Restoration of Juniperus excelsa Bieb. and Olea europaea L. subsp. africana (Mill.) P. S. Green woodlands in Eritrea

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Philip Scott Jones, BSc, RGN, RMN

Department of Biological and Molecular Sciences

University of Stirling, FK9 4LA, Scotland

ABSTRACT

The research aim was to assess the vegetation and soils of the Rora Habab plateau, Eritrea and to develop methods of propagating the native tree species, juniper and olive. The research consisted of vegetation and soil surveys, interviews with local people, archival research, and experiments on propagation of olive and juniper. Junipers are now confined to the north of the plateau. Olives are more abundant in the north but have very few individuals in the centre, where there are many dead trees, or south. Soil erosion was ubiquitous and often severe. Soil morphology and nutrient status were related to vegetation, topography, land use, and erosion status, and varied greatly over short distances. Soil texture was coarser and most chemical factors (except total Ca and exchangeable Na) were lower in the south. Organic C, total N, exchangeable Ca, percent clay, CEC and the sum of bases were higher in soils from grazed land than in cultivated fields. Germination of olive seeds was 92% when the endocarp was removed; stratification had little effect. Rooting of olive stem cuttings attained 76% under mist when parent plants were fertilised and cuttings were treated with rooting hormone. Germination for juniper was 56% after stratification at 5°C for 30 to 60 days. Juniper stem cuttings rooted in only one of three experiments, where rooting was 78% in a well ventilated, cool, low-mist environment. Olive seedlings which were fertilised and watered every 7, 14, or 21 days for two months, were taller, had lower root:shoot ratios and soil moisture than unfertilised plants. Fertilised seedlings watered every 28 days died. Root volume was less for plants watered every 21 days but watering interval had little effect on other variables in unfertilised seedlings. Ecological restoration is urgently required to rehabilitate the Rora plateau, which has Africa's most northerly remnant juniper/olive woodlands.

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War and drought have brought tremendous difficulties and great hardship to the Eritrean people. Despite these most demanding circumstances, my Eritrean colleagues and friends provided me with food, hospitality, pack animals and 4W drive transport, and field assistance during the eight visits it took to complete this stage of our research. On a personal level, they have taught me much about courage, vision and faith.

It is not customary to thank individuals by name in Eritrea, where group effort is regarded as the key to success. Therefore, I thank the staff of the Eritrean Relief Association, in Eritrea and overseas, and the staff of the Agriculture Commission, Transport Commission, Health Department, Information Department and Department of Public Administration of the Eritrean People's Liberation Front, now the Provisional Government of Eritrea. Finally, I thank the villagers of Rora Habab for their assistance, hospitality and friendship. The people of Rora freely gave their time for discussion and help with field work. I was allowed complete access to all parts of the plateau, even when this involved sampling on people's property. .... ንቲ፡ ኹሉ፡ ጽቡቕ፡ ዝገበርኩሙለይ፡ ነመስግነኩም።

OBJECTIVES AND INTRODUCTION TO THESIS

The major objective of this research was to assess the biological and environmental factors which could affect the restoration of the Rora Habab plateau in northern Eritrea using the two dominant native tree species, Juniperus excelsa Bieb. (juniper) and Olea europaea L. subsp. africana (Mill.) P.S. Green (olive). A second objective was to lay the foundation for a new component of ongoing restoration efforts on the plateau, which I will begin in January 1992. There are five main reasons why I undertook this work and which made Rora Habab an appropriate research site. The Rora Habab plateau is virtually unknown, even within Eritrea, except by people who live or work there. Rora Habab is the most northerly location in Africa where moderately intact juniper/olive woodlands remain, from what was once an extensive vegetation type throughout East Africa. Rora Habab is the most northerly location in East Africa where subsistence, rain-fed crop production is practised. The Rora plateau is reportedly losing its remaining woodlands very rapidly and soil erosion is severe. Lastly, ecological restoration methods developed on this very dry, badly degraded site, would provide valuable experience for the restoration of similar woodlands further south in the East African uplands.

In order to accomplish these objectives, I reviewed the political and social context for restoration in Eritrea and the Rora plateau (Chapter 1), the physical geography and agriculture of Eritrea and the Rora plateau (Chapter 2), undertook a detailed survey of the vegetation (Chapter 3) and soils (Chapter 4) of the plateau, conducted several experiments on the germination and vegetative propagation of olive and juniper (Chapter 5), and conducted one experiment on the influence of fertilisation and watering interval on the growth of one year old olive seedlings (Chapter 6). Chapter 7 contains the conclusions and recommendations resulting from this work.

