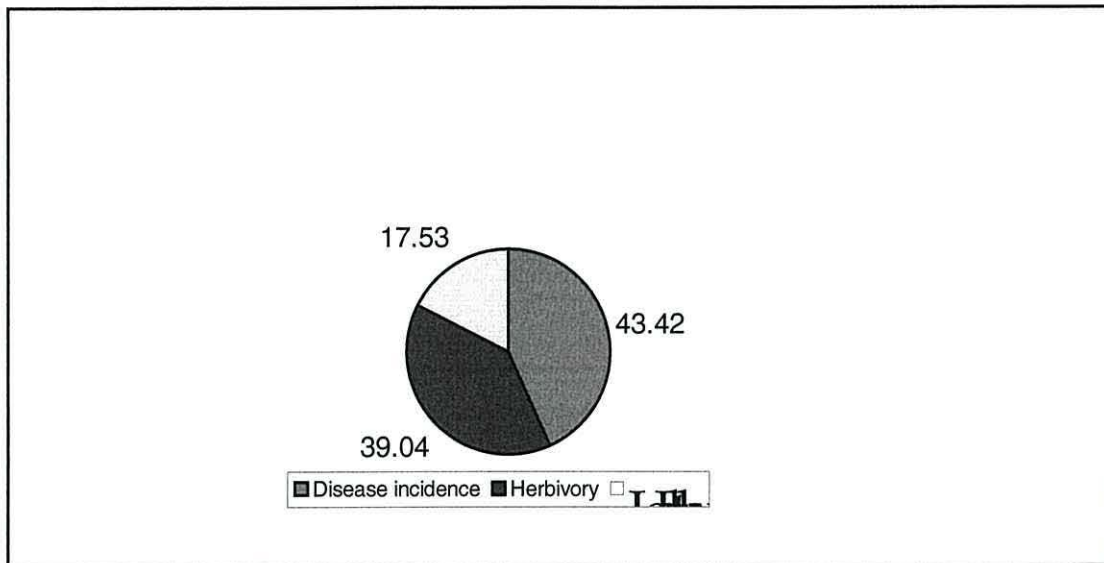
Figure 4.2 Proportion of disease infected, healthy and herbivore attacked seedlings ≤ 100 cm tall.
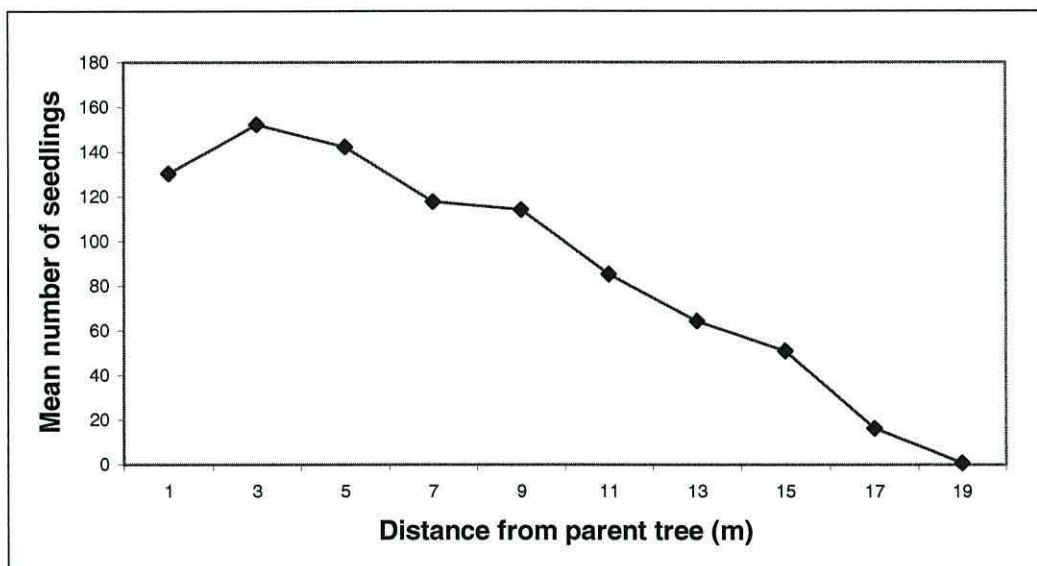
Figure 4.3 Relationship between abundance of seedlings ≤ 100 cm tall and distance from parent tree.

Table 4.3 Analysis of Variance for seedling abundance (m²).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
STAGE	1	551971.014	551971.014	421.53	0.0001
TREE	9	741034.915	82337.216	62.88	0.0001
DISTANCE	9	653275.713	72586.190	55.43	0.0001
TREE*DISTANCE	81	188728.677	2329.984	1.78	0.0101
TREE*STAGE	9	278760.160	30973.351	23.65	0.0001
STAGE*DISTANCE	9	297255.849	33028.428	25.22	0.0001
Error	60	78567.080	1309.451		
Corrected Total	178	2789593.408			

Table 4.4 Duncan's Multiple Range Test for variability in total seedling abundance (m²) by distance; Alpha= 0.05, df= 60. Means with the same letter are not significantly different

Duncan Grouping			Mean	N	DISTANCE
	A		152.35	20	3
B	A		142.30	20	5
B	A	C	130.40	20	1
B		C	117.80	20	7
D		C	114.10	20	9
E	D		89.74	19	11
E	F		75.59	17	13
F			60.56	16	15
	G		20.25	16	17
	G		1.36	11	19

Table 4.5 Duncan's Multiple Range Test for variability in total seedling abundance (m²) by tree; Alpha= 0.05, df= 60. Means with the same letter are not significantly different

Duncan Grouping		Mean	N	TREE
A		217.37	19	6
B		160.79	19	8
C		135.37	19	1
D	C	113.89	19	10
D	E	92.79	19	9
F	E	73.16	19	3
F	G	57.00	17	7
H	G	42.19	16	2
H		27.75	16	5
H		17.19	16	4

Table 4.6 Duncan's Multiple Range Test for variability in seedling abundance (m²) by stage; Alpha= 0.05, df= 60. Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	STAGE
A	146.770	100	1
B	34.937	79	2

Table 4.7 Pearson correlation values (r²) for seedling abundance, percentage disease incidence, percentage herbivory and distance from parent trees

Factors	r value	P value
Abundance * disease	0.363	0.001
Abundance * herbivory	-0.089	0.239
Disease * herbivory	0.408	0.001
Distance * disease	-0.425	0.001
Distance * herbivory	-0.538	0.001
Distance * Abundance	-0.381	0.001

5.3.3.2 Disease infection

Table 4.8 shows total count while table 4.9 shows percentages of seedlings infected by diseases in the ten study trees. The percentage of disease infection in seedlings decreased with an increase in distance from the parent trees, and a decrease in seedling abundance (Fig. 4.4). The differences in disease infection levels at various distances from parent trees were statistically significant (ANOVA, $P < 0.001$) (Tab. 4.10). The highest incidence of disease infection occurred one meter from the parent trees. (Fig.4.4). The variations in disease infection levels between the distances were statistically significant (ANOVA, $P < 0.001$) (Tab. 4.11). There was statistically significant (ANOVA, $P < 0.001$) variation in disease infection among trees (Tab. 4.12) and between younger and older seedlings (Tab. 4.13).

Table 4.8 Total count of all identifiable individual seedlings ≤ 100 cm tall infected by disease at each distance of the ten study trees.

	Distance from parent tree (m)											Total area
	1	3	5	7	9	11	13	15	17	19	Total	
Area (m²)→	1	1	1	1	1	1	1	1	1	1	10	
Tree↓												
1	195	213	219	217	99	76	47	42	24	0	1132	10
2	63	97	59	40	30	19	0	0	0	0	308	10
3	86	136	126	76	48	44	23	7	7	0	553	10
4	32	38	28	13	7	2	0	0	0	1	121	10
5	34	67	32	29	9	0	0	0	0	0	171	10
6	383	419	503	225	109	111	120	70	22	0	1962	10
7	96	83	109	55	54	39	9	0	0	0	445	10
8	352	276	265	170	200	87	83	42	23	0	1498	10
9	124	136	126	109	67	43	34	15	8	0	662	10
10	132	172	121	97	73	58	42	22	17	0	734	10
Total	1497	1636	1588	1031	691	479	358	198	101	1	7580	100

Table 4.9 Percentages of disease infected seedlings ≤ 100 cm tall (m²) at various distances from the parent trees. The figures in the table are percentages of the number of seedlings at each distance concerned for the tree concerned.

	Distance from parent tree (m)										Total area
	1	3	5	7	9	11	13	15	17	19	
Area (m²)→	1	1	1	1	1	1	1	1	1	1	
Tree↓											
1	43	53	62	75	28	28	21	24	28	-	10
2	72	51	48	30	29	41	-	-	-	-	10
3	39	54	56	33	28	33	27	18	24	-	10
4	65	42	56	36	11	40	-	-	-	-	10
5	63	51	29	31	18	-	-	-	-	-	10
6	67	63	64	51	22	25	33	23	30	-	10
7	70	41	63	31	38	41	22	-	-	-	10
8	69	57	58	43	50	28	32	19	47	-	10
9	47	44	47	42	31	23	24	16	25	-	10
10	43	48	40	31	24	26	24	17	33	-	10

Table 4.12 Duncan's Multiple Range Test for variability in percentage disease incidence (m²) by tree; Alpha= 0.05, df= 60. Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	TREE
A			43.704	19	8
A			43.600	19	6
B	A		39.771	19	1
B	A	C	36.536	17	7
B		C	34.758	16	2
B		C	34.705	19	3
B	D	C	32.542	19	9
B	D	C	32.412	19	10
D		C	30.703	16	4
D			24.873	16	5

Table 5.13 Duncan's Multiple Range Test for variability in percentage disease incidence (m²) by stage; Alpha= 0.05, df= 60. Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	STAGE
A	38.250	79	2
B	33.526	100	1

4.3.3.3 Herbivory

Table 4.14 shows total count while table 4.15 shows percentages of seedlings attacked by herbivores in the ten study trees. The proportion of seedlings damaged by herbivores did not show any clear pattern with increasing distance away from the trees although it was lowest for distance nineteen meters from the parent trees (Fig. 4.5). Variation in herbivory levels at different distances from parent trees was

Table 4.11 Duncan's Multiple Range Test for variability in percentage disease incidence (m^2) by distance; Alpha= 0.05, df = 60. Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	DISTANCE
A		61.807	20	1
B	A	55.698	20	3
B		51.976	20	5
C		40.137	20	7
D		29.196	19	11
D		26.735	20	9
D		25.658	16	17
D		23.385	17	13
E		14.658	16	15
F		4.545	11	19
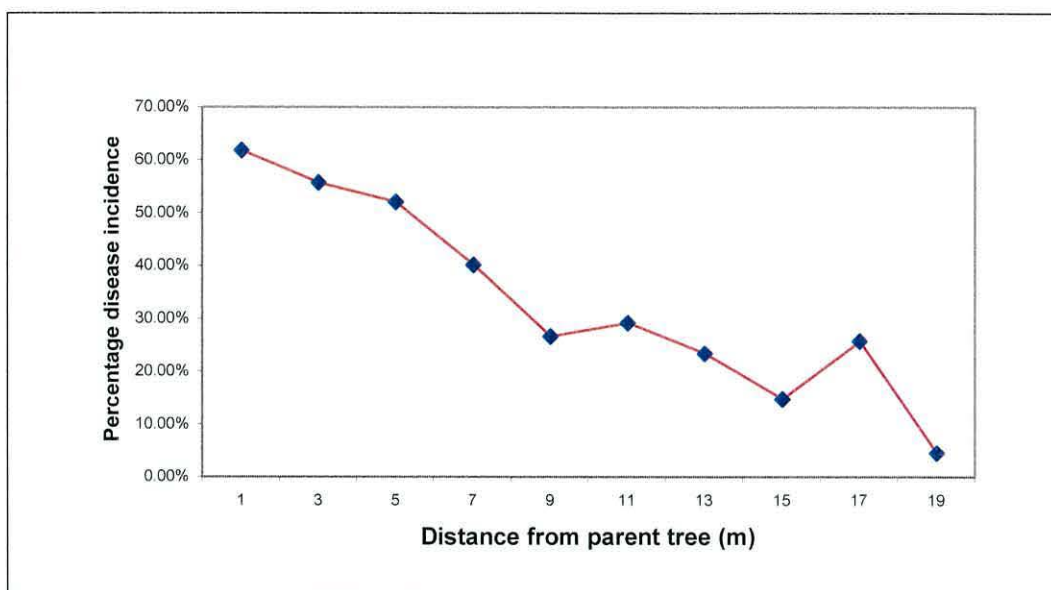
Figure 4.4 Relationship between percentage disease incidence and distance from parent tree; 100% is the total number of seedlings at the distance concerned

Table 4.10 Analysis of Variance for percentage disease incidence (m²)

Source	F	Sum of Squares	Mean Square	F Value	Pr > F
STAGE	1	984.768	984.768	8.08	0.0061
TREE	9	5214.880	579.432	4.75	0.0001
DISTANCE	9	51990.887	5776.765	47.39	0.0001
TREE*DISTANC	81	14433.768	178.195	1.46	0.0619
TREE*STAGE	9	917.712	101.968	0.84	0.5857
STAGE*DISTANCE	9	1115.653	123.961	1.02	0.4372
Error	60	7314.641	121.911		
Corrected Total	178	81972.314			

statistically significant (ANOVA, P<0.001) (Tab.4.16). The highest incidence of herbivory occurred at distances between two and four meters (mean distance three meters) from the parent trees (Fig 4.5). Variation in herbivory with distance was statistically significant (ANOVA, P<0.001) (Tab. 4.17). There were statistically significant (ANOVA, P<0.001) differences in herbivory among trees (Table 4.18) and between stages of seedling development (Tab. 4.19). Although the agent(s) of herbivory was not determined, the variable appearance of damaged leaves suggests that multiple agents are responsible. Fig 4.6 shows the relationship between herbivory and disease incidence. Levels of herbivory where higher compared to disease at greater distances from the parent trees.
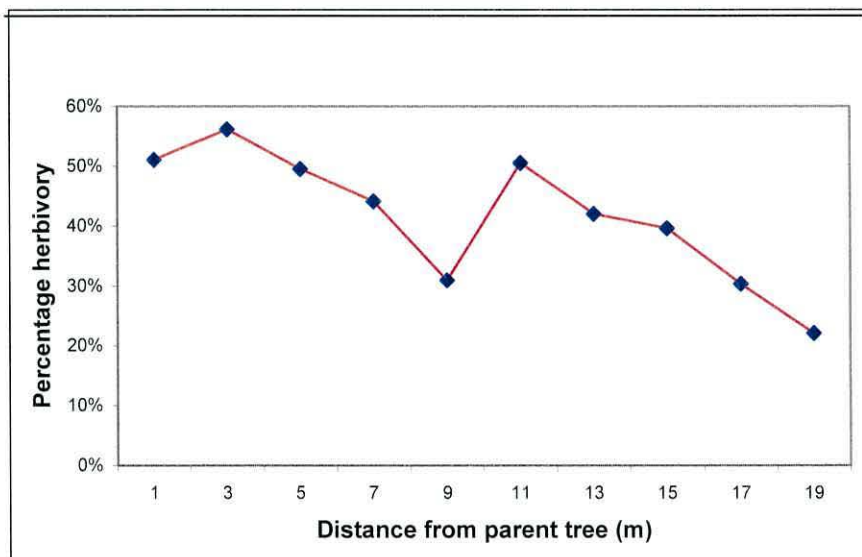
Figure 4.5 Relationship between Percentage herbivory and distance from parent tree; 100% is the total number of seedlings at the distance concerned.

Table 4.14 Total count (m²) of all identifiable individual seedlings ≤ 100 cm tall attacked by herbivores at each distance of the ten study trees.

Area (m²)→	Distance from parent tree (m)										Total	Total area
	1	3	5	7	9	11	13	15	17	19		
	1	1	1	1	1	1	1	1	1	1	10	
Tree↓												
1	156	174	131	158	102	73	50	49	43	0	936	10
2	51	88	46	62	28	22	0	0	0	0	297	10
3	67	115	89	75	44	31	32	40	7	0	500	10
4	23	27	8	5	2	7	0	0	0	0	72	10
5	13	54	36	25	15	0	0	0	0	5	148	10
6	274	304	446	205	104	131	131	77	15	0	1687	10
7	64	72	89	66	54	88	21	0	0	0	454	10
8	209	215	204	124	173	145	94	88	20	0	1272	10
9	103	121	107	106	59	94	52	43	8	0	693	10
10	123	157	108	86	78	55	64	62	21	0	754	10
Total	1083	1327	1264	912	659	646	444	359	114	5	6813	100

Table 4.15 Percentages of herbivory in seedlings ≤ 100 cm tall (m²) at various distances from the parent trees. The figures in the table are percentages of the number of seedlings at each distance concerned for the tree concerned.

Area (m²)→	Distance from parent tree (m)										Total area
	1	3	5	7	9	11	13	15	17	19	
	1	1	1	1	1	1	1	1	1	1	
Tree↓											
1	37	43	37	57	29	27	23	28	50	-	10
2	53	49	36	49	23	46	-	-	-	-	10
3	30	45	37	32	26	23	38	58	21	-	10
4	44	34	19	11	4	12	-	-	-	-	10
5	27	39	35	26	29	-	-	-	-	4	10
6	47	46	56	46	22	30	34	25	21	-	10
7	48	37	50	36	38	91	51	-	-	-	10
8	43	44	45	31	43	46	36	40	43	-	10
9	39	39	40	39	26	49	37	47	25	-	10
10	40	44	34	28	25	25	35	47	38	-	10

Table 4.16 Analysis of Variance for percentage herbivory (m²).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
STAGE	1	30356.422	30356.422	136.24	0.0001
TREE	9	4350.610	483.401	2.17	0.0369
DISTANCE	9	12140.136	1348.904	6.05	0.0001
TREE*DISTANCE	81	31270.561	386.056	1.73	0.0133
TREE*STAGE	9	2131.638	236.849	1.06	0.4029
STAGE*DISTANCE	9	5330.073	592.230	2.66	0.0116
Error	60	13368.801	222.813		
Corrected Total	178	98948.241			

Table 4.17 Duncan's Multiple Range Test for variability in percentage herbivory (m²) by distance; Alpha= 0.05 df= 60. Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	DISTANCE
	A	56.107	20	3
B	A	51.016	20	1
B	A	50.490	19	11
B	A	49.498	20	5
B				
B		44.088	20	7
B				
B		41.982	17	13
B				
B	C	39.577	16	15
D	C	30.931	20	9
D	C	30.296	16	17
D		22.179	11	19

Table 4.18 Duncan's Multiple Range Test for variability in percentage herbivory (m^2) by tree; Alpha= 0.05, df= 60. Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	TREE
	A		49.544	17	7
	A		47.574	19	9
	A		47.109	19	6
	A		45.705	19	8
B	A		44.543	19	3
B	A		43.966	19	1
B	A		42.454	19	10
B	A	C	40.141	16	2
B		C	34.328	16	4
		C	29.894	16	5

Table 4.19 Duncan's Multiple Range Test for variability in percentage herbivory (m^2) by stage; Alpha= 0.05, df = 60. Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	STAGE
A	57.488	79	2
B	31.262	100	1
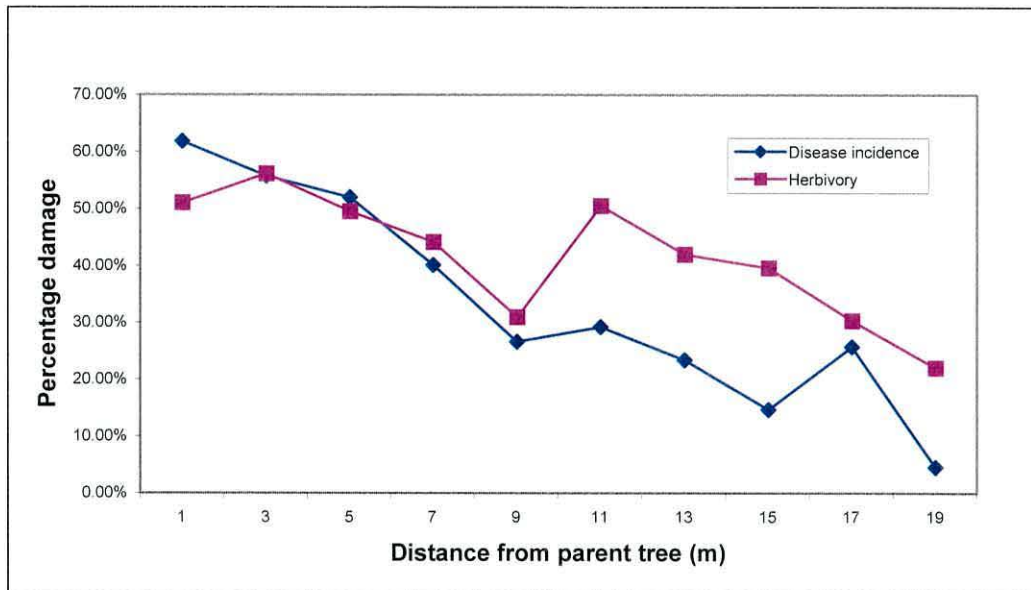
Figure 4.6 Relationship between percentage herbivory, percentage disease incidence and distance from parent tree; 100% is the total number of seedlings at the distance concerned.

4.3.4. Discussion

The proportion of seedlings damaged by herbivores and pathogens at various distances from the parent tree was used to test the escape and colonization hypotheses with regard to *Prunus africana*. Several lines of evidence indicate that either density and/or distance to parent tree do affect the level of seedling damage. The data presented demonstrate that disease infection, probably by fungal pathogens and herbivore damage was higher closer to parent trees and high seedling density, and decreased with an increase in distance from parent tree and decrease in seedling density. This kind of damage can be a major cause of mortality in natural populations of seedlings and the probability of survival increases with distance from the parent. One possible mechanism for such mortality is damage to

the seedling leaves, organs difficult to replace in the light-limited understory. A second potential factor is apical damage. Either type of damage could be caused by pathogens, or herbivores and may cause high mortality in seedling populations since it strikes directly at seedling stages.

The levels of damage by herbivores and pathogens documented in the present study were related both to seedling density and to distance to nearest parent. Thus, a greater proportion of seedlings have a higher chance of survival at distances away from the parent tree. This is expected when density or distance dependent mortality occurs close to adult trees. This evidence is consistent with the Janzen-Connell mode (Janzen, 1970 & Connell,1971) describing the spacing out of recruitment (away from parent trees) through the action of density- or distance responsive herbivores or pathogens.

Dispersal to greater distance from the parent trees lowered the level of disease infection of *Prunus africana* seedlings. This suggests that the disease -causing agent is concentrated to locations near the parent tree. It is possible that a greater concentration of inoculum exists near the parent because of greater availability in past seasons of material in which the pathogen could multiply. The density of seedlings affects both the number of primary foci of infection (Burden & Chilvers, 1975a) and the secondary spread from infected seedlings (Burden & Chilvers, 1975b), but whether the pathogens of *Prunus africana* seedlings were responding in a distance- or density- dependent manner or both cannot be directly ascertained

from this non-experimental study. It is clear, however, that *Prunus africana* seedlings germinating in high-density zones near parent trees suffer higher risks of damage.

Several factors may influence *Prunus africana* seedling regeneration and spatial distribution. They include fruit dispersal, light intensity, herbivory and disease infection. Fruit fall is heavy beneath *Prunus africana* adult trees (Pers. Obs.) but seedlings were found in small clumps in gaps away from the supposed parent trees and where noted to have been only slightly attacked by herbivores and pathogens. It is likely that these clumps represent sites at which animals (especially monkeys) or birds defecated seeds. It was also observed that in areas where pit-sawers had illegally cut *Prunus africana* trees, seedlings responded with rapid growth. This observation supports the colonization hypothesis; seedlings growing in gaps experience a lower level of damage relative to those in the shade. Therefore dispersal of seeds to a gap would be advantageous to the parent.

Survival chances of *Prunus africana* seedlings are increased in gaps partly because they are shade-intolerant, and also because the probability of their incurring disease infection is lowered. Gaps have higher light intensity, lower atmospheric humidity, higher temperature, and higher wind speed than the shaded understory. Since disease infection is favoured by low radiation and high humidity (Nichols, 1990), seedlings are more vulnerable to disease in the shaded understory than in gaps. Seedlings in light gaps accumulate more biomass and become woody sooner

and thus decrease the period when they are most vulnerable to pathogen attack. This indicates like some earlier findings (e.g Schupp 1988; Howe, 1990 and Turner, 1990) that habitat plays a crucial role in seedling establishment.

Contrasting views are held for conditions required for regeneration of *Prunus africana*. Geldenhuys (1981) implies a positive view of shade for regeneration of *Prunus africana* in South Africa. In South Nandi forest, Kenya, (Kigomo, 1987) noted increased regeneration of *Prunus africana* as light penetrating the ground diminished. Light was observed to favour seedling growth in Cameroon (Sunderland & Nkefor, 1997). My observation is that though *Prunus africana* trees are considered light demanding, initial germination of seedlings appears to be independent of the amount of light reaching the forest floor.

A low per capita recruitment was found for *Prunus africana* in different montane forests in Kenya (see population structure studies in this thesis). That a lower per capita recruitment was found than would be expected if distribution reflected initial seed input, may indicate that mortality of potential recruits was caused by density- and /or distance –dependent agents. In sum one can postulate that recruits of *Prunus africana* will be more likely be restricted to gaps, and adult patterns will depend on the location of these gaps relative to parent trees.

4.4   Variation in seedling abundance, herbivory and disease incidence among seedling stages and among parent *Prunus africana* trees

The specific objective of this study was to determine how herbivory and disease incidence vary among seedling stages and among trees.

4.4.1. Materials and methods

The second part of the seedling study took place between November 2001 and January 2002. The study began at the end of the fruiting season and start of germination of seeds. Five reproductive adult trees were chosen for the study (figure 4.1, point B) using the procedure described in subsection 4.3. Study tree number one was located at the edge of the forest were it grades into open grassland. The rest of the trees were located in closed forest, at least fifty meters from the forest edge.

Table 4.20 General information associated with each parent tree

Tree No.	DBH (cm)	Height (m)	Location within forest	Other information
1	41	29	Edge	Open – no undergrowth
2	46	31	Inside	Average density undergrowth
3	39	30	Inside	Average density undergrowth
4	56	35	Inside	Average density undergrowth
5	79	37	Inside	Average density undergrowth

Key. 1. Open –(no undergrowth) – less than 10% undergrowtg per unit area

2. Average density undergrowth – 10-50% undergrowth per unit area

3. Dense undergrowth – more than 50% undergrowth per unit area

A modified Adaptive Cluster Sampling design was used in the study. The procedure is described by Thompson (1991) and Acharya *et al.* (2000). In adaptive cluster sampling designs, an initial probability sample is selected and, whenever the observed value of the variable of interest satisfies a given condition, units in the neighbourhood of that observation are added to the sample. Such designs are in marked contrast to conventional sampling designs, in which the probabilities for selecting samples do not depend on any population values.

In this study, the initial design is selected in terms of primary units, while subsequent sampling is in terms of secondary units. One can think of the study adult tree sites as partitioned into secondary units representing all possible sites at which observations may be made, while the primary units from which the initial sample is selected consists of narrow strips (systematically arranged) of secondary units.

An example of the type of design used in this is illustrated in Fig 4.7, in which the objective is to estimate the mean number of seedlings, herbivory and disease incidence in five adult trees. In Fig 4.7, the initial sample consists of five randomly selected strips (primary units). The secondary units are small, square 1m x 1m plots along the strips. Adjacent plots containing seedlings are not added to the sample. This is a deviation from the 'conventional' adaptive cluster sampling. Adjacent plots were not added because of the large number of closely spaced seedlings present on the ground at each of the study trees, and adding adjacent plots would

have meant a total count of the seedlings under each tree. The final sample for study tree number one resulting from this procedure is shown in Fig.4.7 and table 4.21. For the modified adaptive cluster sampling used in this study, the population is composed of five primary units each 1m x 1m per study tree. Each primary unit contains ten secondary units (1m x 10m quadrats).

As mentioned earlier, *Prunus africana* seedlings undergo four distinct stages that can be recognized on the basis of the fixed number of leaves present at each stage (Tsingalia, 1989). Seedlings were counted in the 1-m^2 quadrats and assigned to the relevant category based on number of leaves and height as an indicator of cohort age.

- 1- seedlings < 10 cm tall, with a single apical meristem without any leaves (Clark & Clark, 1985). Seedlings in this category would be less than three months old.

- 2- seedlings ≥10 < 25cm tall, with two green leaves but without an apparent meristem. Seedlings in this category would be more than three months old and less than one year old.

- 3 - seedlings ≥25 < 50 cm tall, with three to four leaves and a distinct meristem. Seedlings in this category would be more than one year old and up to three years old.

- 4— seedlings ≥ 50 < 100 cm tall, with more than four leaves and a distinct meristem. These seedlings would be about three to five years old.
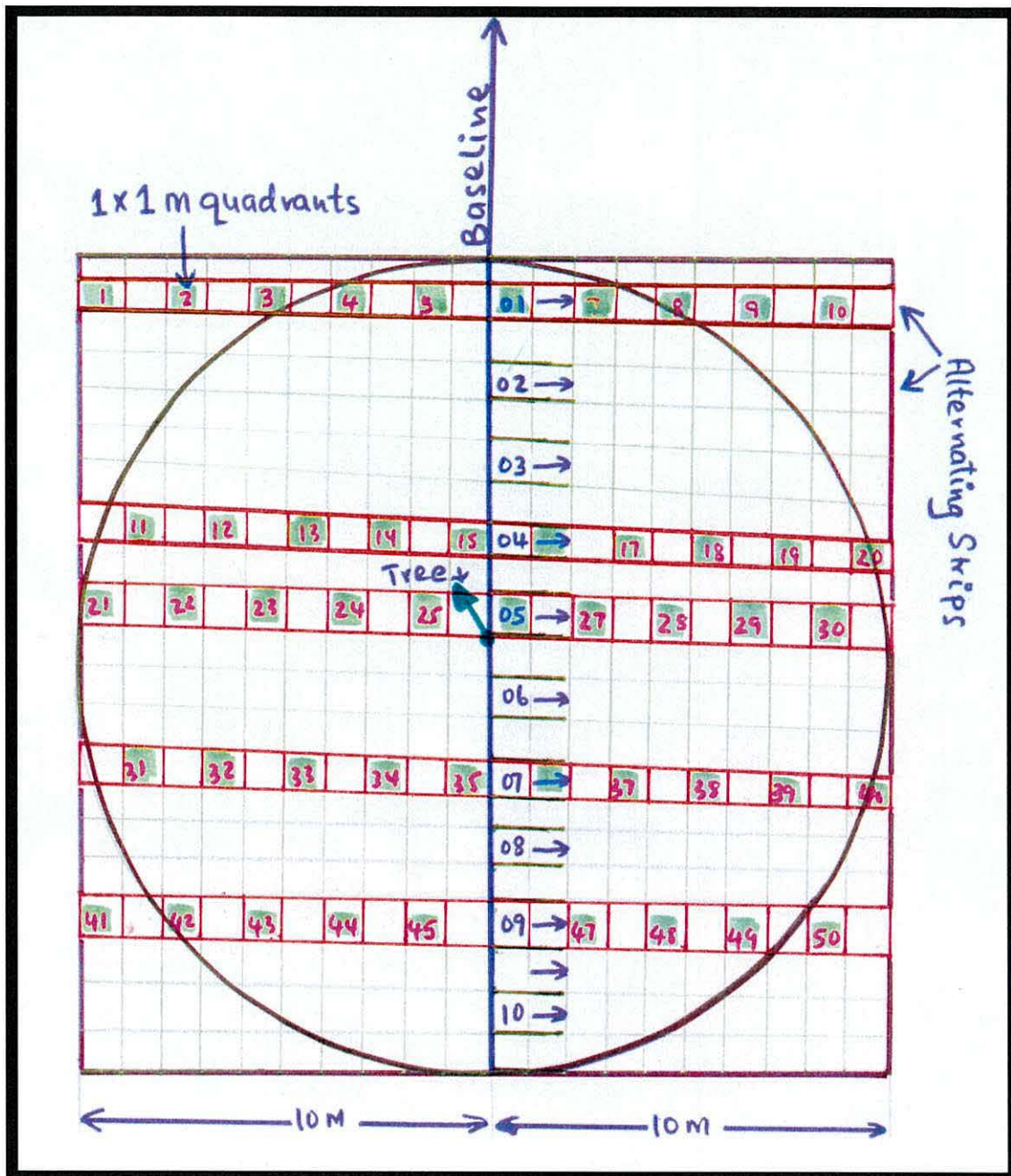
Figure 4.7 Sampling design used in the study

Each seedling was inspected for evidence of disease and/or herbivore attack. Any seedling without a meristem, or which had lost its original colour through decay, or with brown patches or signs of rotting, was considered a victim of disease attack. Seedlings with parts of their foliage missing or with holes in their foliage were considered victims of herbivory.

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Table 4.21 Randomly selected Strips used to sample seedlings in the five study trees

TREE 1	TREE 2	TREE 3	TREE 4	TREE 5
1	1	2	1	1
4	3	5	2	2
5	4	6	4	3
7	6	7	6	5
9	9	9	8	7

4.4.2 Data analysis

Disease incidence and herbivory as percentages of the total count of seedlings for the quadrat and tree concerned was used to asses variation in disease incidence and herbivory. Percentages of disease incidence and herbivory were arcsine transformed before ANOVA to normalize distribution.

Karl Pearson's correlation was undertaken to test the relationship between herbivory, disease incidence, and seedling abundance; one-way ANOVA tests where done to decide whether significant variations occurred in prevalence of seedling attack by disease and herbivores among: (i) stages of seedling development; and (ii) among trees. When significant variations were detected, Duncan's multiple range tests were done to compare variations among levels.

4.4.3. Results

4.4.3.1. Variation in seedling abundance by stages and among trees

Table 4. 22 shows show total counts and percentages of seedlings of all stages at each of the five study trees. The data shows that the abundance of seedlings varied among stages and among study trees (Tab. 4.22 & 4.23). The number of seedlings ranged from 1,683 ($33.7/m^2$) to 8,847 ($176.9/m^2$), with a mean of 6,598 ($132/m^2$). Tree number 1 had lower seedling abundance than the rest of the trees (Table 4.24). There were significantly (ANOVA, $P < 0.001$, Tab. 4.23) more stage two seedlings and fewer stage four seedlings (Tab. 4.25), and this trend was maintained whether one considers the individual trees or the overall abundance of seedlings.

Table 4.22 Total counts of seedlings of all stages at each of the five study trees.

Seedling stage →		Stage 1		Stage 2		Stage 3		Stage 4		
Height (cm)→		<10		≥10 ≤25		≥25 ≤50		≥50 ≤100		
Tree ↓	Area (m²)	Number	%	Number	%	Number	%	Number	%	Total
1	50	155	9.21%	1393	82.77%	115	6.83%	20	1.19%	1683
2	50	795	11.39%	5840	83.67%	331	4.74%	14	0.20%	6980
3	50	246	3.01%	7710	94.40%	209	2.56%	2	0.02%	8167
4	50	283	3.87%	6840	93.51%	180	2.46%	12	0.16%	7315
5	50	375	4.24%	8335	94.21%	131	1.48%	6	0.07%	8847
Total	250	1854	31.72%	30118	448.56%	966	18.08%	54	1.65%	32992
Mean		371	6.34%	6024	89.71%	193	3.62%	10.80	0.33%	6598
Stdev.		249.91	3.72%	2753.60	5.95%	85.73	2.16%	7.01	0.49%	2843.28

Table 4.23. Analysis of Variance for seedling abundance (m^2)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
STAGE	3	2418827.044	806275.681	1340.92	0.0001
TREE	4	176066.328	44016.582	73.20	0.0001
TREE*STAGE	12	408678.957	34056.580	56.64	0.0001
Error	843	506884.686	601.287		
Corrected Total	862	3510457.015			

Table 4.24. Duncan's Multiple Range Test for seedling abundance (m^2) by trees, Alpha= 0.05, df= 835, means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TREE
A	176.4	168	5
A	163.13	172	3
B	146.06	174	4
B	139.52	180	2
C	33.27	169	1

Table 4.25 Duncan's Multiple Range Test for seedling abundance (m^2) by stages, Alpha= 0.05, df= 835, means with the same letter are not significantly different.

Duncan Grouping		Mean	N	STAGE
A		122.555	245	2
B		7.711	239	1
C	B	3.996	228	3
C		0.287	143	4

4.4.3.2 Variation in seedling herbivory by stages and among trees

Table 4.26 shows total counts and percentages of seedlings of all stages attacked by herbivores at each of the five study trees. Percentage herbivory increased gradually from seedlings of stages one to four, and was significantly (ANOVA, P< 0.001, Tab 4.27) higher on seedlings of stage three and four, (Tab. 4.28). Herbivory varied among trees and was higher in seedlings of tree number one as compared to the rest (Tab 4.29).

Table 4.26 Total counts of seedlings of all stages attacked by herbivores at each of the five study trees.

Seedling stage →		Stage 1		Stage 2		Stage 3		Stage 4			
Height (cm)→		<10		≥10 ≤25		≥25 ≤50		≥50 ≤100			
Tree ↓	Area (m²)	Number	%	Number	%	Number	%	Number	%	Total	%
1	50	33	21.29%	310	22.25%	47	40.87%	9	45.00%	399	23.71%
2	50	45	5.66%	979	16.76%	111	33.53%	7	50.00%	1142	16.36%
3	50	8	3.25%	1433	18.59%	106	50.72%	2	100.00%	1549	18.97%
4	50	28	9.89%	1297	18.96%	45	25.00%	1	8.33%	1371	18.74%
5	50	14	3.73%	1640	19.68%	69	52.67%	0	0.00%	1723	19.48%
Total	250	128.00	43.83%	5659.00	96.24%	378.00	202.79%	19.00	203.33%	6184	
Mean		25.60	8.77%	1131.80	19.25%	75.60	40.56%	3.80	40.67%		
Stdev		14.84	7.48%	518.41	1.99%	31.52	11.63%	3.96	39.77%		

Table 4.27 Analysis of Variance for percentage herbivory (m²)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
STAGE	3	235294.496	78431.499	54.82	0.0001
TREE	4	11172.912	2793.228	1.95	0.0999
TREE*STAGE	12	44190.782	3682.565	2.57	0.0023
Error	841	1203199.268	1430.677		
Corrected Total	860	1493857.458			

Table 4.28 Duncan's Multiple Range Test for percentage herbivory (m^2) by stage. Alpha= 0.05, df= 841, means with the same letter are not significantly different

Duncan Grouping	Mean	N	STAGE
A	40.67	143	4
A	40.56	231	3
B	19.25	248	2
C	8.77	239	1

Table 4.29 Duncan's Multiple Range Test for percentage herbivory by tree, Alpha= 0.05, df= 841, means with the same letter are not significantly different.

Duncan Grouping		Mean	N	TREE
	A	23.71	169	1
B	A	19.48	168	5
B	A	18.97	170	3
B	A	18.48	174	4
B		16.37	180	2

4.4.3.3. Variation in disease incidence by seedling stages and among trees

Table 4.30 shows total counts and percentages of seedlings of all stages infected by disease at each of the five study trees. Disease incidence on seedlings decreased from seedlings of stage one to three (Tab. 4.30 & 4.31), and was significantly (ANOVA, $P< 0.001$, Tab 4.32) lower amongst seedlings of stages three and four. Disease incidence was lowest in tree number one as compared to the rest (Tab. 4.33). Although seedling mortality was not determined, it was observed that most of the disease infected seedlings died within 2 weeks.

Table 4.30 Total counts of seedlings of all stages infected by disease at each of the five study trees

Seedling stage →		Stage 1		Stage 2		Stage 3		Stage 4			
Height (cm)→		<10		≥10 ≤25		≥25 ≤50		≥50 ≤100			
Tree ↓	Area (m²)	Number	%	Number	%	Number	%	Number	%	Total	%
1	50	40	25.80	174	12.49	9	7.83	3	0.38	226	13.43%
2	50	329	41.38	1695	29.02	38	11.48	1	7.14	2063	29.56%
3	50	127	51.63	2202	28.56	21	10.05	1	50.00	2351	28.79%
4	50	95	33.57	1829	26.74	19	10.56	2	16.67	1945	26.59%
5	50	101	26.93	2197	26.36	30	22.90	2	33.30	2330	26.34%
Total	250	692	179.31	8097	123.17	117	62.82	9	107.49	8915	
Mean		138.4	35.862	1619.4	24.634	23.4	12.564	1.8	21.498		
Stdev		111.16	10.79	838.43	6.88	11.06	5.93	0.84	20.17		

Table 31 Duncan's Multiple Range Test for percentage disease incidence variability (m²) by stage. Alpha= 0.05,df= 841, means with the same letter are not significantly different

Duncan Grouping	Mean	N	STAGE
A	35.862	239	1
B	24.634	248	2
B C	21.498	143	4
D	12.564	231	3

Table 4.32 Analysis of Variance for percentage disease incidence (m²).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
STAGE	3	210240.766	70080.255	60.27	0.0001
TREE	4	43732.972	10933.243	9.40	0.0001
TREE*STAGE	12	45295.754	3774.646	3.25	0.0001
Error	841	977825.539	1162.694		
Corrected Total	860	1277095.031			

Table 4.33 Duncan's Multiple Range Test for percentage disease incidence variability (m²) by tree. Alpha= 0.05, df= 841, means with the same letter are not significantly different

Duncan Grouping	Mean	N	TREE
A	29.56	180	2
A	28.79	170	3
A B	26.59	174	4
A B	26.34	168	5
B	13.43	169	1

4.4.3.4. Relationship between herbivory, disease incidence and seedling abundance

Disease incidence and herbivory were inversely correlated along the seedling stage gradient (Fig 4.8). The smaller the seedlings the higher was the disease incidence, but lower herbivory. As the seedling size increased, however, damage due to herbivores dominated. Both disease incidence and herbivory were positively correlated with seedling abundance (r^2=0.996 and 0.990 Resp., Tab. 4.34).
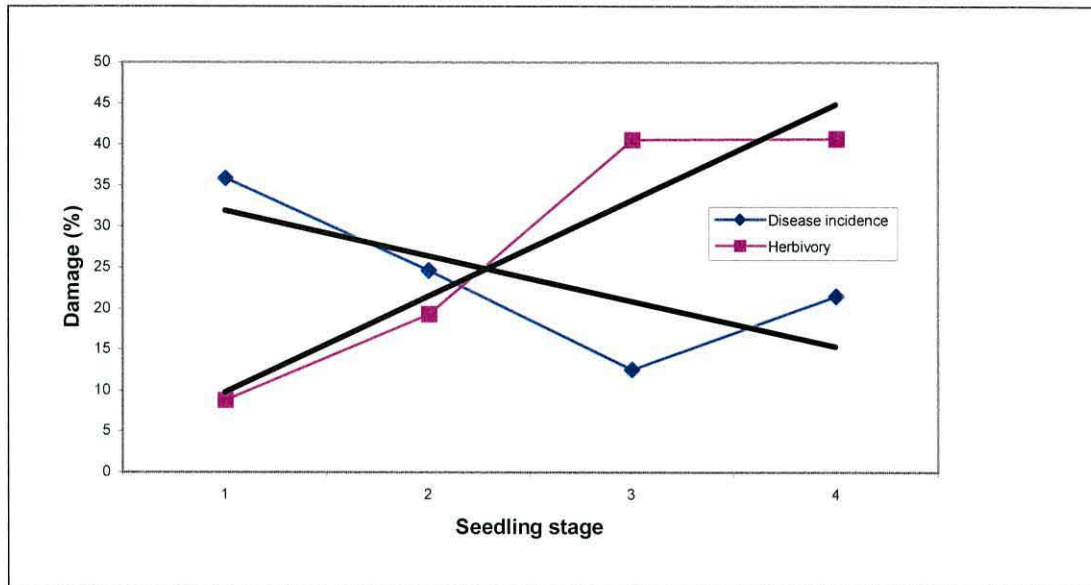
Figure 4.8 Relationship between percentage herbivory and percentage disease incidence (m^2) across the four seedling stages. Damage levels were calculated as the percentage of the number of seedlings at the stage concerned.