A number of special circumstances shaped this research. Throughout my research, Eritrea and Ethiopia were at war, and travellers to Eritrea had to pass through the Sudan. For the early part of this research the southern portions of the plateau were occupied by the Ethiopian Army. There have been three war and drought-related famines in Eritrea since 1984. Rora Habab is a remote area requiring a minimum of seven days' travel from London. Most of the research was conducted on a very limited budget.

These factors limited my research possibilities. My research clearance and logistical support were provided entirely by the Eritrean People's Liberation Front (EPLF), the Eritrean Relief Association (ERA), and village authorities on the plateau, not by the Ethiopian Government. Travel within Eritrea took place at night and only when vehicles were free from duties relating to the war and famine. Manpower shortages were frequent and unpredictable, and the study site had no running water or electricity. Some of the research that I had planned could not be accomplished, for it proved impossible to import a Schollender pressure cylinder or to export live plant material, and soils had to be air-dried for seven days' transport in very high temperatures. All research materials had to pass three customs inspections, to be carried on foot, by camel, or by Landrover to the plateau, and often were unpredictably delayed or lost in the Sudan. Because of the war, I was unable to visit Ethiopia and it was impossible to visit other wooded areas in the Eritrean highlands. Aerial photographs and many published maps of the plateau or surrounding areas were not available.

Restoration and reforestation projects are site-specific, and I wished to conduct most of my experimental work on the Rora plateau. This proved impossible because of problems relating to climate and to personnel shortages. In particular, propagation experiments I established in 1987 were lost to heavy floods and people who were monitoring the experiments had to leave the plateau to fight locust outbreaks.

These constraints suggest that there are insuperable obstacles to conducting research in Eritrea. However, because of the support and help of the Eritrean people, I found that it was possible to conduct a sustained research programme using minimal equipment in the field, and conducting analyses and experiments overseas. Now that the war is over, with the demonstrated commitment of Eritrean collaborators, it will be possible to complete and expand this work in a very promising research environment.

CHAPTER 1

RESEARCH CONTEXT AND STUDY AREA

The purpose of this chapter is to discuss the links between ecological restoration and the political, social, and economic history of Eritrea and of the study site, the Rora Habab plateau. The physical environment of Eritrea has been modified by human habitation for more than 1000 years, and recently by colonisation and 30 years of war. Present day restoration efforts are critically dependent upon government policy, local people's needs and options, the availability of resources, and a physical and economic infrastructure, all of which have been shaped by historical events.

POLITICAL AND SOCIAL CONTEXT OF RESTORATION IN ERITREA

Description of Eritrea

Eritrea is located in the Horn of Africa between 12°30' and 18°00' N, and 36°30' and 43°00' E (Fig. 1.1). Presently considered the northern, maritime province of Ethiopia, Eritrea has an area of 124,320 km^2 and is bordered to the south by Ethiopia and Djibouti, to the north and west by the Sudan, and to the east by the Red Sea. There are nine provinces in Eritrea with the capital, Asmara, located in Hamasien province in the central highlands of the country and the major ports, Massawa and Assab, in the eastern lowland provinces of Semhar and Danakil. My study site is a remote plateau called Rora Habab and is situated in the northern province of Sahel, whose administrative capital is Nacfa (Fig. 1.1).

About 3 to 4 million people from nine nationalities are estimated by various sources to live in Eritrea. However, a complete census has proved