Table 4.34 Pearson correlation values (r^2) for seedling abundance, disease incidence and herbivory.

Factors	r value	P value
Abundance * disease	0.996	0.001
Abundance * herbivory	0.990	0.001
Disease * herbivory	0.978	0.001

4.4.4. Discussion

The data presented indicate that mortality of seedlings in *Prunus africana* is very high, as demonstrated by the decreased abundance of seedlings of stages three and four; the number of seedlings present at each stage decreases as the seedlings develop from one stage to another. Stage one seedlings (<10 cm tall) are clearly of a different cohort from stage four (≥50<100cm tall), therefore stage 4 there are very few seedlings left that will be recruited as adults (Table 4.22). Fungal pathogens and herbivores could be the major cause of mortality in natural populations of *Prunus africana* seedlings, although one cannot preclude the actions of other agents of mortality such as fallen debris and inadequate light. A number of past studies have shown herbivore-induced mortality of seedlings in other tropical forests (e.g. Fried et al., 1988, 80% and Howe, 1990, 51%). In these studies seedlings were marked and re-assessed on different dates.

Seedlings of parent trees located at the forest edge and deep in the forest which differed in microclimate exhibited different abundances, levels of herbivory and disease incidence. This indicates that micro-habitat plays a crucial role in determining seedling density, and levels of herbivory and disease. A higher percentage of stage four seedlings were found at tree one. This tree was located at the forest edge where the forest grades into the grassland. The micro-environment under this tree might have been more suitable for herbivores and less suitable for pathogen infestation. Saplings were also observed in gaps within the forest that

were not within the sampling areas. Low disease attack in the forest edge may account for the abundance of stage four seedlings in tree number one and in forest gaps. The presence of a higher percentage of stage four seedlings at the forest edge, and of saplings in gaps indicates the importance of seedlings escape from disease attack.

The major herbivores in this case were probably blue headed monkeys, and Goliath beetles, which were encountered on several occasions in the study sites. Consequently, abundance of these herbivores is critical to seedling establishment, and hence regeneration of *Prunus africana*. Where damage is minimal, the ability of the seedlings to re-sprout would help them to withstand or recover from such damage as observed in some of the seedlings in this study.

Mwanza *et al.* (1999) found that leaves collected from wildings in natural forests in Kenya were heavily infected with a leaf spot disease caused by *Colletotrichium gloeosporioides*. When infection was severe, the pathogen caused premature leaf fall and die-back of the leader shoot. Athough the samples were not analysed for this pathogens, they are a possible cause of disease in this study, given that Mwanza *et al.* studied seedlings including those collected from Kakamega.

Disease incidence varied inversely with herbivory across the seedling stages (Fig. 4.8). Higher levels of herbivory in stage four seedlings might be due to time effect and because there are more leaves to show damage. Damage due to disease falls

probably because of mortality effects and increased isolation of individuals (lower density). Seedlings are known to be less vulnerable with time (Populer, 1978), as they undergo cell wall thickening and lignification (Walker, 1969). It is for this reason that seedlings might be prone to disease attack at earlier stages, later however, as the seedlings mature, they might become less favourable to pathogens but suitable for herbivores (Coley, 1983). However, it is not known at what stage seedlings of *Prunus africana* get lignified.

The results also indicate that seedling abundance, disease incidence and herbivory varied among trees (Tabs. 4.22, 4.26 & 4.30). Tree number one which was located at the edge of the forest experienced a significantly higher level of herbivory, lower level disease incidence and low seedling abundance as compared to the other trees. The variation in herbivory and disease incidence in the five study trees may be due to: (i) variation in the micro-environmental conditions in the vicinity of the various trees; (ii) variation in trees in their herbivore and pathogen populations; (iii) variation in seed crop among the trees; and (iv) genetic variation among trees in their susceptibility to herbivore and pathogen attack.

4.5. Conclusions

(i)   Disease infection and herbivory documented in the two studies was related both to seedling density and to distance from parent tree. Thus this evidence is consistent with the Janzen-Connell model describing the spacing out of

recruitment (away from parent trees) through the action of density-or distance- responsive herbivores or pathogens

(ii)   The apparent reduced seedling abundance at increasing distances from parent tree may be a consequence of a complex interplay of factors: those that reduce seedling establishment as the distance from parent tree increases (e.g. seed rain etc.) and those that increase mortality of seedlings closer to parent trees e.g. pathogen, herbivores etc.).

(iii)   Since seedlings growing in gaps outside the canopy were also observed to have been attacked by pathogens and herbivores, distance-dependence, or closeness to parent trees, has less clear effect than does the effect of high density.

While specifically addressing regeneration of *Prunus africana*, the results of the present study have broader implications for understanding population and community dynamics in tropical forests. Population growth depends not only on juvenile survival, growth and spatial distribution, but also on the recruitment of new juveniles into the population. The quantity of this new recruitment is a complex outcome of many factors acting to reduce the potential seedling production.

CHAPTER V

BARK PRODUCTION IN *PRUNUS AFRICANA* IN KENYA

This chapter starts with an introduction justifying the need for this aspect of the study and the general objective of the present research activity, followed by a review of bark as a source of medicines (5.2.1); effect of environment on bark development (5.2.2); bark variation in tree species (5.2.3); and cases where trees have been managed for bark production as relevant background (5.2.4). Sections 5.3 and 5.4 present the methodologies used, results, and discussion of studies on variation in bark thickness and bark production in *Prunus africana* respectively.

5.1 Introduction

One of the reasons for the detrimental impact of harvesting *Prunus africana* is that the bark is usually stripped from the entire tree, effectively ringbarking it and causing its death. But it need not be so because the trees, when properly managed, are able to withstand some level of bark removal and to exhibit bark regrowth (Ndibi & Kay, 1997). What are believed to be ecologically sustainable harvesting guidelines have been adopted in Cameroon and Equatorial Guinea. The procedures are to collect only from quarters on opposite sides of the tree, from1.3 cm above ground level to height of the first branch. Bark should only be harvested from trees with diameter at breast height (DBH) > 30 cm. Following these recommendations, only about 50 per cent of the available bark in the harvestable tree should be

stripped; after 7-8 years, the remaining 50 per cent may be removed. This should be sufficient time for the bark to grow back on that part of the bole originally stripped. There are also suggestions that *Prunus africana* bark production should be from successive plantings of trees felled and totally stripped of their bark as in black wattle. It is estimated that when completely stripped, a large tree may yield up to a metric tonne of bark. About 2000 kg of fresh bark representing 1000 kg of dried bark, are needed to make 5 kg of extract (Cunningham *et al.* 1997). It takes between 12-15 years for *Prunus africana* tree to produce bark that is suitable for extraction of the pharmaceutical compounds used to treat prostate problems.

High bark production in trees is necessary whenever the bark of a tree species is of commercial value (Wei & Biralho, *1997*). Because of the potential importance of *Prunus africana* as a commercial medicinal tree, and as cultivation of *Prunus africana* in Kenya and elsewhere gets under way, tree characteristics that affect the overall bark production and hence profitability of the species need to be addressed in order to adopt efficient production strategies. For these, the estimation of bark yield based on measurements of tree size and bark thickness becomes important.

There is virtually no information on variability in the bark thickness in *Prunus africana*, but reports of variation in bark thickness in other tree species e.g (*Eucalyptus grandis*-Wilkins, 1991; *Pinus contorta*- Bengt & Downie, 1992; *Pinus radiata*-Matziris, 1995; and *Eucalyptus urophylla*, Wei & Birralho, 1997; *E Eucalyptus globules* - Quilho & Pereira, 2001;) suggest there might be potential to maximise

bark yield either by selecting high yielding genotypes, or planting trees under ecological conditions that maximize bark production.

The general objectives of the studies in this chapter were to assess available quantities of ecologically sustainable bark yield in *Prunus africana* and characteristics that could influence bark yield.

5.2 Background

5.2.1 Bark as a source of medicines

Bark is an important medicine. Poisonous compounds and many of the most interesting compounds in a tree are in the bark (Prance & Prance, 1993). These substances are present in the bark while they are being transported from one part of the tree to another, or as a defence against predators, especially against bark-boring insects. Some of the most toxic substances are those that are medicinally potent, too, so it is hard to distinguish between poisons and medicines derived from bark (Hedge *et al.*, 1998).

Most indigenous cultures around the world have discovered that bark is a useful source of medicinal compounds (Prance & Prance, 1993). Many of the brews used by native peoples for the treatment of a wide range of diseases come from the bark of trees. It is significant, however, that it is not only folk medicine that derives curative ingredients from bark. Several well-known cures used in modern

medicine owe their existence to bark of trees. The history of treatment of malaria, for example, would have been very different if quinine had not been discovered in the bark of the quinine tree.

The search for medicines in bark continues today as many pharmaceutical companies analyse and test bark chemicals (Hamilton, 1992). The bark of *Taxus brevifolia*, has been found to be effective for the treatment of ovarian cancer, while that of *Prunus africana* is effective in the treatment of prostate complications (Cunningham & Cunningham, 1999). In Kenya the trees whose bark is documented as being used for medicinal purposes include *Waburgia ugandensis*, *Olea capensis and Zanthoxylum macrophyllum* (Kokwaro, 1974).

5.2.2 Effect of environment on bark development

Several authors have recognised that bark development is environmentally influenced. Dezeew (1941) reported that saplings of several species of trees exposed to direct solar radiation formed deep seated periderms sooner than saplings of the same species that were grown under a forest canopy. Beyond these observations, data are lacking on the complex physiological processes involved in the development of bark. However, the effects of several environmental factors on the development of the first periderm have been investigated (Berger, 1973). It is probable that these factors also influence formation of subsequent periderms, and thus influence development of the bark.

Although the time of formation of the first periderm and subsequent phellogen activity vary directly with light intensity, there appears to exist a minimum light intensity requirement for this development (Berger, 1973). Phellogen initiation and activity increases with a rise in temperature until a maximum activity is attained, then decreases with any further temperature increase (Berger, 1973). In some species, however, bark thickness has been reported to be under strong genetic control. In *Eucalyptus urophylla* for example, heritabilities range between 0.41 and 0.7 (Wei & Birralho, 1997).

As currently used, bark is a term that describes all tissue exterior to the vascular cambium (Esau, 1965). Thus bark applies to the aggregation of epidermis, cortex and phloem. The bark of trees serves a protective function, insulating against extremes of temperature, fire, and desiccating winds and against herbivory and microbial infections (Romberger, Hejnowitcz & Hill, 1992). Bark takes many forms. It ranges from the paper-thin, scaling green photosynthetic bark found in many trees in the arid regions to the extremely thick, corky bark of the cork oak. This variety is not haphazard; it is linked to features within a given habitat.

Numerous factors influence the forms that barks take; among them are the tree's growth pattern, its need for defence against predators, its lack of photosynthetic tissue in the leafless condition, and its need for insulation against either heat or cold (Hedge, 1998). Many of these factors are linked to the ecology of the tree, which is to the habitat in which it grows. The link is especially clear in an arid area

where conservation of water is essential to maintain life (Prance & Prance, 1993). In these areas trees remain leafless for up to 10 months, and so green bark assumes the life-sustaining photosynthetic function usually performed by the leaves.

The link between habitat and type of bark is also evident in other situations; for example some habitats are more prone to fires than others (Pinard & Huffman, 1997). In the extremely arid semi-desert habitats, where green barked trees occur most frequently, natural fires are not part of the typical life cycle of the vegetation because usually there is insufficient biomass for the vegetation to catch fire (Pinard & Huffman, 1997). However, in tropical savannas natural fires can occur even if these areas are left undisturbed by people.

5.2.3 Bark variation

The volume of bark produced during the life of a plant is difficult to determine accurately since bark tissues, unlike xylem tissues, are continually shed and do not simply accumulate. However, bark thickness and volume have been determined for diameter and age classes of many commercially valuable temperate species.

Bark thickness generally increases with stem age and diameter (Bengt & Downie, 1992). In *Sequoia simpervirens* a straight-line relationship exists between bark thickness and stem diameter. This relationship probably results from the resistance of bark to weathering and decay and to the persistent nature of the outer bark (Dittman, 1931). In most other species, however, the relationship between diameter and bark thickness is curvilinear, owing to shedding of bark tissues (Hale, 1955). In

addition to varying with stem age and diameter, bark thickness varies with tree vigour. Hale (1955) reported that the average thickness of bark in vigorously growing stems of *Picea glauca* in age class 41-60 years was greater than that of all age classes of less vigorous trees. A study in Gabon showed that the barks of woody species in disturbed forests were more frequently associated with toxic chemicals than the woody species characteristic in less disturbed habitats (Levin, 1976). These observations and those of Richards (1952), Ashton (1969), and Whitmore (1984) suggest that thickness of bark and occurrence of secretions like resins and gums might be correlated with the habitat of the tree species.

It has been noted that barks of tropical rainforest trees are thinner and smoother than those of species in drier habitats (Richards, 1952; Ashton 1969 and Whitmore, 1984). Thick bark like that of the European oak or pine is uncommon in the tropics. Even in large tropical forest trees it is often only a few millimetres thick. Foxworth (1927) gives measurements of the thickness of the bark for a number of Malayan timber trees: the average is 10 mm, maximum over 25 mm and minimum 4 mm.

The smoothness, which is a common feature of the bark of rain-forest trees, is no doubt a consequence of its thinness (Prance & Prance, 1997). The thinness and smoothness of rain-forest trees is well illustrated by comparing *Liphora procera*, a tall tree typical of Guinea-Congolean rainforest (White, 1983), with its close ally *Liphora elata*, which occurs in scrubland and savannas. The former has thin bark,

while in the latter the bark is thick. Some families are fairly homogeneous in bark thickness, but others show great variability (Hedge *et al.*, 1998).

5.2.4 Cases of trees managed for bark production

5.2.4.1 **Quinine** (*Cinchona*)
Family: Rubiaceae

Genus*: Cinchona*

Species: *officinalis, ledgeriana, succirubra, calisaya*

Common names: Quinine Bark, Quinine, Cinchona Bark, Fever Tree

The genus *Cinchona* comprises about forty species of trees reaching 15 to 20 meters in height and producing white, pink or yellow flowers (Lung, 1996). All Cinchonas are indigenous to the eastern slopes of the Amazonian area of the Andes where they grow between 1,500 to 3,000 meters in elevation on either side of the equator (from Colombia to Bolivia) (Mowrey, 1986). They can also be found in the northern part of the Andes, on the eastern slopes of the central and western ranges. They are now widely cultivated in many tropical countries for their commercial value although they are not indigenous to those area. Cinchona, or "Quinine Bark" is one of the rainforest's most famous plants and most important discoveries (Duke, 1985). Throughout the 1600's to mid 1800's Quinine Bark was the most used treatment for malaria, evidencing remarkable results, as well as being used for fever, indigestion, mouth and throat diseases, and cancer (Duke, 1985). In 1820, scientists isolated a quinoline alkaloid in the bark, which provided the highest anti-malarial effect and named it Quinine. Once discovered, methods were developed to extract the quinine from the natural bark to sell as an antimalarial drug. The South American

rainforests benefited from the income generated by harvesting this resource discovered in their territory up until the end of the 19th century. But in the middle of the 19th century, seeds of Cinchona were smuggled out and planted and cultivated in Java, India and Ceylon, soon dominating world production of cinchona and Quinine (ANON, 1983). By 1918, the production of quinine was under the total control of the Dutch "kina burea" in Amsterdam. Huge profits were reaped, but Bolivia and Peru, from where the resource originated saw none of it (ANON, 1983).

The upheavals of the Second World War led to changes in the market, which still remain in effect today. When the Japanese occupied Java in 1942, a severe shortage of quinine on the side of the Allies ensued, and the South American sources of cinchona trees were once again in demand and new African plantations were planted. This shortage of quinine also fueled the research for developing and producing synthetic antimalarials.

In 1944 scientists were able to synthesize the quinine alkaloid in the laboratory based on this unique alkaloid in the bark of a South American rainforest tree. This led to various synthesized quinine drugs to treat malaria and the use of the common bark and the natural quinine extracted from the bark and sold as antimalarial drugs fell out use.

Today, Indonesia and India still cultivates cinchonas, but Democratic republic of Congo has become the top supplier of a world market which is also supplied by other African countries (Burundi, Cameroon, Kenya), and much lower on the list of producers are the South American countries of Peru, Bolivia and Ecuador.

Although all cinchona species are good sources of quinine, *C. succirubra* and *C. ledgeriana* are the species with the highest amount of quinine alkaloids, which is why they are the species of choice for cultivation today (Mowrey, 1986). Early on, the cardiac effect of cinchona bark were noted and quinine bark was used sporadically through the first half of the 18th century for cardiac problems and arrhythmia with purified quinine becoming a standard component of cardiac therapy in the 2nd half of the 19th century (Duke, 1985). Another chemical called *quinidine* was discovered to be responsible for this beneficial cardiac effect. Quinidine, a compound essentially produced by semi-synthesis from quinine is still used for cardiac problems today and is sold as a prescription drug. It is sales demand for quinidine that still generates and leads the market demand for harvesting cinchona bark today since scientists have been unsuccessful in synthesizing this chemical without the utilizing the natural quinine found in cinchona bark.

Quinine bark is harvested today much as it has been for hundreds of years and almost all commercial sources of cinchona come from plantations established during World War II (ANON, 1983). The tree trunks are beaten and the peeling bark is removed. The bark partially regenerates on the tree and after a few years

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and several cycles of removing the bark and letting it grow back, the trees are uprooted and new ones planted. The cinchona and quinine market is difficult to calculate. It is thought that 300 to 500 metric tons of quinine are extracted annually from 5,000 to 10,000 metric tons of bark annually. Nearly half of the cinchona harvest is directed to the food industry for the production of quinine water, tonic water, and as a bitter additive, and 30 to 50% is converted to quinidine, a prescription cardiac drug (Duke, 1985).

Despite the pharmaceutical drugs replacing the use of natural Quinine barks for malaria, the use of the natural bark is still employed in herbal medicine around the world. Natural quinine extracted from *Cinchona* bark as well as the use of the natural bark tea and/or bark extracts are making a comeback in the management and treatment of malaria (Duke, 1985). As with any living and evolving organism, malaria has evolved over the years to develop a resistance and defense mechanism against our standard synthesized antimalarial drugs. It was shown early on that an effective dose of natural *Cinchona* bark extract elicited the same antimalarial activity as an effective dose of the quinine drug. Scientists are now finding that strains of drug resistant malaria can still be treated effectively with natural quinine and/or *Cinchona bark* extracts (Mowrey, 1986). This implies that the future of Commercial *Cinchona* production in plantations is still ensured.

5.2.4.2 Cork oak (*Quercus suber*)

Cork Oak, *Quercus suber* L. (Fagaceae) is an evergreen tree about 15-20 m tall, with an ample and rather untidy crown (Sauer, 1993). In mature plants of at least 15-20 years of age, the bark consists of a thick layer of cork that tends to peel off from the tree trunk.

Cork Oak is indigenous to the Mediterranean region where it occurs in open woodlands on hills and lower slopes. It is grown commercially for the thick cork bark which is harvested mainly for producing corks for wine bottles, although the cork also makes a good heat and electrical insulator and is therefore used for gaskets in engines and for insulative materials in home interiors (Turok *et al.*, 1997).

Only the outer, dead, corky bark is cut off. The tree is then able to regenerate new cork tissue from the underlying live bark. In this way it is possible to cut off cork from a tree about every 9-12 years. Fonseca and Parresol (2001) report a yield range of 18.8 - 47.6 kg/tree for trees ranging 25-60 cm DBH in Portugal. The tree itself is able to live for about 200 years (Sauer, 1993).

Portugal is the world's major producer of cork products. Not surprisingly, cork products are Portugal's main export. Spain also grows cork commercially but to a much lesser extent than Portugal. There have been attempts to grow Cork Oaks commercially in other parts of the world but these other countries have not been able to compete with Portugal in terms of skilfulness and cheapness of labour

(Sauer, 1993). Cheap plastic stoppers for wine bottles are to some extent a threat to the cork industry but for the better wines, cork stoppers are still preferred (Turok *et al.*, 1997). There is no real substitute for cork, natural or man-made. It is a substance that is water repellent, fire resistant, and indigestible to animals, plus cork does not conduct electricity. Owing to the efforts of the EU and various environmental groups, cork oak production is expected to increase due to the active efforts to protect existing forests and sponsorship of significant new plantings (Sauer, 1993). Typically, virgin cork is not removed from saplings until the 25th year, and reproduction cork (the first cycle) may not be extracted for another 9-12 years. Cork suitable for wine stoppers is not harvested until the following 9-12 year cycle, so farmers have invested over 40 years before natural wine corks are produced.

Cork bark is removed from trees in spring or summer. At this time of year the cork comes away easily from the trunk because the tree is growing, the new, tender cork cells being generated break easily. A cylindrical incision is made at the base of the trunk and then up to the first large branch, a lengthwise cut is made, and then the sheet of periderm is pried from the tree in a way that does not damage the vascular cambium. Harvest difficulties occur if the process is not carried out when the tree is in full growth. As soon as it is evident that the cork is being stripped too early or too late in the season the stripping is brought to a halt, a year's delay in cork extraction is preferred to damage to the tree.

To keep the trees in good productive health, there are laws, which regulate the harvest of cork oaks. In Portugal, trees are harvested every 9 years and on the island of Sardinia (Italy) the harvest occurs every 12 years. Numbers are painted on the bark to keep track of when a tree was stripped. Harvest forecasting is based on 9 or 12 year cycles, i.e. projections for the year 2003 Portuguese cork harvest are based on the kilos harvested in 1994.

As land is being passed between generations, there is increased interest in forest management. There is an emphasis on creating balance in a tree, much like a grapevine, whereby a properly managed tree has the optimal balance of leaves, branches and cork for vitality. Additionally, cork producers have more active representation in the field and are continually working on increasing cork quality where it starts - in the forest.

5.2.4.3 Black wattle (*Acacia mearnsii*)

Black wattle is a leguminous tree species indigenous to Australia. *A. mearnsii* now occurs worldwide and is used as source of tannin, fuelwood, charcoal, poles, props, green manure and windbreaks. In Australia it ranges widely from hot Queensland south to cool Tasmania and up to elevations of 1100 m. Introduced to Africa early last century, it became widely distributed naturally and in tannin plantations.

The black wattle is widely planted in the cooler tropics. It is moderately frost tolerant and vigorous at high elevations in India and East Africa. Height growth was over 10 m in 3 years at 2000 m elevation in Kenya under mean annual temperatures of 13-17⁰ C (NAS, 1980).

Originally distributed as a source of tannin, black wattle is now recognized as a valuable fuelwood and also yields a high-quality charcoal (NAS, 1980).

Wattle bark is the most widely used tannin material in the world. It contains 30-45% (dry weight basis) high-quality tannins that are used in tanning many classes of leather. Such tannins are particularly effective on hard leathers for shoes and saddles. They give better colour to leather than other tannins, do not precipitate in acid solution, and penetrate hides faster (NAS, 1980).

Wattles grow to 20 m, and are erect with blackish bark and feathery foliage. Twigs are angled, young foliage yellowish, flowers clustered, yellow and sweet in scent. They grow rapidly, e.g., over 8 m in 2 years on a site with 22⁰ C average annual temperature (NAS, 1980).

In Kenya, black wattle was first introduced in 1885 (Trzebinski, 1985). By 1919, around 4,000 ha of wattle plantations had been established on European farms, and a factory was built in Njoro to process the bark from these plantations (Huxley, 1935). The 1919 Economic Commission which was set up to explore commercial

opportunities for the colony noted with regard to wattle that the industry required very little labour and its prospects were excellent (Government of the United Kingdom 1919).

The Administration first began actively encouraging farmers to plant wattle and *Eucalyptus* trees around 1911 (Cowen, 1978). At first, the administration's objective was to reduce pressures on the indigenous forests for fuelwood and building timber that had greatly increased since the demarcation of the boundaries of the Forest Reserves between 1900 and 1910. A push by the Administration to encourage the planting of trees on farms began in earnest in 1910, but was widely resisted. By the late 1920's, the situation had radically changed and wattle was being widely planted as a response to the bark trade.

There was limited capacity to process the bark at this early stage in the development of the industry, and most of it was exported. Extracting factories were opened in Limuru and Thika in the early 1930s. The Limuru facilities were largely dependent on wattle produced by European farmers, while the Thika factories were almost entirely dependent on smallholder production. In order to ensure that the facilities in Limuru and Thika had sufficient bark to operate, a vigorous marketing network was established. Increased access to markets for bark, which accompanied the establishment of these factories, greatly contributed to the popularity of wattle as a smallholder crop. The Native Affairs Department reported that in 1935 the total area under wattle had nearly doubled since the previous year

(from 18,000 ha to 40,000 ha) and that there were plans to add another 20,000 ha the following year (Kitching, 1980).

Presently in Kenya, black wattle is an ideal agroforestry species because it can be easily incorporated into farming systems; it is nitrogen-fixing, produces wood-based products for the household, is easily grown and can generate income from the sale of bark.

In 1990, a hectare of mature wattle when harvested after 8 years could produce around KSh 3870 for its bark, and around KSh 2880 for charcoal at the roadside (a total of around US$1100 at prevailing 1990 exchange rates) (Dewees & Saxena 1995). In South Africa, one 7-year-old tree in a well-managed plantation produces 3-5 kg of dried bark (Dewees & Saxena 1995). Currently, wattle still accounts for as much as 20 percent of farmland in some areas. There are still a number of very large woodlots in the country, some larger than 50 ha.

The cases of the three tree species provide examples of how a natural product can progress from indigenous use to world trade. They also exemplify how indigenous people and countries with important non-timber forest products can benefit by domesticating and commercializing them.

5.3 Variation in bark thickness in *Prunus africana* in Kenya

5.3.1 Objective of the study

The objective of the present study was to assess variations in bark thickness and relative bark thickness among populations of *Prunus africana* in two closed canopy natural forest (Kakamega and Elgeyo) and adjacent farmland. Other factors being equal, bark thickness is an indicator of bark yield per tree. The information obtained will guide in designing appropriate silvicultural and management methods to increase bark production.

5.3.2   Methodology

The aim was to sample at least 30 trees of 10 cm DBH or more in each habitat. The irregularity of the bark of trees makes it necessary that uniform methods of measurement be applied in order to obtain comparable and unbiased results. A bark borer, 3 cm in diameter was used to remove the portion of the bark to be measured. Callipers was used to measure bark thickness (BKT). To reduce sampling errors, bark thickness of a tree was measured at two diametrically opposite points of the stem at the same height (1.3m) above the ground avoiding warts, thorns or other protuberances (Hedge *et al.* 1998). The average of the two measurements was then recorded. Diameter at breast height (DBH) over bark of the tree was also measured. Relative bark thickness (BKR) was expressed as a ratio between BK and DBH.

5.3.3 Results

The original data set as recorded in the field is presented in appendix 2a.

Population averages for bark thickness (BKT) per diameter class are shown in Table 5.1a and 5.1b. Relative bark thickness (BKR) (the ratio between BKT and DBH) is shown in Table 5.2a and 5.2b.

The trees exhibit a wide range of variation in DBH in these habitats. The higher DBH classes were more frequent in Elgeyo natural forest that is a less disturbed habitat. The average bark thickness increased from 6.6 mm at 10-19 cm DBH class to 23.6 mm at ≥70class. There is a tendency for bark thickness to increase and relative bark thickness to decrease in the trees from open farmland as compared to closed canopy forests and was statistically significant($P < 0.05$, t-test) at middle DBH classes (30-39, 40-49 and 50-59). BKT and was greater and BKR lower in Kakamega farms than in Elgeyo farms or in the two closed canopy forest habitats. As expected in all cases, BKT showed a positive relationship with DBH, with bigger trees tending to have thicker bark. However when expressed as the ratio of BKT to DBH (BKR), it generally showed negative correlations with DBH.

Table 5.1a and 5.1b Population mean bark thickness for different diameter classes and students t-test comparing means in natural closed canopy forest and farms

Table 5.1a

| DBH Class | Kakamega | | | | | | |
| | Natural Forest | | | Farms | | | |
	Mean	StDev	n	Mean	StDev	n	P value
10-19	6.6	1.5	5	-	-	-	-
20-29	9.0	1.2	11	9.7	0.9	12	0.130
30-39	10.8	0.9	11	13.1	0.7	10	0.001
40-49	14	1.6	9	15	0.8	7	0.062
50-59	15	0.9	6	17.0	0.8	4	0.003
60-69	17.4	1.1	5	18	0	1	0.088
≥70	-	-	-	-	-	-	

Table 5.1b

| DBH Class | Elgeyo | | | | | | |
| | Natural Forest | | | Farms | | | |
	Mean	StDev	n	Mean	StDev	n	P value
10-19	6.3	1.4	6	7.0	1.4	6	0.116
20-29	8.6	0.7	9	10.1	0.8	9	0.001
30-39	11.0	0.8	10	12.0	0.8	7	0.012
40-49	12.2	0.8	5	14.3	0.6	3	0.004
50-59	15.5	1.0	4	16.5	0.6	4	0.066
60-69	17.7	0.6	3	18	0	1	0.247
≥70	23.6	4.0	9	-	-	-	

Table 5.2a and 5.2b Population mean relative bark thickness for different diameter classes and students t-test comparing means in natural closed canopy forest and farms

Table 5.2a

Kakamega							
DBH Class	Natural Forest			Farms			
	Mean	StDev	n	Mean	StDev	n	P value
10-19	0.89	0.11	5	-	-	-	-
20-29	0.74	0.12	11	0.87	0.07	12	0.001
30-39	0.63	0.04	11	0.75	0.06	10	0.001
40-49	0.62	0.06	9	0.74	0.05	7	0.001
50-59	0.56	0.04	6	0.64	0.01	4	0.001
60-69	0.56	0.04	5	0.31	0	1	0.144
≥70	-	-	-	-	-	-	-

Table 5.2b

Elgeyo							
DBH Class	Natural Forest			Farms			
	Mean	StDev	n	Mean	StDev	n	P value
10-19	0.87	0.14	6	0.93	0.14	6	0.211
20-29	0.69	0.05	9	0.81	0.08	9	0.001
30-39	0.63	0.04	10	0.72	0.06	7	0.001
40-49	0.56	0.02	5	0.63	0.02	3	0.001
50-59	0.58	0.02	4	0.61	0.02	4	0.31
60-69	0.58	0.03	3	0.31	0	1	0.120
≥70	0.48	0.08	9	-	-	-	-

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5.4.4 Discussion

Tables 5.1 and 5.2 summarises the data on bark thickness (BKT) and relative bark thickness (BKR) for the four habitats. Evidently, there is a clear tendency for greater prevalence of thicker bark in the farms which are basically open habitats consisting of planted trees or remnant trees from deforestation. It is common practice in Kenya to save some of the trees after forest clearance for agriculture or livestock production. This meets both practical needs (shade, edible fruits, timber, firewood, etc.), and cultural traditions.

Genetic, environmental or an interaction of both may exhert an influence on BKT and BKR. The influence of stand characteristics on BKT and BKR varies between studies. Pederick (1970) and Monserud (1979) claimed in studies of *Pinus teada* and *Pseudotsuga mensiesii* that environmental influences were low or did not follow any trends. On the other hand, Wei and Birralho (1997) found that faster growing provenances of *Eucalyptus urophylla* in South East China did not necessarily have thicker bark or higher proportion of bark. Bark of *Pinus elliottii* is relatively thicker on well-drained soils than on damp soils. Matziris (1995) found a positive correlation between bark thickness and growth rate in *Pinus radiata* grown in Greece, while Quilho and Pereira (2001) found that bark thickness in *Eucalyptus globulus* in Portugal was higher in sites with better growth. It is possible therefore that the variation in bark thickness observed in this study could be related to higher growth rates in the open farmlands due to favourable growing conditions.

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The influence of tree age on BKT and BKR is uncertain. Investigations of age variation in BKT and BKR are rare. Studies on Norway spruce have shown that age has a low influence on BKT at a given diameter (Holmsgaard & Jacobsen, 1970). In *Pinus radiata*, BKR is not changed by tree age in the lower and central parts of the stem (Gordon, 1983).

The value of this study was to elucidate how BKT and BKR vary among populations from closed canopy forests and open habitats, and the influence some factors have on them. In general BKT and BKR in *Prunus africana* is strongly influenced by DBH. The influence of habitat on BKT and BKR is significant; with constant DBH they are higher in open habitats than in closed canopy forests. The causes of the variation between open habitats and closed canopy forests could be differences in light intensity, temperature, soil fertility, growth rates or competition, but it is not possible to unequivocally separate these effects. It could be argued that soil fertility would have a major impact on BKT and BKR. Brandel (1990) has shown that bole form varies with different forest vegetation types. However, the four localities in this study are all fertile, and variation due to this factor is probably limited. Variation due to competition is likely to be important since densities in open farmland habitats are low. There is a great difference in the level of illumination and temperature in closed canopy forests and open farmlands. Variation in light intensity and temperature in open farmland and closed canopy forests could be the variables of major importance for BKT and BKR in this study.

5.4. Estimating ecologically sustainable bark yield per tree of *Prunus africana* in Kenya

5.4.1 Objective of the study

The objective of the present study was to assess available quantities of ecological sustainable bark yield in *Prunus africana* and characteristics that could influence bark yield.

5.4.2 Methodology

A closed canopy natural forest stand of *Prunus africana* in Kapsaret forest, Kenya (0°15'N, 34°58'E), and adjacent farms were selected for this study. 30 trees from forest and 30 trees from farmland were sampled. In the forest, trees were randomly sampled along a belt transect (50*900m) that had been established in the stand. Because of the low density of *Prunus africana* (about 5 trees/ha in forests and sometimes less than 1 in farms), the aim was to sample at least 30 trees per habitat type of 20 cm DBH and more, including at least 3 trees in each one of the DBH Classes (to the nearest centimetre) of 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, 80-89, 90-99 and 100 cm and over. After selecting an initial healthy tree of 20 cm DBH or more, nearest neighbour trees was sampled along the transect until a particular size class was filled. In open farmland, trees of 20 cm DBH and more were sampled depending on the DBH classes in each farm, and the number of trees the farmer allowed to be sampled until all size classes had been filled. Because sampling involved stripping the bark from trees, some farmers only allowed a limited number of trees to be sampled. A total of 8 farms were sampled in total.

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On sampled trees, bark was harvested from quarters on opposite sides of the tree, from 1.3 m above ground level to height of the first branch as shown in figures 5.1 and 5.2. Ndibi & Kay (1997) reported 1.3 m as the lower stripping limit on the bole. Trees with DBH < 50 cm were debarked on two strips in opposite sides, each tree ¼ of the circumference of the tree. Trees with DBH ≥ 50 cm were debarked in 4 strips equally distributed around the circumference, each 1/8 of the circumference. The yield of bark in trees is partly a function of the diameter of the tree and other tree characteristics such as height, the height up to the first big branch, and the thickness of the bark, therefore for *Prunus africana*, these variables were measured in order to determine their relationship with bark yield. DBH, tree height, height up to the first big branch were measured. The thickness of the bark at breast height (1.3m) was also directly measured at the cut ends. The harvested bark was sun dried for a week (separating samples from each tree) and its dry weight measured.
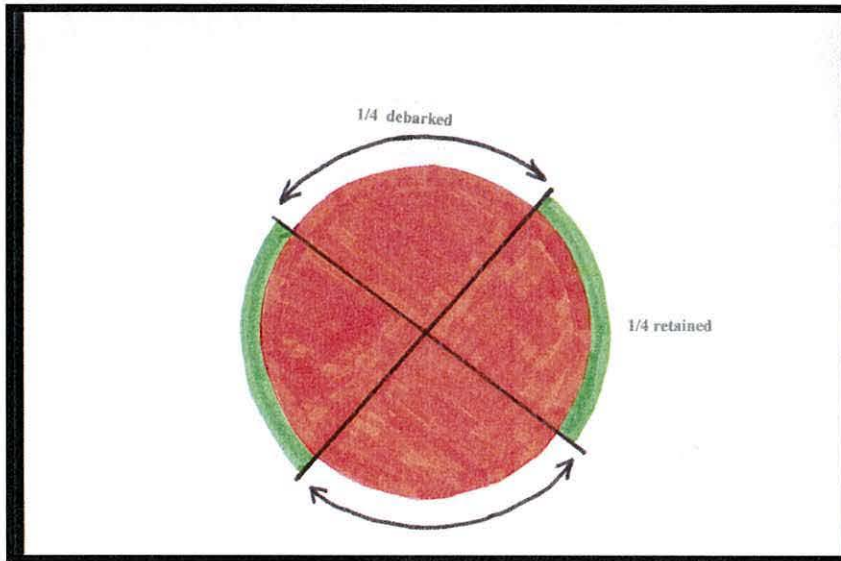
Figure 5.1 Bark harvesting technique for *Prunus africana*, where DBH is greater than 30 cm but less than 50 cm
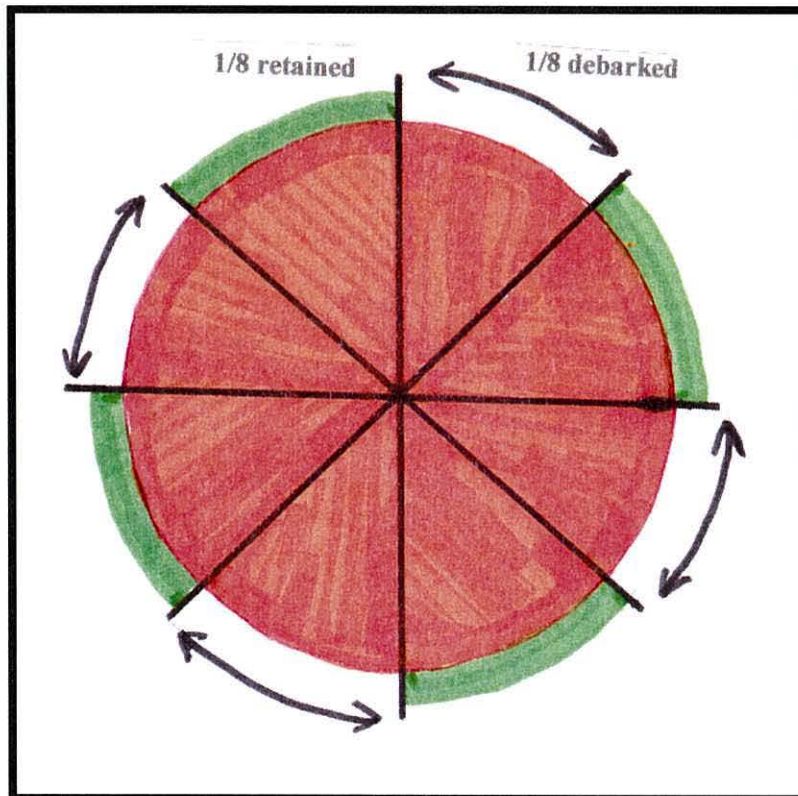
Figure 5.2 Bark harvesting technique for *Prunus africana*, where DBH is greater than 50 cm

5.4.2 Data Analysis

The relationship between bark yield (bark quantity) and DBH, height, height to the first branch and bark thickness were assessed by plotting dry bark weight from each of the 30 measured trees against (i) DBH and (ii) height (iii) height to the first branch and (iv) bark thickness. Coefficient of regression (R^2) was used to select the best regression equation. Regression method was eventually used to prepare a sustainable bark yield table showing average bark yield in terms of DBH.

5.4.3 Results

The original data set as recorded in the field is presented in appendices 2b and 2c.

Tables 5.3a and 5.3b show mean total weight per tree of exploitable bark harvested from trees in closed canopy natural forest and open farmlands with their respective diameter at breast height (DBH), tree height, height to first branch, and bark thickness. The mean bark yield per tree is 75.81 kg and 73.38 kg respectively.

Using all possible linear regressions including multiple regressions of the four variables and their interactions, it was decided to compare the models with and without logarithmic transformation of the variables. DBH accounted for most of the variation in bark yield, followed by bark thickness, height to first branch and tree height in that order. Interactions or transformations did not provide any improvement. Scatter plots, regression equations and R^2 of DBH, tree height, height to first branch and bark thickness is shown of figure 5.3. DBH has the highest R^2 and explains 99.7 % (R^2 = 0.9965) of the observed bark yield values followed by

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bark thickness (99.4 %, R^2 = 0.9939). DBH was chosen for single tree bark weight modelling, considering its easiest field application. The computed sustainable yield table of *Prunus africana* in closed canopy natural forest based on DBH only is presented on table 5.4.

Table 5.3a Mean total weight per tree of exploitable bark harvested from trees in closed canopy natural forest in Kapseret, Kenya and diameter at breast height (DBH), tree height, height to first branch, and bark thickness of the individual trees.

DBH Class		DBH (cm)		Tree Height (m)		Height to first branch (m)		Bark thickness (mm)		Bark Weight (kg)	
Class	n	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
20-39	7	30.9	5.8	19.4	1.3	7.7	0.6	6.4	1.3	20.2	8.4
40-59	8	48.5	6.4	23.5	1.4	9.6	0.7	10.1	1.9	50.7	11.1
60-79	6	69.2	6.2	25.8	0.8	11.4	0.5	14.7	1.37	90.2	14.1
≥80	9	92.2	10.2	29.1	1.2	12.8	0.5	19.3	1.9	130.3	17.8
Mean bark yield per tree (kg)										75.38	

Table 5.3b Mean total weight per tree of exploitable bark harvested from trees in open farmland in Kapseret Kenya, and diameter at breast height (DBH), tree height, height to first branch, and bark thickness of the individual trees.