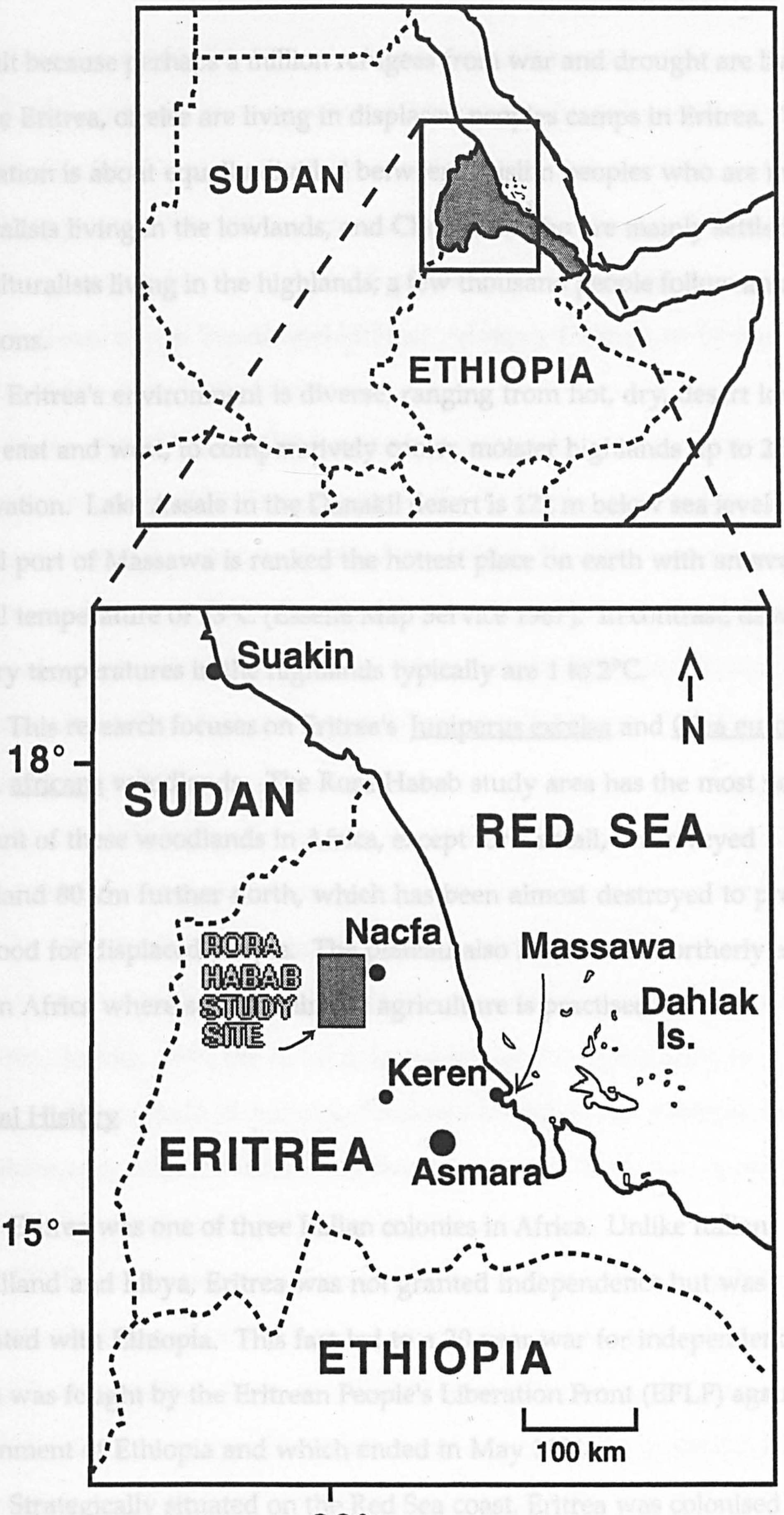

Fig. 1.1. Location of Eritrea and the Rora Habab study site in northeast Africa.

difficult because perhaps a million refugees from war and drought are living outside Eritrea, or else are living in displaced peoples camps in Eritrea. The population is about equally divided between Muslim peoples who are mostly pastoralists living in the lowlands, and Christians who are mainly settled agriculturalists living in the highlands; a few thousand people follow animist traditions.

Eritrea's environment is diverse, ranging from hot, dry, desert lowlands in the east and west, to comparatively cooler, moister highlands up to 2 550 m in elevation. Lake Assale in the Danakil desert is 172 m below sea level and the coastal port of Massawa is ranked the hottest place on earth with an average annual temperature of 33°C (Esselte Map Service 1987). In contrast, dawn January temperatures in the highlands typically are 1 to 2°C.

This research focuses on Eritrea's Juniperus excelsa and Olea europaea subsp. africana woodlands. The Rora Habab study area has the most northerly remnant of these woodlands in Africa, except for a small, unsurveyed woodland 80 km further north, which has been almost destroyed to provide fuelwood for displaced people. The plateau also is the most northerly area in eastern Africa where settled, rain-fed agriculture is practised.