DBH Class		DBH (cm)		Tree Heigh (m)		Height to first branch (m)		Bark thickness (mm)		Bark Weight (kg)	
Class	n	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
20-39	7	30.3	5.5	16.4	1.5	7.1	0.4	7.4	1.1	21.4	4.0
40-59	8	49.8	5.8	20.5	1.2	8.9	0.7	11.4	1.0	52.8	10.0
60-79	6	70	5.9	24.2	1.2	10.9	0.4	16.4	1.4	88.8	10.5
≥80	9	92.2	10.6	27.1	1.8	12.2	0.6	20.8	2.5	123.2	14.8
Mean bark yield per tree (kg)										73.81	
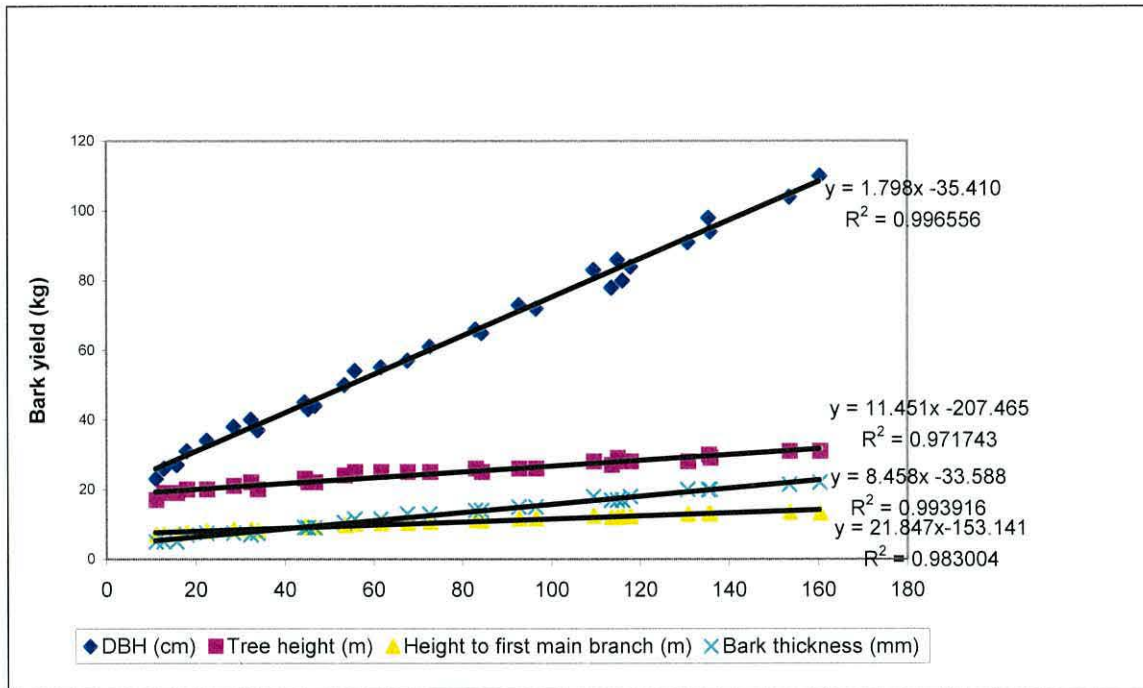
Figure 5.3 Scatter plots, regression equations and R^2 of DBH, tree height, height to first branch and bark thickness plotted against bark yield using original data set as recorded in the field.
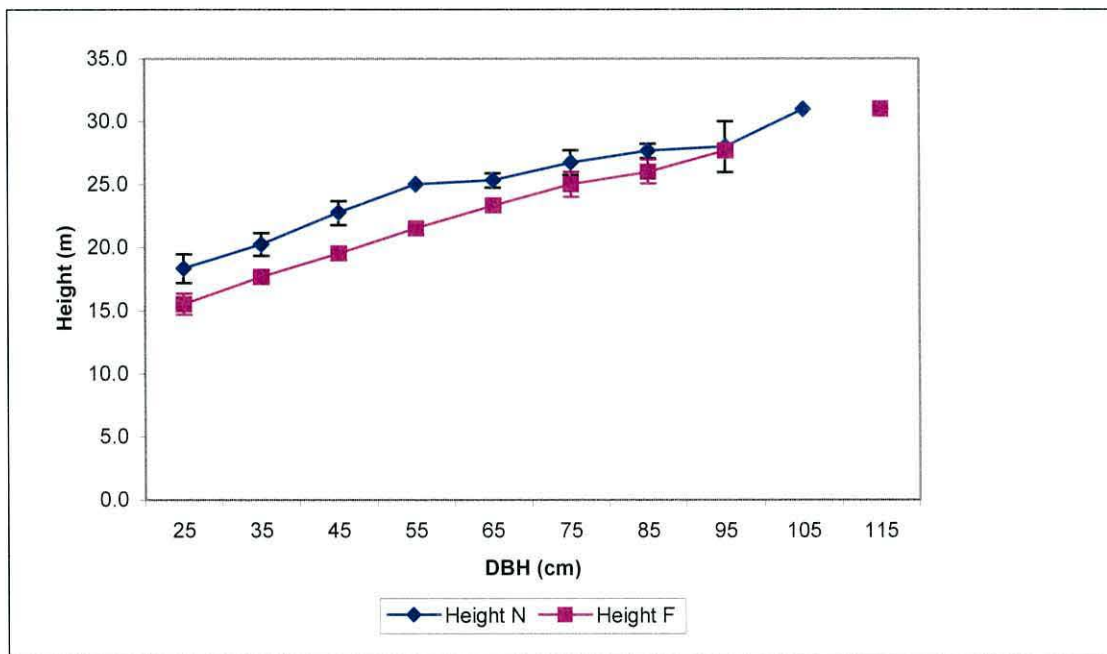
Figure 5.4a A comparison of height variability with increasing DBH of trees in closed canopy forest and open farmland, where Height N=Closed canopy natural forest, Height F= Open farm lands

Table 5.4 Sustainable yield table of *Prunus africana* in closed canopy natural forest based on DBH only.

Sustainable yield = 1.798dbh-35.410)

DBH (cm)	Estimated sustainable yield (kg)	DBH (cm)	Estimated sustainable yield (kg)
30	18.0	66	82.8
31	19.8	67	84.6
32	21.6	68	86.4
33	23.4	69	88.2
34	25.2	70	89.9
35	27.0	71	91.7
36	28.8	72	93.5
37	30.6	73	95.3
38	32.4	74	97.1
39	34.2	75	98.9
40	36.0	76	100.7
41	37.8	77	102.5
42	39.6	78	104.3
43	41.4	79	106.1
44	43.2	80	107.9
45	45.0	81	109.7
46	46.8	82	111.5
47	48.6	83	113.3
48	50.4	84	115.1
49	52.2	85	116.9
50	54.0	86	118.7
51	55.8	87	120.5
52	57.6	88	122.3
53	59.4	89	124.1
54	61.2	80	125.9
55	63.0	91	127.7
56	64.8	92	129.5
57	66.6	93	131.3
58	68.4	94	133.1
59	70.2	95	134.9
60	72.0	96	136.7
61	73.8	97	138.5
62	75.6	98	140.3
63	77.4	99	142.1
64	79.2	100	143.9
65	81.0		

A comparison of the two habitats (closed canopy forest and open farmland) revealed that trees in the closed canopy forest were significantly taller than the

ones from open farmland (Fig 5.4a), and also exhibited a higher height to first main branch (Fig 5. 4b). Trees in open farmlands had significantly thicker barks than those from closed canopy natural forest (Fig 5.4c), but this did not translate to a higher bark yield (Fig 5.4d).
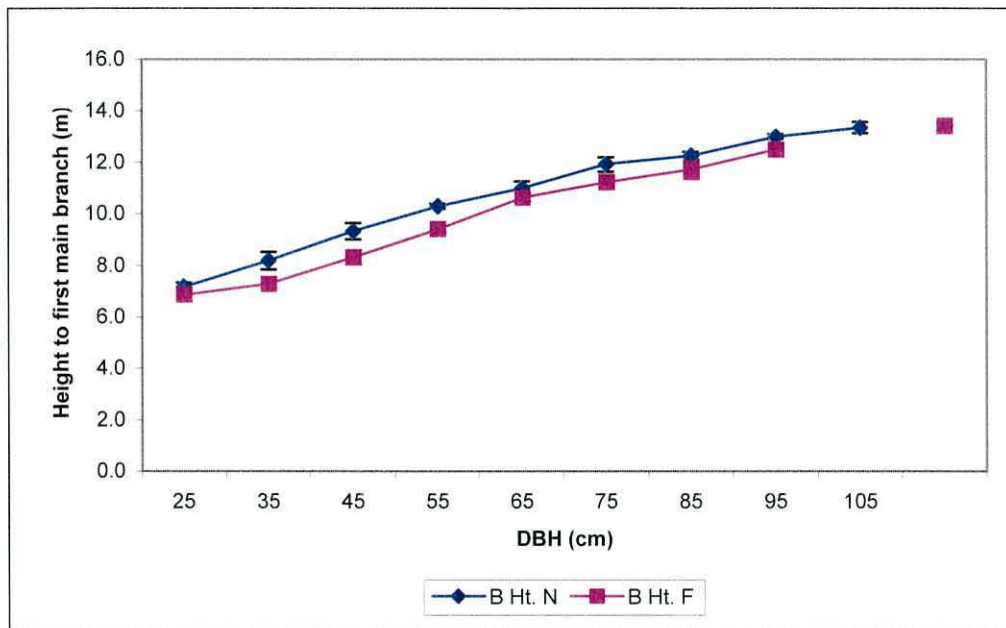
Figure 5.4b A comparison of variability in weight to first main branch with increasing DBH of trees in closed canopy forest and open farmland, where B Ht. N =Closed canopy natural forest, B Ht. F = Open farmlands.
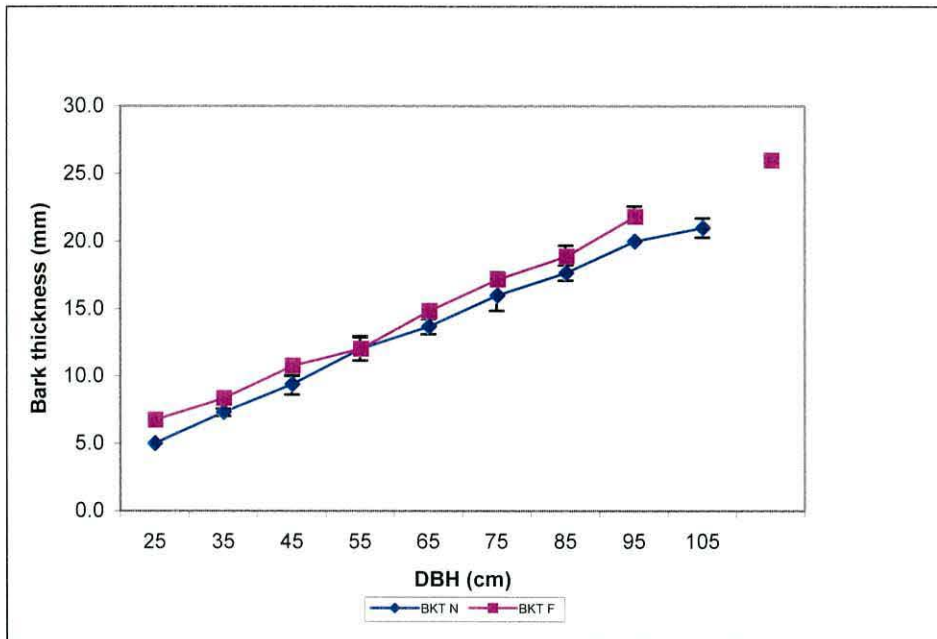
Figure 5.4c A comparison of variability in bark thickness with increasing DBH of trees in closed canopy forest and open farmland, where BKT N=Closed canopy natural forest, BKT F= Open farmlands.
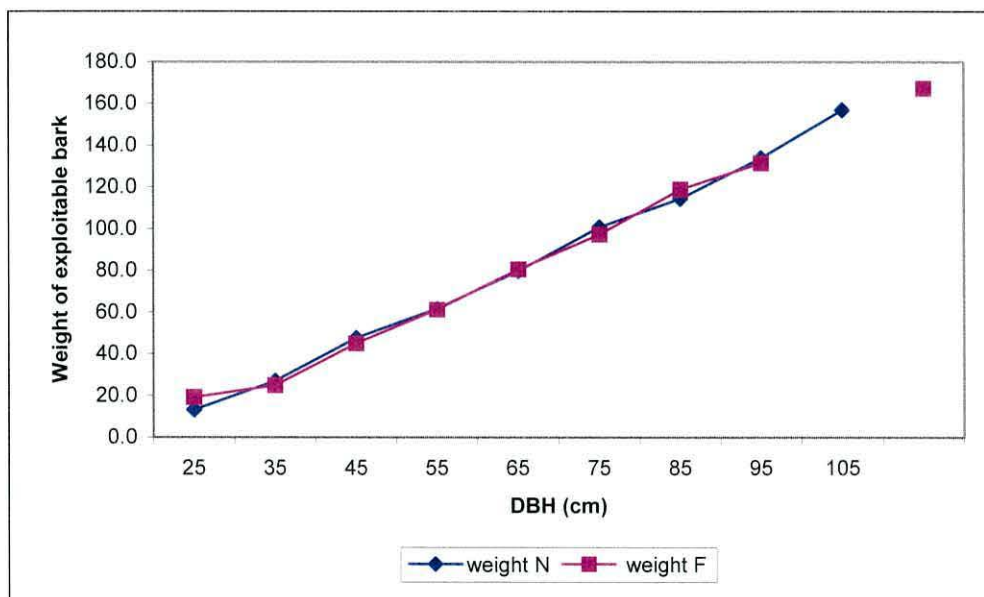
Figure 5.4d A comparison of height variability with increasing DBH of trees in closed canopy forest and open farmland, where weight N=Closed canopy natural forest, weight F= Open farm lands

5.4.4 Discussion

The results indicated that trees from closed canopy forest where taller than those from open farmlands. This could be due to competition among trees in closed canopy forest for light. This competition for light also affects the height to the first main branch, and as consequence, trees in closed canopy forest branch at higher heights than those from open farmland.

The mean bark yield per tree in closed canopy forest was 75.81 kg while in open farmland it was 73.38 kg. The higher bark thickness observed in trees from open farmland did not translate to higher bark yield probably because the benefits of higher bark thickness was offset by lower tree height and lower height to the first main branch observed in the trees from open farmland.

Modelling of singletree bark production is best done with an independent variable, easily measured in the field. Of the set of variables used in this study, DBH and Bark thickness are the best estimators of bark yield, however users of this models should bear in mind that a regression function provides a point estimate that has a variance. Estimation of a stand total bark yield is a straightforward summation of the predictions of individual trees. This has important implications for sustainable utilization and management of this highly valued resource. Assuming that Kapseret populations show the same pattern of variation and same quantitative bark characters as shown by the variation in bark thickness data (Section 5.3 this Chapter) and from the population structure study in chapter 3, the mean

population densities for the four forests are 10.9, 4.1, 8.8 and 6.2 trees per hectare for Timboroa, Elgeyo, Kinale and Kakamega forests respectively. Estimated bark production per hectare would be (75.81* density per hectare) 826, 310, 667 and 470 kg per hectare respectively.

5.5. Conclusions

Although a testing programme covering a wide range of environments is needed, the implications of the study on bark thickness are that it should be possible to improve bark production by planting *Prunus africana* at wider spacing than would ordinarily be found in a closed canopy forest, thus exposing the trees to maximum illumination. This is in view of the fact that sale of the bark is based on quantity.

The ability of *Prunus africana* to withstand bark damage offers the potential for sustainable harvesting, the value of the bark and the potential income derived from bark production point to the need for forecasting. Variability in tree form between different habitats may require separate equations for accurate predictions. The model presented here allows users to predict productivity for a 7-8 year production cycle on closed canopy natural forests in Kenya. More research work is necessary for the correlation between bark production and bark quality, considering its chemical properties.

CHAPTER VI

GENERAL DISCUSSION

In this chapter, the findings in relation to natural regeneration and bark production are re-examined in relation to sustainable utilization, conservation and management in the light of the pre-existing knowledge base for *Prunus africana* and studies conducted on other tropical species or ecologically comparable taxa. Major current utilization and management problems are specified and considered in relation to the species regeneration process. Possible sustainable utilization and conservation approaches are highlighted.

World wide interest in the medicinal properties of *Prunus africana* bark has resulted in growing apprehension that exploitation of the bark of the species for commercial purposes may be having adverse effects on the natural genepool of the species. Available information on the species is, however, insufficient to guide sustainable bark utilization and overall conservation strategies. This thesis has examined natural regeneration and bark production in *Prunus africana* populations in Kenya.

The results from the study show a relatively low density (6 trees/ha) of *Prunus africana* and a high proportion (83%) of trees greater than 20 cm DBH, and 17% were between 10-20 cm in all sample plots. The population structure typically shows an imbalance between smaller size classes (≤29 cm DBH) and mature trees (≥30 cm DBH). In all sample sites, size class distributions were skewed and indicated low or sporadic recruitment. Partly this is explained as an effect of

seedling herbivory and disease attack. The contribution of episodic regeneration events, limited forest disturbance, and scarcity of suitable regeneration sites in mature forests needs to be investigated. *Prunus africana* is usually described as a light-demanding species, with regeneration tied to canopy disturbance. Accordingly *Prunus africana* trees were most abundant in disturbed sites and at forest margins. Saplings were more abundant where there was good light penetration into forest. *Prunus africana* should therefore do well in agroforestry situations. The information on natural regeneration, amenability to vegetative propagation, and the findings that bark is thicker in open farmland suggests that this species should be relatively easy to grow artificially. Light demanding species are well suited for agroforestry systems.

A few small plantations *Prunus africana* occur in Kenya. Studies could be carried out on these existing plantations to determine growth rates and potential bark yields from trees of different ages and sizes. There are existing trees on farms, either planted by farmers or left during clearing of forests for farming, and a number of farmers are planting *Prunus africana* with the assistance of ICRAF/KEFRI and Forest Department (as woodlots, along boundaries and scattered trees in grazing land and with food crops).

The sporadic and poorly understood nature of seed production and seed viability has significant implications for cultivation potential. A constant supply of propagule material (seed or vegetative) is imperative for continued cultivation and

an understanding of the reproductive biology and phenology of *Prunus africana* is essential if long-term cultivation of the species is to be successful.

The findings emphasize the potentially serious effects of felling or killing large *Prunus africana* trees where there is low population density and low recruitment of large trees. Harvesting of *Prunus africana* has been banned in Kenya bending further research.

For sustainable bark harvesting of *Prunus africana*, general guidelines have been prescribed on how to harvest bark from trees (Chapter V). The results of the study indicates that following those guidelines, mean bark yield per tree would be 75 kg, and with an average *Prunus africana* density of 6 trees/ha, sustainable bark yield is then 450 kg per hectare. This yield is partly a function of the diameter of the tree; bark thickness and height to the first branch. There is a tendency for greater prevalence of thicker bark in trees growing in farms which are basically open habitats consisting of planted trees or remnant trees from deforestation (Chapter V).

This study has addressed questions pertaining to natural regeneration, population structure and bark production of *Prunus africana,* and recommends guidelines for future conservation and management.

From the results, it is concluded that *Prunus africana* exhibits the characteristics of a mid-late secondary species (*i.e.* light demanding especially at seedling and pole stages and inadequate recruitment in mature-phase forest shown by skewed size-class distribution). However the recalcitrant nature of the seed, high initial germination and high seedling mortality, are more suggestive of a climax species. To reconcile these contradictions will require further studies.

As a relatively fast-growing indigenous tree, *Prunus africana* has great potential for reforestation of deforested areas around forest remnants, enrichment planting of degraded forests and the establishment of plantations. The inclusion of *Prunus africana* in agroforestry schemes and the planting of the species on-farm should be encouraged. Managed sustainable bark harvesting is possible with *Prunus africana* because of the remarkable bark recovery of a high proportion of trees after bark removal. However, the resources (money and manpower) required of the Forestry Department and Kenya Wildlife Service is not available and is unlikely to become so with the current economic situation in Kenya.

The collection of bark provides a relatively small return to harvesters compared with the profits of the companies marketing the ultimate products. However, the poverty of collectors and the lack of alternative sources of income mean that they will make considerable efforts to harvest trees. What is clearly necessary is a multi-pronged approach to the problem that incorporates provision of alternative sources of supply, cultivation by subsistence and commercial farmers, *ex situ* conservation,

and improved protection of wild stocks (through the combined efforts of forestry and conservation bodies as well as concerned resource users such as rural herbalists, entrepreneurs and pharmaceutical industries). Reduction of exploitation rates in wild populations is clearly necessary for the species to be sustainably managed.

CHAPTER VII

GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study enabled the following conclusions to be drawn:

1. Size structure suggests that *Prunus africana* recruitment into large size classes is episodic and may be dependent on fine-scale canopy openings, and therefore the species can be characterised as having a gap-phase regeneration mode. Selective logging of mature trees of associated timber species would produce canopy openings that might facilitate recruitment of *Prunus africana* juveniles

2. Although the pattern of diameter distribution in *Prunus africana* in natural closed canopy forests is unbalanced, there is a potential for sustainable management based on small-scale gaps.

3. The Janzen-Connell hypothesis describing the spacing out of recruitment (away from parent trees) through the action of density or distance responsive herbivores or pathogens, is too simple in determining the final recruitment pattern in *Prunus africana*. Other factors or mechanisms confound or mask the outcome of density/distance-dependent attack processes.

4. The ability of *Prunus africana* to withstand bark damage offers the potential for sustainable harvesting.

5. Variability in tree form between different habitats implies need for separate yield prediction equations. Although a testing programme covering a wide range of environments is needed, the implications of the study on bark thickness are that it

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should be possible to improve bark production by planting *Prunus africana* at wider spacing than would ordinarily be found in a closed canopy forest.

6.   Although *Prunus africana* has been heavily over-exploited in parts of its range in Kenyan montane forests, it is not in danger of extinction at the species level. However, certain tree populations have been depleted, and valuable genetic resources may have been lost. While there is an urgent need to conserve *Prunus africana*, the distribution and biology of the species are insufficiently known. It will not be possible to determine the optimal approaches for sustainable utilization and conservation if this gap is not filled.

7.2 Recommendations

7.2.1 Management recommendations

1. Inadequate inventory data on the size of populations is a constraint to the possibilities to determine sustainable harvesting levels. It is recommended that a full-scale inventory and resource assessment of *Prunus africana* be done in Kenya. This should be undertaken as soon as possible to allow the preparation of appropriate sustainable utilization, conservation and management strategies.