Political History

Eritrea was one of three Italian colonies in Africa. Unlike Italian Somaliland and Libya, Eritrea was not granted independence but was federated with Ethiopia. This fact led to a 30 year war for independence which was fought by the Eritrean People's Liberation Front (EPLF) against the government of Ethiopia and which ended in May 1991.

Strategically situated on the Red Sea coast, Eritrea was colonised by Italy in the 1880's during the reign of Ethiopian Emperor Menelik II. Following Italy's defeat in the region in 1941, Britain administered Eritrea until 1952, when

Eritrea was federated with Ethiopia under United Nations resolution 390a(V). In 1962, Haile Selassie (then emperor of Ethiopia) unilaterally revoked this resolution by forcibly annexing Eritrea, and used various economic and military measures to consolidate political control over Eritrea. After much unrest and a devastating famine, Haile Selassie's US-backed regime fell in the coup of 1974. It was replaced by the Provisional Military Advisory Council, or Dergue, led by Colonel Mengistu Haile Mariam.

In the mid 1970's the EPLF gained control of the whole of Eritrea except the capital, Asmara. With Soviet support, the Ethiopian military forced the EPLF into a strategic withdrawal in the late 1970's. The EPLF continued a guerilla war from their 'Base Area' in Sahel province while the Dergue continued to fight other revolutionary movements in Ethiopia. Thousands of Eritreans were killed during the widely-reported Ethiopian 'Red Terror' campaigns of 1977-9.

Several Ethiopian offensives in the 1980's failed to dislodge the EPLF and in 1984 the war moved from guerilla operations to open, mechanised battle. In 1988 the Eritreans conducted major offensives south of their Base Area and during 1989 and 1990, the EPLF army defeated several Ethiopian garrisons. In May 1991, the EPLF defeated a large Ethiopian army in Decamere, 40 km south of Asmara. President Mengistu fled Ethiopia for Zimbabwe and, with the collapse of the government, Ethiopian opposition groups took control of the Ethiopian capital, Addis Ababa.

EPLF forces entered Asmara on 24 May 1991 and the war in Eritrea ended the next day when the Eritrean army captured the port of Assab. Ethiopia's main military force, the 120,000 strong 2nd army, was routed with the EPLF taking more than 80,000 prisoners and capturing or destroying all their equipment. I returned from Eritrea in August 1991, and at the time of writing, the EPLF has established a provisional government in Eritrea pending a referendum on the political independence of the country in 1993. There now seems little doubt that Eritrea will be an independent country following this referendum.

Social Effects of War and Drought

The war and droughts have had a destabilising effect on customary land use practices and management of natural resources throughout Eritrea. While Eritrea has roughly equal numbers of settled, highland Christians and nomadic, lowland Muslims, this oversimplifies a society in which there are nine language groups and a variety of environmental conditions and lifestyles (Pool 1982). People's response to war and drought reflect this cultural diversity but it is possible to make some generalisations. The most salient effects of war and drought have been migration from affected areas, the use of vegetation for food and fuel, public health problems associated with water, and the adverse effects of the torrential rains and locusts following drought periods.

As a result of migration and the death of livestock, normal family, social and economic relationships have become increasingly difficult to maintain. Frequent bombing by the Ethiopian air force and the long-term nature of the drought have made even the wealthiest people poor, blurring previous economic distinctions. The conventional division into "poor, middle and rich" peasants (Barnett 1983) is now much less relevant.

During drought years, crop yields and food availability decline abruptly and a variety of different plants are used for food. In 1984, 1989 and 1990 the harvest failed completely over much of Eritrea and many people were eating wild berries, leaves, seeds and roots. This was associated with an increased incidence of food poisoning and diarrhoea, leading village assemblies and the EPLF Health Department to expand public education about which wild plants were safe to eat (Assefaw Tekeste, Director, EPLF Civilian Health Department, personal communication).

When the rains returned, they were associated with many tropical wet season health problems, especially with an increased incidence of respiratory diseases and water mediated diseases. Such problems exacerbated the difficulties people had in maintaining and preparing land for agricultural use.

Heavy rains also had a direct impact on the land, especially in 1985/6 and 1990. While the total amount of rainfall in the 1985/6 period was encouraging, long periods of dry weather between precipitation events resulted in the failure of crops in some areas, and in severe soil erosion. Further problems have arisen from locust swarms. Locusts emerge in small numbers in most years but heavy rains following a drought bring their numbers to epidemic proportions. Their destructiveness requires that major efforts are made to combat them, especially in the ground dwelling stages of the insects' life cycle before wings fully develop and sexual maturity is reached. The labour and costs involved greatly tax extension workers and their other work must necessarily give way. Such a scenario occurred in 1988 and resulted in the loss of my two core experiments to flood water and then to locusts.

These examples illustrate some of the ways in which the success or failure of the rains and the prevailing military situation affect the Eritrean economy and people's use of natural resources. Although the Rora Habab study area has been outside much of the fighting, the inhabitants of the plateau have experienced the same level of disruption and impoverishment as the rest of Eritrea as a consequence of thirty years of war.

THE RORA HABAB STUDY AREA

Description of the Rora Habab Plateau

Rora Habab is a mountain plateau situated about 120 km NW of Asmara in Sahel province, northern Eritrea (16°36' N, 38°20' E) (Fig. 1.1). Rora is between 1900 and 2600 m above sea level and extends about 40 km north to south (Fig. 1.2). Rising up to 1 000 m above the surrounding countryside with near vertical rocky slopes in many places, the plateau is a natural fortification. A dirt road constructed in 1983 permits nine-month access by vehicle to the top of the plateau. Most trade and travel, including seasonal migration of local people and animals, occurs by foot along trails of unknown age. Like most of Eritrea, the villages of Rora Habab have been subject to several famines in recent years, to deforestation, and to severe soil erosion.

Today there are thirteen villages along Rora Habab with a total population of about 15 000 (Fig. 1.2). The Tigre-speaking, Muslim farmers who live along the plateau grow wheat, barley and, since 1987, some potatoes. They also rely heavily on animals, mostly sheep, goats, and cattle. The name of the plateau is taken from the name of the Habab (ሓባብ) tribe. Rora (ሮ ራ) means "high place" or "plateau" in the Tigre language. This thesis is based on research mainly carried out in three villages along Rora; Bacla (ባቅላ) in the north, Berige (በሪጀ), 15 km south of Bacla, and Laba (ላባ), 7 km south of Berige (Fig 1.2).

The Human History of Rora Habab

A complete history of human habitation on Rora is difficult to establish. However, archival research, oral histories, rock carvings, and ruins of ancient sculptures reveal a fascinating history of human settlement and indicate that Rora's natural resources have been managed by people for many centuries. This summary is based on a longer account which I published in Azania (Jones 1991).