2. Harvesting regulations and quotas for harvesting *Prunus africana* in Kenya should be developed and enforced to achieve sustainability.

3. In most study site; *Prunus africana* is not ecologically dominant in the ecosystems, which contain it. Therefore, *in situ* management strategies should focus on conservation of forest blocks rather than on the management of *Prunus africana* alone. To promote the recovery of *Prunus africana* populations in harvested areas

interventions should include opening the canopy around, and clearing the undergrowth beneath seed bearing trees.

6.3.2   Research recommendations

1.   More research work is necessary to assess the correlation between bark production and bark quality, considering its chemical properties.

2.   The results of the study indicate that tree-fall gaps and density-dependent mortality may influence spatial patterns of recruitment. The interactions between these two factors needs to be better understood and to be taken into account in managing natural regeneration of the species more adequately.

3.   The influences of limited forest disturbance, densities of dispersal agents and patterns of occurrences of suitable regeneration sites in mature forests need to be investigated as factors affecting *Prunus africana* recruitment.

4.   An independent study should be made to determine the best sustainable bark harvesting techniques, minimum exploitable diameter and intervals for sustainable bark harvesting of *Prunus africana* under Kenyan conditions.

CHAPTER VIII

REFERENCES

Abrahams, P. 1992. Herbal sales set to grow. Financial Times. London, UK, 2nd October 1992. *In*: Hamilton A., International trade in medicinal plants: Conservation issues and potential roles for botanic gardens. The proceedings of the Third International Botanic gardens Conservation Congress. Rio de Janeiro 19-25 October 1992.

Acharya, B.; Bhattarai, G.; de Gier, A. & Stein, A. 2000. Systematic adaptive cluster sampling for assessment of rare tree species in Nepal. Forest Ecology and Management, 137:65-73.

Achieng, J. 1999. African medicinal tree threatened with extinction. Third World Network.

Acworth, J. & Ewusi, B.N. 1999. *Prunus afr*icana. Striving for sustainable and equitable resource management in Cameroon. Mount Cameroon Project, Limbe. 5 pp.

Akerele, O.; Heywood, V. & Synge, H. (eds) 1991. Conservation of medicinal plants. Cambridge University press, Cambridge UK.

Albrecht, J. (ed) 1993. Tree Seed Handbook of Kenya Forestry Seed Centre Muguga: GTZ, 214-215 pp.

Andro, M.C. & Riffaud, J.P. 1995. *Pygeum africanum* extract for the treatment of patients with benign prostatic hyperplasia: A review of 25 years of published experience. Current Therapeutic research, 56: 796-817.

ANON, 1992. Urology: Risk of benign prostatic hyperplasia (BHP) underestimated. Hospital and Specialist Medicine. 58 pp.

ANON, 1999. Ethnobotany in Eastern and Southern Africa. People and Plants, May 1999.

Arap Sang, F.K. 1988. Forest diseases and pests with special reference to eastern Africa experience and assessed potential in Rwandan forestry practice. *In*: Pleines V. (ed). Compe-rendu du preierseminaire national sur la sylviculture des plantationsforestieres au Rwanda. Departement de Foresterie de l'Institut de sciences Agronomiques du Rwanda, Butare.

Ashton, P.S. 1969. Speciation among tropical forest trees: some deductions in the light of recent evidence. Biological Journal of the Linnean Society, London. 1:155-196.

Aubreville, A. 1938. La foret Coloniale. Les forets del'Afrique occidentale, 9:1-245.

Augspurger, C.K. & Kelly C.K. 1984. Pathogen mortality of tropical tree seedlings: experimental studies of effects of dispersal distance, seedling density and light conditions. Oecologia, 61: 211-217.

Augspurger, C.K. 1983a. Offspring recruitment around tropical trees: changes in cohort distance with time. Oikos, 20: 189-196.

Augspurger, C.K. 1983b. Seed dispersal of the tropical tree, *Platypodium elegans*, and the escape of its seedlings from fungal pathogens. Journal of Ecology, 71: 759-771.

Augspurger, C.K. 1984. Seedling survival of tropical trees: interaction of dispersal distance, light gaps and pathogens. Ecology, 65: 1705-1712.

Ayres, P.G.1992. Pests and pathogens: plant responses to foliar attack. Bios Scientific Publishers Limited.

Barbosa, B. & M.R. Wagner, 1989. Introduction to forest and shade tree insects. London Academic Press, Inc.

Bassman, J.H. & D.I. Dickman 1985. Effects of defoliation in the developing leaf zone of young *Populus euroamericana* plants. II. Distribution of 14 C-Photosynthate after defoliation. Forest Science, 31: 358-366.

Beardmore, J.A. 1983. Extinction, survival and genetic variation. *In*: Schoenwald-cox; Chambers, S.M.; Macbrydge, B. & Thomas L. (eds). Genetics and conservation. Benjamib Cummings, Menlo Park California. 125-151 pp.

Becker, P.L.; Lee, W.; Rothma;,E.D. & W.D. Hamilton, 1985. Seed predation and the coexistence of tree species: Hubbells model revisited. Oikos 44: 382-390.

Bengt, P. & Dwnie, B. 1992. Variation in Bark Thickness of young *Pinus contorta* Var. Latifolia Englem. In Sweden. Scandinavian Journal of Forestry Reasearch 7: 99-106.

Berger, G.A. 1973. Development and shedding of the bark. *In*: Kozlowski, T.T. (ed). Shedding of plant parts. Academic Press, New York.

Bombardelli, E. & Morazzoni, P. 1997. *Prunus africana* (Hook f) Kalm. Fitoterapia, 68: 205-218.

Brokaw, N. 1985. Treefalls, regrowth, and community structure in tropical forests. *In*: Pickett, S.T.A. & White P.S. (eds.). The ecology, and natural disturbance and patch dynamics. Academic press New York, 53-71 pp.

Brown, V.K. 1982. The phytophagous insect community and its impact on the early successional habitats. Proceedings of the 5th International Symposium on Insect-Plant Relations. Wageningen, Pudoc. 205 pp.

Brown, V.K.; Gange, A.C.; Evans, I. & Storr, A.L. 1987. The effect of insect herbivory on the growth and reproduction of two annual *Vicia* species at different stages in plant succession. Plant Ecology, 75: 1173-1189.

Buongiorno, J.; Dahir, S.; Lu, H.S. & Lin, C.R. 1994. Tree size diversity and economic returns in Uneven-aged forest stand. Forest Science 40: 83-103.

Burden, J.J. & Chilvers, G.A. 1975a. A comparison between host density effects on the frequency of primary infection foci in Py*thium*-induced damping-off disease. Australian Journal of Botany, 23: 899-904.

Burden, J.J. & Chilvers, G.A. 1975b. Epidemiology of damping- off disease (*Pythium irregulare*) in relation to density of *Lepidium sativum* seedlings. Annals of Applied Biology, 81: 135-143.

Burkey, T.V. 1994. Tropical tree species diversity: a test if the Janzen-Connell model. Oecologia 97: 533-540.

Campbell, D.G. 1989. Quantitative inventory of Tropical Forests. *In*: Campbell D.G & Hammond D.H. (eds.). Floristic inventory of Tropical Countries. The New York Botanical Garden Publishers.

CERUT 1999. The state of *Prunus africana* in the Muanenguba Mountain forest. Centre for Environment and Rural Transformation, Limbe. 17 pp.

Chen, J. & Franklin, J.J. 1995. Growing season microclimate gradients from clearcut edges into old-growth Douglas-fir forests. Ecological Applications, 5:4-86.

CITES, 1999. http:www.wcmc.org.uk/CITES/English/index.html (November 1999).

Clark, D.A. & Clark, D.B. 1984. Spacing dynamics of a tropical rain forest tree: evaluation of the Janzen-connell model. American Naturalist, 124: 769-788.

Coates, K.D. & Burton, P.J. 1997. Gap-based approach for development of silvicultural systems to address ecosystem management objectives. Forest Ecology and Management, 99: 337- 344.

Coley, P.D. & J.A. Barone, 1996. Herbivory and plant defences in tropical forests. Annual Review of Ecology and Systematics, 27: 305-335.

Coley, P.D. 1983. Herbivory and defence characteristics of tree species in a lowland tropical forest. Ecological Monographs 53: 209-233.

Commonwealth of Australia, 1995. Therapeutic goods administration: Approval terminology for drugs. Government Publishing Service, Canberra.

Condit, R.; Hubbell, S.B. & Foster, R.B. 1992. Recruitment near conspecific adults and the maintenance of tree and shrub diversity in a neotropical forest. American Naturalist, 140: 261-288.

Connell, J.H. 1971. On the role of natural enemies in preventing competitive exclusion in some marine animals and in rainforest trees. *In*: den Boer P.J. & Gladwell R.G. (eds.). Dynamics of populations, Pudoc, Wageningen, The Netherlands.

Connell, J.H. 1978. Diversity in tropical rainforests and coral reefs. Science, 199: 1302-1310.

Connell, J.H.; Tracey, G &. Webb, L.J. 1984. Compensatory recruitment, growth and mortality as factors maintaining rainforest tree diversity. Ecological monographs, 54: 141-164.

Conway, G.R. 1976. Man versus pests. *In*: May R.M. (ed.). Theoretical ecology: principles and applications. Blackwell Scientific Publication, Oxford. 257-281 pp.

Cowen, M.P. 1978. Capital and household production: the case of wattle in Kenya's

central province. 1903 - 1964. PhD dissertation, University of Cambridge, Cambridge, UK (unpublished).

Crawley, M.J. 1997. Plant Ecology. Blackwell Scientific Publishers, Oxford, U.K.

Crow, T.R.; Haney, A. & Walker, D.M. 1994. Report on the scientific round table on biological diversity convened by the Chequamegon and Nicolet National Forest. Unites States Forest Service General Technical Report. NC –166. Saint Paul MN.

Cunningham, A.B. & Mbenkun, F.T., 1993. Sustainability of harvesting *Prunus africana* bark in Cameroon: A medicinal plant in international trade. People and Plant working paper No. 2, UNESCO, Paris, 28 pp.

Cunningham, A.B.; Ayuk, E.; Franzel, S.; Duguma, B. & Asanga, C. 1998. An economic evaluation of medicinal tree cultivation: *Prunus africana* in Cameroon. People and Plants Working Paper 6. UNESCO, Paris.

Cunningham, M.; Cunningham, A.B. & Schippman, U. 1997. *Prunus africana* and the implementation of CITES. German Federal Agency for Nature Conservation. 52 pp.

Cunningham, A.B. 1999. Management of non-wood forest products in protected areas: lessons from a case study of multiple -use in Bwindi Impenetrable National park, Uganda. *In*: Sunderland, T.C.H.; Clark, L.E. & Vantomme, P. (eds.). Non-wood Forest Products of Central Africa. Current Research Issues and Prospects for Development. Proceedings of International Expert meeting on Non-wood Forest

Products in Central Africa, The Limbe Botanical garden Cameroon, 10-15, May 1998 143-159 pp.

Daubenmire, R. 1968. Plant communities: a text book of synecology. Harper & Row, New York.

Dawson I K., Powell, W. 1999. Genetic variation in the Afromontane tree *Prunus africana*, an endangered medicinal species. Molecular Ecology, 8: 151-156.

Dawson I.K.; Simons, A.J.; Wangu, R., & Powell, W., 1995. Diversity and genetic differentiation among subpopulations of *Gliricidia sepium* revealed by PCR-based assays. Heredity, 74: 10-18.

Dawson, I.K., 1997. "*Prunus africana*: How agroforestry can help save an endangered medicinal tree." Agroforestry Today, 9: (2) 15-17.

Day, K.R. & S.R. Leather 1997. Threats to forestry by insect pests in Europe. *In*: Watt, A.D.; N.E. Stock & M.D. Hunter, (eds.). Forest and Insects. Chapman and Hall. London, 177-205 pp.

De Smet, P.A.G.M.; Keller, K; Hansel, R. & Chandler, R.F. 1993. Adverse effects of herbal drugs, 2. Springer-Verlag, Berlin.

Denslow, J.S. 1987. Tropical rainforest gaps and tree species diversity. Annual Review of Ecology and Systematics. 18: 432-452.

Dewees, P.A. & Saxena N.C., 1995. Wood Products Markets as incentives for Farmer Tree Growing. *In*: Arnold, M.J.E. & Dewees, P.A. (eds.). Tree

Management in farmer strategies: responses to agricultural intensification. 209-219 pp.

Dittman, C.P. 1931. The Relation of Bark Thickness to the Diameter of Western Yellow Pine. Idaho Forester 39: 44-47.

Duke, J.A. 1985. (ed.). CRC Handbook of medicinal Plants. CRC Press Boca Raton, FL.

Eggeling, W.J. 1947. Observations on the of Budongo rainforest, Uganda. Journal of Ecology, 34: 20-87.

Ericson, A.; Hellgvist,C.; Langstrom, B.; Larson, S. & Tenow , O. 1985. Effects on growth of stimulated and induced shoot pruning by *Tomicus piniperda* as related to carbohydrate and nitrogen dynamics in Scots pine. Journal of Applied Ecology, 22: 105-124.

Esau, K. 1965: Plant anatomy. John Wiley and Sons Ltd. Inc., NY.

Farnsworth, N.R.; Akerele, O; Heywood, V. & Soejarto, D.D. 1991. Global importance of medicinal plants. Cambridge University Press, Cambridge, UK, 25-51 pp.

Fichtl, R. & Adi A. 1994. Honeybee Flora of Ethiopia. Weikersheim, Margraf Verlag.

Forget, P.M. 1994. Recruitment pattern of *Vouacapoua Americana* (Caesalpiniaceae) a rodent-dispersed tree species in French Guiana. Biotropica, 26: 408-419.

Foster, D.R.; Orwig, D.A. & Mclachlan, J.S. 1996. Ecological and Conservation insights from reconstructive studies of temperate old-growth forests. Trends in Ecology and Evolution, 11: 419-424.

Franklin, S.B.; Robertson, P.A.; Fralisch, J.S. & Kettler, 1993. Overstory vegetation and successional trends of land between lakes. USA Journal of Vegetation Science, 4: 509-520.

Fried, J.S.; Tappeinner, J.C. & Hibbs, D.E. 1988. Big leaf maple seedling establishment and early growth in Douglas-fir forests. Canadian Journal of Forest Research, 18: 1226-1233.

Gadgil, M. 1971. Dispersal: population consequences and evolution. Ecology, 52: 253-261.

Geldenhuys, C.J. 1981. *Prunus africana* in the Bloukrans River Gorge, Southern Cape. South African Forestry Journal, 118: 61-66.

GOK, 1994 a. Kakamega District Development Plan 1994-1996. Nairobi Government Printer. 1-5 pp.

Gordon A, 1983. Estimating bark thickness in *Pinus radiata*. New Zealand Journal of Forestry Science. 13: (3) 340-353.

Graham, R.A., 1960. Rosaceae. London, Crown Agents.

Grau, H.R. 2000. Regeneration patterns of *Cidrela lilloi* (meliaceae) in North Western Argentina subtropical montane forests. Journal of Tropical Ecology, 2000 16: (2) 227-242.

Grubb, P.J. 1986. Problems posed by sparse and patchily distributed species in species rich plant communities. 207-225 pp.

Hale, J.D., 1955. Thickness and density of bark: trends of variation for six pulpwood species. Pulp and Paper Magazines, 56: (12) 113-117.

Hall, J.B., O'Brien, E.M. & Sinclair, F.L. in Press. *Prunus africana*: a monograph. School of Agriculture and Forestry Sciences publication number x, University of Wales Bangor.

Hamilton, D.W. & May, R.M. 1977. Dispersal in stable habitats. Nature, London 269: 578-581.

Hamilton, A., 1992. Botanic gardens in a changing world. The proceedings of the Third International Botanic Gardens Conservation Congress. Rio de Janeiro, 19-25 October 1992.

Hamilton, A., 1996. Medicinal Plants. Word Wide Fund for Nature.

Harper, J.L. 1977. Population Biology of plants Academic press London.

Hart, T.B.; Hart, J.A. & Murphy, P.G. 1989. Monodominant species-rich forests of the humid tropics: Causes for their co-occurrence. American Naturalist, 133: 613-633.

Hartshorn, G.S. 1975. A matrix model of tree population dynamics. Tropical Ecological Systems. *In*: Golley, F.B.,& Medina, E. (eds.). Trends in Terrestrial and Aquatic Research. Springer Verlag, New York. 41-51 pp.

Haukioja, E. &. Honkanen, T. 1997. Herbivore induced responses in trees: internal versus external explanations. *In*: Watt, A.D.; Stock, N.E. & Hunter, M.D. (eds.) Forest and Insects. Chapman and Hall, London. 69-79, pp.

Haukioja, E.; Ruohomaki, K.; Senn, K.; Suomela, J &. Walls, M. 1990. Consequences of herbivory in the mountain birch (*Betula pubescens* ssp. *tortuosa*): importance of the functional organization of the tree. Oecologia, 82: 238-247.

Hedge, V; Chandran, M.D.S.; & Gadgil, M. 1998. Variation in bark thickness in a tropical rainforest community of west Ghats in India. British Ecological Society, Functional Ecology, 12: 313-318.

Hollman, A. 1991. Plants in medicine. Chelsea Physics Garden, London, UK.

Holmsgrad, E. & Jacobsen, B. 1970. Bark thickness and bark percentage for hardwoods and conifers Forsh. Forsogv. Damn 32: 267-294.

Horsfall, J.G. & Cowling 1981, E.B. Plant disease: an advanced treatise. Vol I . How disease is managed. Academic Press, Inc. New York 465 pp.

Horston, M. 1994. Biological diversity. Coexistence of Species on Changing Landscapes. Cambridge University Press, Cambridge, UK. 430 pp.

Howe, H.F. & Smallwood, J. 1982. Ecology of seed dispersal. Annual Review of Ecology and Systematics 13: 201-228.

Howe, H.F. 1989. Scatter- and clump –dispersal and seedling demography. Oecologia, 79: 417-426.

Howe, H.F. 1990. Survival and growth of juvenile *Virola surinamensis* in Panama: effects of herbivory and canopy closure. Journal of Tropical Ecology, 6: 259-280.

Hubbell, S.P. 1980. Seed predation and the coexistence of tree species in tropical forests. Oikos, 35: 214-229.

Hunter, M.D. 1997. Incorporating variation in plant chemistry into spatially explicit ecology of phytophagous insects. *In*: Watt, A.D.; Stock, N.E. & Hunter, M.D. (eds.). Forest and Insects. Chapman and Hall, London..81-96 pp.

Huxley, E. 1935. **White man's country:** Lord Delamere and the making of Kenya. Chatto and Windus, London, UK.

ICRAF, (1997). Project concept note for: *Prunus africana* (Pygeum) for pharmaceutical products used in treatment of prostatitis and timber. Draft proposal submitted to prosynthese. International Centre for Research in Agroforestry, Nairobi, Kenya, 32pp.

ICRAF, 1992. A selection of useful trees and shrubs for Kenya. Notes on their identification; propagation and management for use by farming and pastoral communities. Nairobi, ICRAF. 171 pp.

Itoh, A.; Yamakura, T.; Ogino, K.; Lee, H.S & Ashton, P.S. 1997. Spatial distribution patterns of two predominant emergent trees in a tropical rain forest of Sarawak, Malaysia. Plant Ecology, 132: 121-136.

IUCN, 1994. Centres of plant diversity. 1. Europe, Africa, South -west Asia and Middle East. WWF & IUCN, Cambridge, United Kingdom.

IUCN, 1995. Centres of plant diversity. 2. Asia Australia and Pacific. WWF & IUCN, Cambridge, United Kingdom.

Iversen, C. 1993. Dossier on *Prunus africana* (Hook.f.) Kalkman Rosaceae. Bangor, UK, Science Library, University of Wales: 9.

Janzen, D.H. 1970. Herbivores and the number of tropical tree species in tropical forests. American Naturalist, 104: 501-528.

Kant, H. 1992. Land productivity: Non-wood Products. Kenya Forestry Master Plan , Nairobi.

Kenkel, N.C. 1988. Pattern of self-thinning in Jack pine: testing the random mortality hypothesis. Ecology, 69: (4) 1017-1024.

KIFCON, 1994. Management Guidelines for Natural Forests. Kenya Indigenous Forest Conservation Programme, Nairobi.

KIFCON, 1994a . Kakamega Forest Reserve. A Guide. Nairobi. Real Press Karura.

KIFCON, 1994b. Conservation of biodiversity, ecological services and productivity of closed indigenous forests in Kenya. KIFCON, Phase 1 Report, Nairobi. Real Press, Karura.

Kitajima, K & Augpurger, C.K. 1989. Seed and seedling ecology of a monocarpic tropical tree, *Tachigalia vesicolor*. Ecology, 70: 1102-1114.

Kitching, G. 1980. Class and economic change in Kenya. Yale University Press, New Haven, Connecticut, USA.

Knowles, P. & Grant, M.C. 1983. Age and size structure analyses of Engelmann spruce, ponderosa pine, lodgepole pine and limber pine in Colorado. Ecology, 64: 1-9.

Kohyama, T. 1991. A functional model describing sapling growth under a tropical forest canopy. Functional Ecology 5: 83-90.

Kohyama, T. 1993. Size-structured tree populations in gap dynamic forest- the forest architecture hypothesis for stable coexistence of species. Journal of Ecology, 81: 131-145.

Kokwaro, J.O. 1976. Medicinal Plants of East Africa. East African Literature Bureau, Nairobi.

Kozlowski, T.T. 1949. Light and water in relation to competition of a piedmont forest tree species. Ecological monographs, 19: 207-231.

Kuuluvainen, T.; Penttinen, A.; Leinonen, K & Nygren, M. 1996. Statistical opportunities for comparing stand structural heterogeneity in managed and primeval forests. An example from boreal spruce forests in Southern Finland. Silvae Fennica 30: 315 –328.