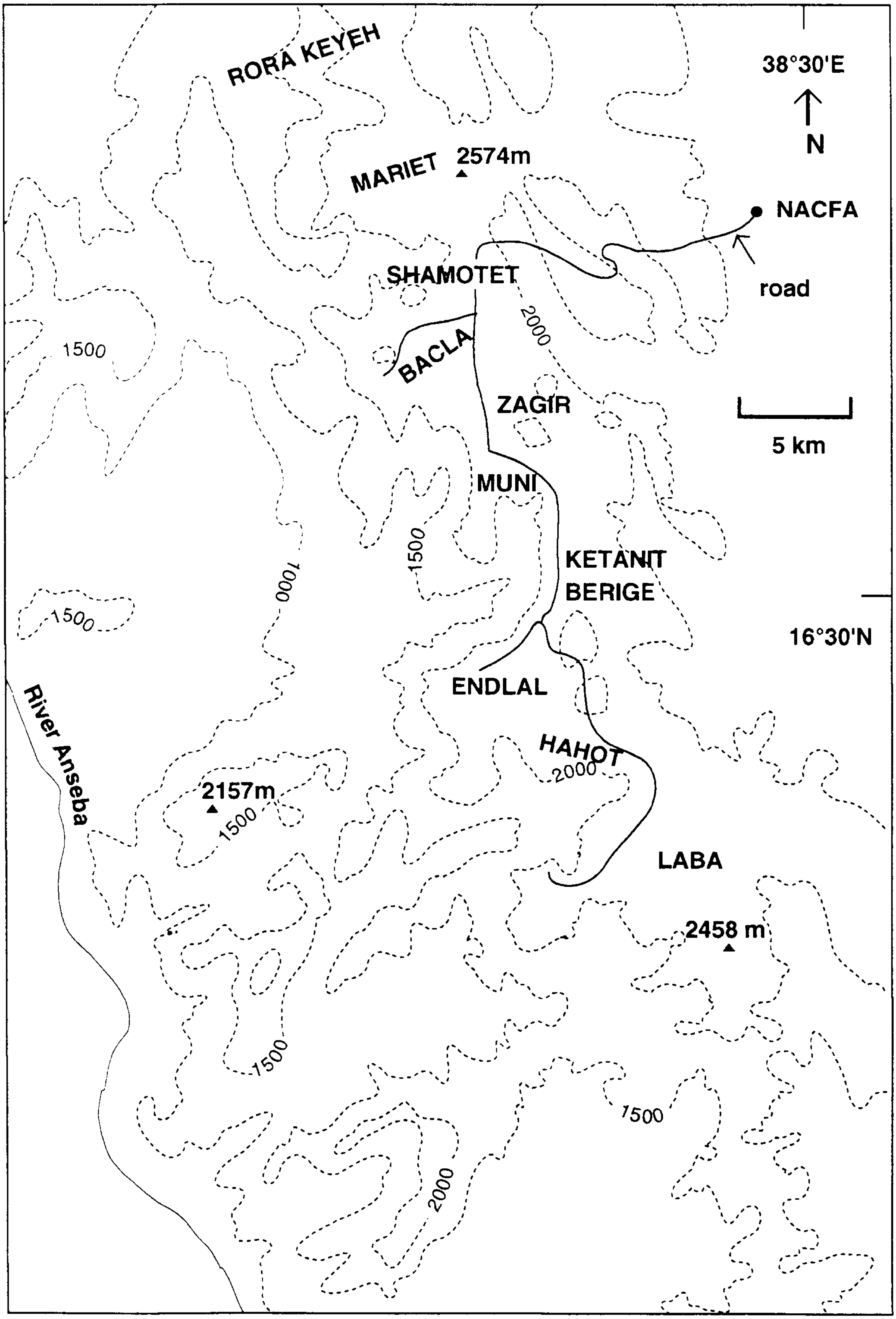

Fig. 1.2. The villages of the Rora Habab plateau, Sahel province, northern Eritrea. Villages are dispersed settlements. The road is often impassable in the rainy season, and the River Anseba flows only in the rainy season.

Evidence from Historical Maps and Artefacts

A map published in 1720 by N. de Fer refers to "les peuples errans de Bekla" located in a zone of "forests and mountains" north of Asmara and coastward of a large river. A second map published in 1730 by G. de l'Isle places "Bekla errans" just west of Asmara. These maps confirm the accounts of several elderly farmers in Bacla village who told me that Rora Habab was once the centre of a powerful state, the Bacla Kingdom.

In 1987 I photographed rocks with animal figures etched into them in Bacla village. In the early 1900's, several Italian visitors described sculptures and standing stones in Endlal and Laba. Photographs published by Conti Rossini (1928; figs 153-155, table 50) show two standing stones at Laba, each with a decapitated lion sculpted at the top. I visited and photographed these stones in 1989 (Plate 1.1).

Italian visitors in the early 1900's were impressed by evidence of former civilisations on Rora Habab. Naldini (1916:236) states: "{t}he ... productivity {of Rora} must have been enormous formerly, judging from the remains of colossal terracing works; ... numerous roads, competently engineered; the ruins of masonry houses; and the most advanced works of sculpture so far encountered." Agriculture and terracing of cultivated lands apparently were a feature of the Aksumite period (John Sutton, British Institute, Nairobi, personal communication).

Petazzi (1920:32) described Endlal as "... a dry-wall fortress constructed on a basaltic promontory ... {its} ruins were visited at the end of 1851 by G. Sapeto ... {Sapeto suggested} ... that Enzelal had been the seat of the Bishopric of Tacsci before the heresy of Entiche (5th century) ... {and} ... found inscriptions of mixed Ethiopic and Amharic letters." Dainelli (1913:10-11) describes "... the Roras of the Habab" as having had an "... advanced civilisation ... from a long time ago, traces of which have been found only recently." These documents and artefacts suggest that previous civilisation(s) on Rora were "advanced" and relied on settled agriculture.

Settlements

Although exact dates are uncertain, there seem to have been at least two periods of prolonged settlement on the plateau since the early centuries AD, perhaps before. Earlier occupation of Rora certainly seems possible. For example, Fattovich (1984:184) discusses possible movements of people in the Sudan/Eritrea border areas from the 3rd millenium BC onwards, noting that lowland peoples travelling south and inland would have met groups living in and travelling from the interior. The first period of settlement about which we can be fairly certain occurred at some point during the existence of the Aksumite kingdom, which centred on the city of Aksum, 300 km south of Rora, and arose in the early centuries AD (Plate 1.1). The plateau now called Rora Habab was important in linking Aksum with the Suakin on the Red Sea coast and Jerusalem (Fattovich 1984:184).