Leakey, R.R.B., & Izac, A.M.N. 1996. Linkages between domestication and commercialization of non-timber forest products: Implications for agroforestry. *In*: Leakey, R.R.B.; Temu, A.B.; Melynk, M. & Vantomme, P. (eds.). Domestication and commercialization of non-

timber forest products in agroforestry systems. Proceedings of an International Conference held in Nairobi, Kenya, 19-23 February 1996. 1-7 pp.

Levin, D.A. 1976. Alkaloid bearing plants: An ecogeographic perspective. American Naturalist 110: 261-284.

Lewington, A., 1992. Results of survey of the import into Europe of *Prunus africana* and implications for its conservation. Report for WWF International, Gland Switzerland. Mimeo.

Lieberman, D. 1986. Demography of tropical tree seedlings: a review. *In*: Swaine M.D. (ed.). The ecology of tropical tree seedlings. P. 131-138. UNESCO, Paris and Parthenon Publishing, Carnforth, UK.

Lorimer, C.G. 1980. Age structure and disturbance history of Southern Appalachian Virgin forest. Ecology, 6: 1169-1184.

Long, J.N. & Smith, E.W. 1992. Volume increment in *Pinus Contorta* Var Latifolia. The influence of stand development and crown dynamics. Forest Ecology and Management, 53: 53-64.

Lowman, M.D. & Heatwole, H. 1992. Spatial and temporal variability in defoliation of Australian eucalypts. Ecology, 73: 129142.

Lowman, M.D. 1997. Herbivory in forests: from centimetres to mega meters. *In*: Watt, A.D.; Stock, N.E. & Hunter, M.D (eds.). Forest and Insects. Chapman and Hall. London, 135-149 pp.

Lubanga, M., 1991. The use of indigenous plants by forest dwellers: Findings from sample community in the S.W. Mau forest. KIFCON, Nairobi.

Lukandu, G. W., 1991. An interim checklist of Medicinal Plants of Arabuko Sokoke Forest. KIFCON, Nairobi.

Lung, A. & Foster, S. 1996. Encyclopaedia of Common Natural, Ingredients, Wiley & Sons New York.

Macleod, H.L. 1986. The conservation of Oku Mountain Forest. International Council for Bird Preservation Study Report, 15. 1-90 pp.

Manion, P.D. 1981. Tree disease concepts. Prentice-hall Inc. Engelwool Cliffs, New Jersey. 1-16 pp.

Martinez- Ramoz, M.; Alvarez-Buylla & SaruKhan, J. 1989. Tree dynamics and gap dynamics in a tropical rain forest. Ecology, 70: (3) 555-558.

Mattson, W.J. &. Addy, N.D 1975. Phytophagous insects as regulators of forest primary production. Science, 190: 515-522.

Matziris, D.I. 1995. Provenance variation of Pinus radiata grown in Greece. Silvae Genetica, 44: 2-3.

Mbuya, L.P.; Msanga, H.P.; Ruffo, C.K.; Birnie, A., & Tengnas, B. 1994. Usefull Trees abd Shrubs of Tanzania- Identification, Propagation and Management for agricultural and Pastoral communities. Regional Siol Conservation Unit (RSCU), Swedish International Development Authority, 412-413 pp.

Mcalpine, T. & Warrier 1992. Competitive positioning: Who's doing what in the herbal medical industry. Consultancy report. Private Publishers UK.

McNaughton, S.J. 1983. Compensatory plant growth as a response to herbivory. Oikos, 40: 329-336.

Menges, E.S. 1991. The application of minimum viable population theory to plants. *In*: Falk, D.A. & Holsinger, K.E. (eds.). Genetics and conservation of rare plants. Oxford University Press, New York. 45-61 pp.

Moeur, M. 1993. Characterizing spatial patterns of trees using stem-mapped data. Forest Science 39: 756-775.

Monserud, R.A. 1979. Relations between inside and outside bark diameter at breast height for Douglas-fir in northern Idaho and north western Montana. US Department of Forest and Agriculture, Forest Service, International Forest Range Experiment Station. INT.- 266.

Morandola, P.; Jallous, H.; Bombardelli, E. & Morazzoni, P. 1997. Main phytoderivatives in the management of benign prostatic hyperplasia. Fitoterapia, 68: 195-204.

Mowrey, D. 1986. The scientific Validation of Herbal Medicine. Keats Publishing. New Canaan, CT.

Mueller-Dombois, D. & Ellenberg, H. 1974. Aims and methods of vegetation ecology. Wiley, New York.

Munjuga , M. Were; J. Dawson, I.; Ruigu, S. & Simons, A. in press. Reproductive biology of the over-exploited, medicinal tree *Prunus africana*: studies

in Central Kenya. East African Agriculture and Forestry Journal.

Mutangah, J.G.; Mwangangi, O. M. & Mwaura P.K. 1993. Mau Forest Complex: a
vegetation survey KIFCON/NMK, Nairobi.

Mwanza, E.J.; Waithaka, S.; Mibey, R.K. & Kariuki, G. 1999. First report of
Colletotrichium gloeospoioides as a Foliar and dieback pathogen of
Prunus africana in Kenya. Plant and Disease, 83: 79.

NAS 1980. Firewood crops. Shrub and tree species for energy production. National
Academy of Sciences, Washington, DC.

Ndam, N., 1998. Tree regeneration, vegetation dynamics and the maintenance of
biodiversity on Mt. Cameroon: the relative impact of natural and
human disturbance. PhD. Thesis, School of Agriculture and Forest
Sciencs, UW, Bangor. 195-223 pp.

Ndam, N.; Ewusi, B.; Lee, D.K.; Kim, G.T. & Young, Y.C. 2000. Income from non-
timber forest products. *In*: Price, M.F. & Butt, N., (eds.). Forests in
sustainable mountain development: a state of knowledge report 2000.
Task force on Forests in Sustainable Mountain Development. 300-311
pp.

Ndibi, B.P. & Kay, E.J. 1997. The regulatory framework for the exploitation of
medicinal plants in Cameroon: the case of *Prunus africana* on Mount
Cameroon. Biodiversity and Conservation, 6: 1409-1412.

Nichols, J.P. 1990. Generic promotions for agricultural exports: effectiveness and management issues. Staff Paper Series – Texas Agricultural Experimental Station, No. SP 1P 14pp.

Noad, T.C. & Birnie, A. 1989. Trees of Kenya. T.C. Noad & A. Bernie, Nairobi. 245-247 pp.

Nzilani, N. J. 1999. The status of *Prunus africana* in Kakamega forest and the prospects for its vegetative propagation. MPhil Thesis. Moi University Eldoret, Kenya.

Ogden, J. 1985. Past, Present and future: studies on the population dynamics of some long-lived trees. *In*: White J. (ed.). Studies on plant demography. Academic Press, London. 3-16 pp.

Okuda, T.; Kachi N; Yap, S.K & Manokaran, N. 1997. Tree distribution pattern and fate of juveniles in a lowland tropical rainforest – implications for regeneration and maintenance of species diversity. Plant ecology, 131: 155-171.

ONADEF. 1997. Rapport d'inventaired'amenagement du massif forestier du Mont Cameroon (46848.32). Office National de Development des Forets, Yaounde. 27 pp.

Pederick, L. 1970. Variation and inheritance of stem form and bark thickness in young loblolly pine, North Carolina University Technical report 41.

Piene, H. & Piercy, K.E. 1984. Changes in needle morphology, anatomy, and mineral content during recovery of protected balsam fir trees initially

defoliated by the spruce budworm. Canadian Journal of Forestry Research, 14:(2) 238-245.

Pinard, M. A. & Huffman, 1997. Fire resistance and bark properties of trees in a seasonally dry forest in eastern Bolivia. Journal of Tropical Ecology 13: 727-740.

Populer, C. 1978. Changes in host susceptibility with time. Plant disease Vol. II. How disease develops in populations . *In*: Horsfall, J.G. & Cowling , E.B. (eds.) . Academic Press, New York. 239-262 pp.

Prance, G.T. & Prance, A.E. 1993. Bark: The formation, characteristics and uses of the bark around the world. Timber Press Portland Oregon. 23-75 pp.

Pretsch, H. 1997. Analysis and modelling of spatial stand structures. Methodological considerations based on mixed Birch-Larch stands in lower Saxony. Forest Ecology and Management, 97: 237-253.

Prins, A.H. & Verkaar, H.J. 1992. Defoliation: do physiological and morphological responses lead to (over) compensation? *In*: Ayres, P.G. (ed.). Pests and pathogens: plant responses to foliar attack: BIOS Scientific Publishers Limited, 13-31 pp.

Quilho, D. & Pereira, H, 2001. Within and between tree variation in bark content and wood density in *Eucalyptus globulus* in commercial plantations. IAWA , 2:(3) 255-265.

Read, J. ; Hollman, P.; & Cherrier, J.F. 1995. The anomaly of monodominant tropical forests: Some preliminary observations in *Nothofagus-*

dominated rainforests of New Caledonia. Journal of Tropical Ecology, 11: 359-389.

Reichie, D.A.; Goldstein, R.A.; Van Hook, JR & Dodson, G.J. 1973. Analysis of insect consumption in a forest canopy. Ecology, 54: 1076-1084.

Richards, P.W. 1952. The Tropical Rainforest. Cambridge University Press, Cambridge.

Romberger, J.A.; Hejnowicz, Z. & Hill, J.F. 1992. Plant structure: Function and Development. Springer-Verlag, Berlin.

Sano, J. 1997. Age and size distribution in longterm forest dynamics. Forest Ecology and Management, 92: 39-44.

Sauer, J.D. 1993. Historical geography of crop plants - a select roster. CRC Press, Boca Raton, Florida.

Schaefer, C., 1990. Seed testing on species indigenous to Kenya. Tropical Tree Seed Research, Forestry Training Centre, Gympie, Queensland, Australia, ACIAR Proceedings series.

Schroth, G.; Krauss, V; Gasparotto, L.; Duarte Aguilar, J.A. & Vohland, K. 2000. Pests and diseases in agroforestry systems of humid tropics. Agroforestry systems, 50: (3) 199-241.

Schupp E.W. 1988. Seed and early seedling predicting in the forest understory and tree fall gaps. Oikos, 51: 71-78.

Simons, A.J., 1996. ICRAF's strategy for domestication of non-wood tree products. *In*: Leakey, R.R.B., Temu, A.B., Melynk, M. & Vantomme, P., (eds.). Domestication and commercialization of non-timber forest products in agroforestry systems. Proceedings of an International Conference held in Nairobi, Kenya, 19-23 February 1996. 8-22 pp.

Smith, D.M. 1986. Practice of silviculture, 8th edn. Wiley and Sons, New York. USA.

Spies, T.A. & Franklin, J.F. 1989. Gap characteristics and vegetation response in coniferous forests of the Pacific North West. Ecology, 70: 543-545.

Spies, T.A. & Franklin, J.F. 1991. The structure of natural, young, mature and old-growth Douglas-fir forest in Oregon and Washington. *In*: Ruggiero, L.F.; Aubry, K.B.; Cares, A.B. & Huff, M.M. (eds.). Wildlife and the Vegetation of Unmanaged Douglas-fir Forests. USDA Forest Service General Technical Report. PNW – 285, Pacific Northwest Research Station. Portland OR, 91-210 pp.

Sterner, R.W.; Ribic, C.A. & Schartz, G.E. 1986. Testing for life-history historical changes in spatial patterns of four tropical tree species. Journal of Ecology, 74: 621-633.

Sunderland, T.C.H. & Tako, C.T. 1999. The exploitation of *Prunus africana* on the island of Bioko, Equatorial Guinea. A report for the People and Plants Initiative, WWF-Germany and the IUCN/SSC Medicinal Plant Specialist Group.

Sunderland, T.C.H. & Nkefor, J. 1997. Conservation through cultivation. A case study: The Propagation of *Prunus africana*.

Swaine, M.D. & Whitmore, T. C. 1988. On the definition of ecological species groups in tropical forests. Vegetatio, 75: 81-86.

Fonsceca, J.F.t. & Parresol, B.R. 2001. A model for cork weight estimation in Northern Portugal with methodology for construction of confidence intervals. Forest Ecology and Management, 152: 132-139.

Thomson, S.K. 1991. Adaptive Cluster sampling: design with primary and secondary units. Biometrics, 47: 1103-115.

Tchoundjeu, Z.; Avana, M.L.; Simons, A.J.; Dawson, I.K.; Were, J. & Jaentsche, H. 1999a. Domestication of *Prunus africana*: the contribution of vegetative propagation (poster). American Society of Agronomy Symposium, November, 1999, Salt Lake City.

Tchoundjeu, Z.; Duguma, B.; Tiencheu, M.L & Ngo Mpeck, M.L 1999b. The domestication of indigenous agroforestry trees: ICRAF's strategy in the humid tropics of west and central Africa. *In*: Sunderland, T.C.H; Clark, H.E. & Vantomme (eds.). Current research issues and prospects for conservation and development . FAO, Rome. 161-170 pp.

Trzebinski, E. 1985. The Kenya pioneers._Heineman, London, U.K.

Tsingalia, M.H. 1989. Variation in seedling predation and herbivory in *Prunus africana* in Kakamega Forest Kenya. African Journal of Ecology. 27 : 207-217.

Turner, I.M. 1990. Tree seedling growth and survival in a Malaysian forest. Biotropica 22: 146-154.

Turok, J.; Varela, M.C. & Hansen, C. 1997. *Quercus suber* Network. Report of

United Kingdom, government of the (1919). East Africa Protectorate. Economic Commission Final Report. Part 1.

Usher, M.B. 1966. A matrix approach to the management of renewable resources with special reference to selection forests. Journal of Applied Ecology, 3: 355-367.

Veblen, T.T. 1992. Regeneration dynamics. *In*: Glen-Lewin, D.C.; Peet, R.K. & Veblen. T.T. (eds.). Plant Succession: theory and prediction., Chapman and Hall, London. 152-187 pp.

Walker, J.C. 1969. Plant pathology. McGraw Hill, New York.

Walter, G.H. & Perr, W.H. 1994. Insect pests of forage tree legumes: Biology and no-chemical control. *In*: Gutteridge, R.C. & Shelton, H.M. (eds.). Forage tree legumes in tropical agriculture. CAB International, London. 309-321 pp.

Walter, S. & Rakotonirina, J.C.R. 1995. L'exploitation de *Prunus africana* a Madagascar PCDI Zahamena et la Direction des Eaux et Forets , Antananarivo, Madagascar, 23 pp.

Watt, A.S. 1947. Patterns and processes in the plant community. Journal of Ecology, 35: 1-22.

Wei, X., & Borralho, N.M.G. 1997. Genetic control of wood basic density and bark thickness and their relationships with growth traits in *Eucalyptus europhylla* in South East Asia. Silvae Genetica 46: (4) 245-250.

White, F. (1983). The vegetation of Africa: a Descriptive Memoir to Accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa by White, UNESCO/Paris.

Whitemore, T.C. 1984. Tropical rainforest of the Far East. Clarendon Press, Oxford, 352 pp.

Whittaker, R.H. 1966. Forest dimensions and production in Great Smoky Mountains. Ecology, 47: 103-121.

Wilkins, A.P.1991. Sapwood, heartwood and bark thickness of Siviculturally treated *Eucalyptus grandis*. Wood science and Technology 25: 415-423.

Willson, M.F. 1988. Spatial heterogeneity of post-dispersal survivorship of Queensland rainforest seeds. Australian Journal of Ecology, 13: 137-145.

Willson, M.F. 1993. Dispersal mode, seed shadows and colonization patterns. Vegetatio, 107: 261-280.

Wright. S.I.; Hall, R.W. & Peacock, J.W. 1989. Effect of stimulated insect damage on growth and survival of northern red oak (*Quercus rubra* L.) seedlings. Environmental Entomology, 18: (2) 235-239.

WWF, 1996. Medicinal Plants. World Wide Fund for Nature.

Zimmerman, D.A. 1972. The avifauna of the Kakamega forest Western

Kenya, including a population study. American Museum

of Natural history, 149: 257-337.

APPENDICES

Appendix 1a. Table of total seedling counts in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	100	21	47	10	8	147	33	122	65	78
	R2	101	24	57	5	13	139	30	110	52	77
	R3	116	20	49	11	12	155	38	117	60	85
	R4	125	23	67	17	16	128	33	141	86	70
3 m	R1	88	43	65	19	37	164	52	124	76	93
	R2	107	49	60	25	28	175	48	102	67	79
	R3	90	39	53	25	35	150	60	130	79	75
	R4	111	49	75	8	32	171	42	128	86	108
5 m	R1	88	28	52	15	25	198	40	108	64	71
	R2	83	29	61	16	19	203	52	97	63	69
	R3	94	26	58	10	33	199	41	121	57	83
	R4	90	43	54	11	26	194	41	121	82	81
7 m	R1	70	32	50	12	22	109	37	97	65	74
	R2	66	28	70	9	24	129	52	98	60	71
	R3	51	33	49	9	28	99	34	108	62	78
	R4	88	40	59	14	20	103	57	88	74	87
9 m	R1	88	25	41	14	9	120	35	105	54	67
	R2	100	30	45	14	14	125	36	114	54	74
	R3	82	20	47	9	11	114	27	90	56	85
	R4	82	27	39	17	17	122	45	91	55	82
11 m	R1	66	11	32	3	2	111	21	77	47	52
	R2	66	6	34	0	0	113	22	70	38	59
	R3	70	15	29	1	0	109	21	65	48	46
	R4	66	14	40	1	0	107	31	100	51	63
13 m	R1	57	0	21	0	0	90	8	65	36	38
	R2	55	0	26	0	0	92	9	52	27	41
	R3	60	0	13	0	0	86	9	55	43	42
	R4	49	0	25	0	0	96	15	91	33	51
15 m	R1	44	0	7	0	0	76	0	54	20	28
	R2	52	0	8	0	0	68	0	65	23	31
	R3	40	0	10	0	0	76	0	51	19	38
	R4	41	0	13	0	0	89	0	51	29	36
17 m	R1	22	0	9	0	0	17	0	10	5	12
	R2	22	0	12	0	0	17	0	15	6	15
	R3	25	0	6	0	0	21	0	10	11	11
	R4	17	0	7	0	0	18	0	12	10	14
19m	R1	0	0	0	0	1	0	0	0	0	0
	R2	0	0	0	0	5	0	0	0	0	0
	R3	0	0	0	0	7	0	0	0	0	0
	R4	0	0	0	0	2	0	0	0	0	0

Appendix 1b. Table of total seedling counts ≥25<100cm tall in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	11	2	5	4	1	9	3	11	5	5
	R2	8	1	4	0	0	13	1	13	3	8
	R3	13	4	3	2	3	8	5	8	7	6
	R4	14	4	10	4	1	11	4	15	6	5
3 m	R1	7	6	4	4	3	16	3	17	8	10
	R2	13	8	6	6	2	19	6	11	6	7
	R3	11	5	4	2	2	13	4	14	9	6
	R4	13	7	5	1	4	18	7	13	10	13
5 m	R1	12	1	9	2	4	17	7	10	7	6
	R2	10	0	12	1	2	14	9	14	11	8
	R3	11	3	7	0	7	20	4	15	8	9
	R4	14	4	10	5	3	17	9	13	9	14
7 m	R1	7	5	7	3	3	16	7	15	10	11
	R2	9	7	13	1	2	18	11	19	9	15
	R3	6	3	8	4	4	12	5	11	13	9
	R4	7	8	11	5	4	21	14	16	9	12
9 m	R1	17	4	8	5	1	22	6	19	11	11
	R2	21	2	6	3	3	16	3	21	15	13
	R3	14	5	11	2	5	25	5	16	9	15
	R4	17	4	7	6	7	23	13	23	9	16
11 m	R1	14	3	5	1	1	25	5	17	11	11
	R2	19	0	3	0	0	21	9	13	7	9
	R3	11	4	6	0	0	28	6	16	5	8
	R4	15	5	8	0	0	25	8	23	14	15
13 m	R1	14	0	4	0	0	22	0	13	7	9
	R2	18	0	7	0	0	19	3	11	6	7
	R3	13	0	2	0	0	23	4	10	9	11
	R4	11	0	8	0	0	25	2	20	9	13
15 m	R1	10	0	0	0	0	20	0	14	6	7
	R2	13	0	3	0	0	17	0	12	4	8
	R3	9	0	1	0	0	28	0	17	8	11
	R4	9	0	4	0	0	24	0	15	9	12
17 m	R1	6	0	6	0	0	6	0	3	0	3
	R2	9	0	7	0	0	8	0	4	3	2
	R3	6	0	4	0	0	9	0	5	4	4
	R4	4	0	3	0	0	4	0	4	2	4
19m	R1	0	0	0	0	0	0	0	0	0	0
	R2	0	0	0	0	2	0	0	0	0	0
	R3	0	0	0	0	7	0	0	0	0	0
	R4	0	0	0	0	0	0	0	0	0	0

Appendix 1c. Table of total seedling counts ≤25 cm tall in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	89	19	42	6	7	138	30	111	60	73
	R2	93	23	53	5	13	126	29	97	49	69
	R3	103	16	46	9	9	147	33	109	53	79
	R4	111	19	57	13	15	117	29	126	80	65
3 m	R1	81	37	61	15	34	148	49	107	68	83
	R2	94	41	54	19	26	156	42	91	61	72
	R3	79	34	49	23	33	137	56	116	70	69
	R4	98	42	70	7	28	153	35	115	76	95
5 m	R1	76	27	43	13	21	181	33	98	57	65
	R2	73	29	49	15	17	189	43	83	52	61
	R3	83	23	51	10	26	179	37	106	49	74
	R4	76	39	44	6	23	177	32	108	73	67
7 m	R1	63	27	43	9	19	93	30	82	55	63
	R2	57	21	57	8	22	111	41	79	51	56
	R3	45	30	41	5	24	87	29	97	49	69
	R4	81	32	48	9	16	82	43	72	65	75
9 m	R1	71	21	33	9	8	98	29	86	43	56
	R2	79	28	39	11	11	109	33	93	39	61
	R3	68	15	36	7	6	89	22	74	47	70
	R4	65	23	32	11	10	99	32	68	46	66
11 m	R1	52	8	27	2	1	86	16	60	36	41
	R2	47	6	31	0	0	92	13	57	31	50
	R3	59	11	23	1	0	81	15	49	43	38
	R4	51	9	32	1	0	82	23	77	37	48
13 m	R1	43	0	17	0	0	68	8	52	29	29
	R2	37	0	19	0	0	73	6	41	21	34
	R3	47	0	11	0	0	63	5	45	34	31
	R4	38	0	17	0	0	71	13	71	24	38
15 m	R1	34	0	7	0	0	56	0	40	14	21
	R2	39	0	5	0	0	51	0	53	19	23
	R3	31	0	9	0	0	48	0	34	11	27
	R4	32	0	9	0	0	65	0	36	20	24
17 m	R1	16	0	3	0	0	11	0	7	5	9
	R2	13	0	5	0	0	9	0	11	3	13
	R3	19	0	2	0	0	12	0	5	7	7
	R4	13	0	4	0	0	14	0	8	8	10
19m	R1	0	0	0	0	1	0	0	0	0	0
	R2	0	0	0	0	3	0	0	0	0	0
	R3	0	0	0	0	0	0	0	0	0	0
	R4	0	0	0	0	2	0	0	0	0	0

Appendix 1d. Table of total disease infected seedling counts in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	49	11	18	5	6	96	23	89	28	34
	R2	57	18	26	6	8	78	18	81	36	35
	R3	50	15	11	8	10	113	26	73	30	29
	R4	36	19	31	9	7	96	27	97	30	34
3 m	R1	46	27	33	8	18	104	20	68	34	41
	R2	60	20	38	9	11	97	15	64	36	43
	R3	44	16	40	9	13	124	25	60	28	40
	R4	60	29	25	6	25	94	23	84	37	48
5 m	R1	57	14	23	4	9	128	27	65	37	31
	R2	50	18	32	7	7	139	22	53	33	30
	R3	48	13	35	11	9	100	30	68	36	23
	R4	64	15	36	7	5	138	30	75	20	37
7 m	R1	53	9	14	5	4	53	12	43	21	21
	R2	55	12	17	2	5	64	16	44	21	21
	R3	40	9	24	6	9	48	12	49	31	30
	R4	58	10	21	3	11	60	15	34	36	25
9 m	R1	21	6	11	5	1	29	13	51	12	20
	R2	24	9	13	0	3	20	16	49	19	17
	R3	23	8	13	1	3	32	10	40	19	15
	R4	29	7	11	0	2	23	15	60	17	21
11 m	R1	18	5	7	2	0	27	10	17	8	13
	R2	13	6	10	0	0	32	13	24	13	19
	R3	22	2	8	0	0	22	7	24	10	14
	R4	23	6	19	0	0	30	9	22	12	12
13 m	R1	10	0	6	0	0	28	6	15	6	9
	R2	16	0	10	0	0	38	0	21	4	10
	R3	9	0	4	0	0	28	1	14	11	9
	R4	12	0	3	0	0	27	2	33	13	14
15 m	R1	7	0	0	0	0	14	0	8	4	6
	R2	13	0	2	0	0	19	0	14	2	3
	R3	9	0	4	0	0	26	0	13	8	6
	R4	13	0	1	0	0	11	0	7	1	7
17 m	R1	4	0	0	0	0	6	0	5	2	4
	R2	6	0	4	0	0	8	0	5	0	6
	R3	3	0	3	0	0	5	0	5	6	2
	R4	11	0	1	0	0	3	0	7	0	5
19m	R1	0	0	0	0	0	0	0	0	0	0
	R2	0	0	0	0	0	0	0	0	0	0
	R3	0	0	0	0	0	0	0	0	0	0
	R4	0	0	0	0	0	0	0	0	0	0

Appendix 1e. Table of total seedling counts ≥25<100 cm tall infected by disease in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	6	0	2	0	0	7	0	10	1	4
	R2	6	0	3	2	0	11	1	10	5	2
	R3	3	2	0	4	2	4	1	5	7	3
	R4	9	4	5	0	1	9	4	7	1	2
3 m	R1	5	6	4	1	2	11	2	5	6	3
	R2	12	4	5	3	0	9	2	7	3	3
	R3	7	2	3	2	0	10	4	5	2	5
	R4	10	4	3	0	2	15	0	6	5	6
5 m	R1	6	0	2	0	1	9	2	8	3	5
	R2	8	1	5	1	1	12	1	7	6	7
	R3	3	0	1	1	0	14	3	3	1	4
	R4	4	3	7	1	1	8	5	12	3	6
7 m	R1	6	1	0	2	0	7	1	10	0	0
	R2	2	0	2	0	0	10	3	6	4	4
	R3	1	3	3	2	2	9	2	8	2	5
	R4	6	3	5	0	3	13	3	4	5	3
9 m	R1	2	0	3	2	1	6	0	6	1	6
	R2	3	0	2	0	0	3	1	8	3	0
	R3	9	3	4	0	1	7	1	3	6	4
	R4	6	0	3	0	0	2	5	7	2	2
11 m	R1	2	2	0	0	0	7	4	1	0	2
	R2	0	1	0	0	0	5	5	5	3	3
	R3	3	0	3	0	0	4	3	9	4	5
	R4	5	0	4	0	0	11	4	5	2	2
13 m	R1	2	0	2	0	0	7	3	2	0	3
	R2	5	0	3	0	0	9	0	4	0	1
	R3	3	0	1	0	0	12	0	3	3	5
	R4	2	0	0	0	0	4	0	8	3	4
15 m	R1	0	0	0	0	0	1	0	0	1	1
	R2	4	0	0	0	0	3	0	3	1	1
	R3	6	0	0	0	0	7	0	4	3	3
	R4	1	0	0	0	0	2	0	1	0	1
17 m	R1	0	0	0	0	0	3	0	2	0	1
	R2	3	0	1	0	0	3	0	4	0	2
	R3	1	0	2	0	0	1	0	0	3	0
	R4	3	0	1	0	0	2	0	3	0	1
19m	R1	0	0	0	0	0	0	0	0	0	0
	R2	0	0	0	0	0	0	0	0	0	0
	R3	0	0	0	0	0	0	0	0	0	0
	R4	0	0	0	0	0	0	0	0	0	0

Appendix 1f. Table of total seedling counts ≤25 cm tall infected by disease in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	43	11	16	5	6	89	23	79	27	30
	R2	51	18	23	4	8	67	17	71	31	33
	R3	47	13	11	4	8	109	25	68	23	26
	R4	27	15	26	9	6	87	23	90	29	32
3 m	R1	41	21	29	7	16	93	18	63	28	38
	R2	48	16	33	6	11	88	13	57	33	40
	R3	37	14	37	7	13	114	21	55	26	35
	R4	50	25	22	6	23	79	23	78	32	42
5 m	R1	51	14	21	4	8	119	25	57	34	26
	R2	42	17	27	6	6	127	21	46	27	23
	R3	45	13	34	10	9	86	27	65	35	19
	R4	60	12	29	6	4	130	25	63	17	31
7 m	R1	47	8	14	3	4	46	11	33	21	21
	R2	53	12	15	2	5	54	13	38	17	17
	R3	39	6	21	4	7	39	10	41	29	25
	R4	52	7	16	3	8	47	12	30	31	22
9 m	R1	19	6	8	3	0	23	13	45	11	14
	R2	21	9	11	0	3	17	15	41	16	17
	R3	14	5	9	1	2	25	9	37	13	11
	R4	23	7	8	0	2	21	10	53	15	19
11 m	R1	16	3	7	2	0	20	6	16	8	11
	R2	13	5	10	0	0	27	8	19	10	16
	R3	19	2	5	0	0	18	4	15	6	9
	R4	18	6	15	0	0	19	5	17	10	10
13 m	R1	8	0	4	0	0	21	3	13	6	6
	R2	11	0	7	0	0	29	0	17	4	9
	R3	6	0	3	0	0	16	1	11	8	4
	R4	10	0	3	0	0	23	2	25	10	10
15 m	R1	7	0	0	0	0	13	0	8	3	5
	R2	9	0	2	0	0	16	0	11	1	2
	R3	3	0	4	0	0	19	0	9	5	3
	R4	12	0	1	0	0	9	0	6	1	6
17 m	R1	4	0	0	0	0	3	0	3	2	3
	R2	3	0	3	0	0	5	0	1	0	4
	R3	2	0	1	0	0	4	0	5	3	2
	R4	8	0	0	0	0	0	0	4	0	4
19m	R1	0	0	0	0	0	0	0	0	0	0
	R2	0	0	0	0	0	0	0	0	0	0
	R3	0	0	0	0	0	0	0	0	0	0
	R4	0	0	0	0	0	0	0	0	0	0

Appendix 1g. Table of total seedling counts attacked by herbivores in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	37	12	14	3	3	65	16	51	25	31
	R2	40	14	21	4	1	80	19	55	20	37
	R3	33	7	16	9	6	54	14	63	28	26
	R4	54	14	16	3	3	68	15	40	30	29
3 m	R1	38	21	26	5	13	76	16	52	29	38
	R2	45	19	33	11	16	73	16	50	35	40
	R3	50	22	22	5	11	78	23	60	28	35
	R4	36	26	32	5	12	77	19	53	29	44
5 m	R1	35	11	19	1	10	108	22	50	26	24
	R2	30	11	26	2	8	112	24	43	27	23
	R3	26	8	18	3	7	102	20	52	26	29
	R4	40	15	20	4	11	124	21	54	28	27
7 m	R1	38	16	19	2	5	50	15	28	25	18
	R2	43	12	17	3	8	56	16	29	25	21
	R3	35	16	16	0	6	48	11	26	27	21
	R4	42	21	21	0	5	48	22	39	25	26
9 m	R1	25	2	10	1	4	24	13	42	15	17
	R2	29	5	11	0	6	26	10	49	14	20
	R3	24	8	11	1	3	23	18	43	14	21
	R4	24	8	12	0	2	31	13	39	14	20
11 m	R1	20	5	6	3	0	33	20	31	20	13
	R2	12	8	6	1	0	28	17	40	19	13
	R3	20	6	7	0	0	40	27	31	23	15
	R4	20	2	12	2	0	30	22	43	28	14
13 m	R1	9	0	7	0	0	30	4	23	11	15
	R2	12	0	12	0	0	28	6	29	16	17
	R3	10	0	5	0	0	38	7	17	8	16
	R4	19	0	8	0	0	27	4	25	17	13
15 m	R1	11	0	2	0	0	17	0	24	10	12
	R2	14	0	7	0	0	23	0	23	9	17
	R3	9	0	4	0	0	21	0	24	8	22
	R4	15	0	9	0	0	16	0	17	16	11
17 m	R1	8	0	0	0	0	3	0	5	4	4
	R2	8	0	4	0	0	3	0	5	0	6
	R3	16	0	2	0	0	8	0	6	3	7
	R4	11	0	1	0	0	1	0	4	1	3
19m	R1	0	0	0	0	1	0	0	0	0	0
	R2	0	0	0	0	2	0	0	0	0	0
	R3	0	0	0	0	2	0	0	0	0	0
	R4	0	0	0	0	1	0	0	0	0	0

Appendix 1h. Table of total seedling counts ≥25<100 cm tall attacked by herbivores in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	7	2	3	1	1	9	2	8	4	3
	R2	4	1	4	2	0	11	0	6	3	4
	R3	5	1	2	2	0	6	3	9	5	1
	R4	12	0	4	0	0	10	2	10	4	5
3 m	R1	3	5	3	3	2	12	3	7	4	4
	R2	6	8	6	4	1	14	1	9	6	3
	R3	9	4	3	0	1	9	4	5	7	4
	R4	8	6	3	1	1	16	5	7	5	9
5 m	R1	11	1	4	1	3	11	4	9	6	6
	R2	9	0	7	0	2	8	2	8	4	7
	R3	7	1	5	0	2	14	4	5	8	8
	R4	7	1	6	2	0	16	5	11	3	7
7 m	R1	5	4	6	1	1	10	4	7	7	3
	R2	3	3	1	1	2	13	6	9	9	8
	R3	6	2	5	0	2	11	4	10	5	2
	R4	4	5	7	0	2	7	3	8	8	6
9 m	R1	8	1	5	0	1	5	3	6	8	6
	R2	6	2	2	0	2	4	2	8	5	3
	R3	10	0	4	0	1	8	5	4	9	8
	R4	7	2	4	0	0	10	1	9	4	6
11 m	R1	9	1	1	1	0	13	4	2	5	3
	R2	5	2	3	1	0	12	6	6	6	5
	R3	11	1	0	0	0	16	5	4	5	2
	R4	5	0	5	2	0	14	5	9	7	5
13 m	R1	4	0	3	0	0	19	2	9	3	6
	R2	3	0	6	0	0	15	1	10	5	5
	R3	6	0	2	0	0	21	4	5	2	9
	R4	10	0	2	0	0	16	0	7	7	3
15 m	R1	3	0	0	0	0	7	0	11	3	4
	R2	4	0	3	0	0	9	0	4	4	6
	R3	2	0	1	0	0	5	0	9	2	8
	R4	6	0	4	0	0	7	0	7	5	5
17 m	R1	2	0	0	0	0	1	0	2	2	1
	R2	4	0	2	0	0	2	0	1	0	2
	R3	5	0	0	0	0	4	0	3	0	2
	R4	1	0	1	0	0	0	0	2	0	1
19m	R1	0	0	0	0	1	0	0	0	0	0
	R2	0	0	0	0	2	0	0	0	0	0
	R3	0	0	0	0	2	0	0	0	0	0
	R4	0	0	0	0	1	0	0	0	0	0

Appendix 1i. Table of total seedling counts ≤25 cm tall attacked by herbivores infected by disease in the ten study trees at various distances from the parent tree along four transects

Distance	Replicate	Trees									
		1	2	3	4	5	6	7	8	9	10
1 m	R1	30	10	11	2	2	56	14	43	21	28
	R2	36	13	17	2	1	69	19	49	17	33
	R3	28	6	14	7	6	48	11	54	23	25
	R4	42	14	12	3	3	58	13	30	26	24
3 m	R1	35	16	23	2	11	64	13	45	25	34
	R2	39	11	27	7	15	59	15	41	29	37
	R3	41	18	19	5	10	69	19	55	21	31
	R4	28	20	29	4	11	61	14	46	24	35
5 m	R1	24	10	15	0	7	97	18	41	20	18
	R2	21	11	19	2	6	104	22	35	23	16
	R3	19	7	13	3	5	88	16	47	18	21
	R4	33	14	14	2	11	108	16	43	25	20
7 m	R1	33	12	13	1	4	40	11	21	18	15
	R2	40	9	16	2	6	43	10	20	16	13
	R3	29	14	11	0	4	37	7	16	22	19
	R4	38	16	14	0	3	41	19	31	17	20
9 m	R1	17	1	5	1	3	19	10	36	7	11
	R2	23	3	9	0	4	22	8	41	9	17
	R3	14	8	7	1	2	15	13	39	5	13
	R4	17	6	8	0	2	21	12	30	10	14
11 m	R1	11	4	5	2	0	20	16	29	15	10
	R2	7	6	3	0	0	16	11	34	13	8
	R3	9	5	7	0	0	24	22	27	18	13
	R4	15	2	7	0	0	16	17	34	21	9
13 m	R1	5	0	4	0	0	11	2	14	8	9
	R2	9	0	6	0	0	13	5	19	11	12
	R3	4	0	3	0	0	17	3	12	6	7
	R4	9	0	6	0	0	11	4	18	10	10
15 m	R1	8	0	2	0	0	10	0	13	7	8
	R2	10	0	4	0	0	14	0	19	5	11
	R3	7	0	3	0	0	16	0	15	6	14
	R4	9	0	5	0	0	9	0	10	11	6
17 m	R1	6	0	0	0	0	2	0	3	2	3
	R2	4	0	2	0	0	1	0	4	0	4
	R3	11	0	2	0	0	4	0	3	3	5
	R4	10	0	0	0	0	1	0	2	1	2
19m	R1	0	0	0	0	0	0	0	0	0	0
	R2	0	0	0	0	0	0	0	0	0	0
	R3	0	0	0	0	0	0	0	0	0	0
	R4	0	0	0	0	0	0	0	0	0	0

Appendix 2a. Original raw data set for variation in bark thickness. KK Nat – Kakamega natural forest, ELG Nat – Elgeyo natural forest, KK Farm – Kakamega farms and ELG Farm – Elgeyo farms.

KK Nat		ELG Nat		KK Farm		ELG Farm	
DBH	BKT	DBH	BKT	DBH	BKT	DBH	BKT
41	11	38	11	21	9	32	11
34	11	29	9	21	10	54	16
44	13	50	15	40	15	54	17
42	14	40	11	41	15	25	10
48	13	127	27	24	10	36	13
50	14	75	20	42	14	30	11
33	10	169	30	20	10	25	10
46	16	64	17	38	13	19	7
58	14	24	8	20	9	14	7
52	15	21	8	26	11	14	8
61	16	35	11	26	11	25	10
55	16	25	9	58	18	29	9
53	15	37	12	30	12	60	18
49	16	22	7	39	13	19	9
35	12	24	9	33	13	25	11
23	8	27	9	42	14	23	10
22	9	62	18	20	8	30	12
32	10	162	29	26	10	27	11
29	8	90	23	37	13	46	14
24	10	70	19	39	14	12	5
25	9	11	4	32	12	20	9
38	11	14	6	40	16	54	16
25	9	27	9	53	17	30	12
57	16	14	7	22	9	17	8
60	17	36	12	22	10	26	11
32	10	41	12	60	18	37	12
65	18	15	8	20	9	55	17
26	10	52	15	32	13	44	14
14	6	30	10	53	17	39	13
20	10	16	6	33	14	48	15
35	12	25	9	40	15		
47	14	18	7	41	16		
64	17	31	11	38	14		
28	9	47	13	50	16		
31	10	39	12				
32	10	43	12				
28	10	36	11				
11	5	46	13				
47	15	33	10				
44	15	55	15				
19	9	59	17				
60	19	66	18				
17	6	34	10				
36	11	77	21				
14	7	84	22				
27	9	86	22				
35	12						

Appendix 2b. Total weight per tree of exploitable bark harvested from trees in closed canopy natural forest and diameter at breast height (DBH), tree height, height to first branch, and bark thickness of the individual trees.

Tree No.	DBH (cm)	Tree Height (m)	Height to first branch (m)	Bark thickness (mm)	Bark production (kg)
1	50	24	9.80	10.50	53.2
2	43	22	9.10	9.00	45.1
3	54	25	10.20	11.50	55.5
4	57	25	10.40	13.00	67.4
5	27	19	7.30	5.00	15.6
6	38	21	8.50	7.50	28.3
7	66	26	11.20	14.00	82.7
8	72	26	11.70	15.00	96.3
9	73	26	11.70	15.00	92.5
10	110	31	13.20	22.00	160.2
11	37	20	8.20	7.50	33.7
12	83	28	12.40	18.00	109.4
13	80	28	12.30	17.00	115.9
14	44	22	9.20	9.00	46.6
15	31	20	7.70	7.00	17.8
16	45	23	9.20	9.00	44.3
17	65	25	11.10	14.00	84.1
18	61	25	10.70	13.00	72.4
19	78	27	12.00	17.00	113.4
20	84	28	12.30	18.00	117.7
21	98	30	13.10	20.00	135.3
22	55	25	10.30	11.50	61.4
23	104	31	13.50	21.50	153.4
24	23	17	7.00	5.00	10.9
25	34	20	8.00	7.50	22.3
26	94	29	13.00	20.00	135.6
27	86	29	12.10	17.00	114.8
28	26	19	7.20	5.00	12.7
29	91	28	12.90	20.00	130.6
30	40	22	8.50	7.00	32.2
				Mean bark yield per tree (kg)	75.38

Appendix 2c. Total weight per tree of exploitable bark harvested from trees in open farmland and diameter at breast height (DBH), tree height, height to first branch, and bark thickness of the individual trees.

Tree No.	DBH (cm)	Tree Height (m)	Height to first branch (m)	Bark thickness (mm)	Bark production (kg)
1	81	25	11.60	18.50	1030.4
2	82	25	11.50	18.00	112.9
3	96	28	12.50	22.00	126.4
4	100	28	12.60	22.50	126.6
5	56	22	9.60	11.00	66.7
6	42	19	8.00	10.50	41.3
7	90	27	12.00	20.50	120.7
8	85	26	11.50	19.00	123.5
9	58	22	9.60	11.00	60.1
10	48	20	8.60	11.00	46.3
11	30	17	7.10	7.00	18.8
12	32	17	7.20	7.00	19.8
13	28	16	7.00	7.00	20.2
14	25	15	6.80	6.50	17.8
15	23	14	6.50	6.50	19.3
16	36	18	7.50	9.00	28.5
17	43	19	8.10	10.50	45.9
18	51	21	9.00	13.00	50.2
19	63	23	10.60	14.50	78.1
20	65	24	10.80	14.50	79.6
21	71	25	11.00	16.50	94.3
22	79	26	11.50	18.00	105.8
23	88	27	12.30	20.00	114.7
24	93	27	12.40	21.00	123.3
25	115	31	13.40	26.00	157.1
26	38	18	7.70	9.00	25.4
27	46	20	8.50	11.00	45.6
28	54	21	9.40	13.00	66.8
29	68	23	10.50	15.50	83.9
30	74	24	11.20	17.00	91.3
				Mean bark yield per tree (kg)	73.81