Italian sources earlier this century also note the connection between Aksum and Rora. Marazzani Visconti Terzi and other Italian settlers found evidence of Aksumite settlement in the northern Eritrea/Sudan border areas (cited in Fattovich 1984:177). Kobischanov (1979:17) states that Dainelli and Marinelli documented Aksumite (possibly pre-Aksumite) sites in Rora Laba in the early 1900's.

Of the period following the demise of the Aksumite kingdom, around the 8th or 9th centuries AD, nothing is known for sure. The next clear indication of settlement on Rora dates from the end of the 16th century with the arrival of the Habab. Petazzi (1920:32) states that Rora Habab and the surrounding lowlands have "... the name of the Asghede family of the Decchi Minab who immigrated here around the middle of the 16th century, today forming the noble caste of the Habab tribe." Petazzi's account of the coming of the Asghede in the middle of the 16th century is in broad agreement with the later accounts of Paul (1954:81), Longrigg (1974 [1945]:64-66) and Crawford (1958:205-211), although Crawford provides evidence to suggest that 1500 or thereabouts is a better estimate (1958:209). Petazzi (1920:32) also notes "... The Asghede were Christians and agriculturalists, they became pastoralists of camels but became Muslims three generations ago {i.e. 1840-1850}. Only last year {i.e. 1919} they attempted to start cultivation again in Laba." This change of religion seems to have obliterated any oral histories about the origins and significance of the stone carvings and sculptures on the plateau.

In summary, on Rora Habab today, there is fairly clear evidence of long-term settlement at some time during the Aksumite period, and by the Habab people from about 1600. Extant artefacts from early occupation include several dozen rocks etched with animals and with symbols, two sculpted lion statues, and at least one part of an inscribed stele. I have not so far found burial cairns, traces of roads or buildings, or other remains which were documented in a few Italian publications earlier this century. If ancient agricultural terraces still exist on Rora, they may have been incorporated into the terraces built as part of the agricultural development programme underway since 1985, or else require a more thorough search, preferably with aerial survey, to locate them.

It is difficult to attribute the artefacts on Rora to exact dates without further archaeological work. The early history of Rora therefore remains speculative, and we must hope that now the war has ended, a full examination of the sites can take place. Nevertheless, it is clear that Rora Habab's ecology has been modified by grazing, cultivation, and construction of earthworks for at least the past 1000 to 1700 years.

Recent Economic Development on Rora Habab

The development efforts and ideological goals of the EPLF are not separable. Since its formation in 1970, the EPLF has been seeking independence for Eritrea and building a self-reliant, though not yet self-sufficient, democratic society. All EPLF officials I have spoken with regard meeting people's basic needs and economic development as one part of "independence", the other being political independence from Ethiopia. The General Secretary of the Provisional Government and other senior EPLF officials have stated that reforestation and sustainable use of natural resources has the highest priority in post-war Eritrea. There now exists the political will in Eritrea to support ecological restoration.

Ecological restoration depends upon an understanding of land tenure and the use and ownership of water, forests, and agricultural resources. Customary land tenure on Rora Habab is similar to the Risti system described in Chapter 2. The EPLF approach to land reform is discussed by Houtart (1980:99-105) who considers the examples of two villages further south in Eritrea. Because the process of land reform on Rora Habab is in its infancy, I have not yet discussed with villagers the role of land reform in relation to restoration efforts.

Since 1985 all thirteen villages on Rora Habab have participated in an integrated rural development scheme (IRDS) coordinated by the EPLF and the Eritrean Relief Association (ERA). The IRDS includes efforts to improve agricultural productivity, build small dams and reservoirs, and to provide various social services relating to health, education, community shops, flour mills and workshops. In Bacla village, for example, IRDS staff have worked closely with villagers in the distribution of barley and wheat seed, terracing fields, manufacturing and distributing agricultural tools, vaccinating livestock, building a school and a clinic and commencing a small reforestation programme with non-native tree species, principally Eucalyptus spp. and Schinus molle. Three small concrete dams and five earthen dams have been completed on Rora, providing reservoirs to meet local needs for water. Full details for all villages are given in a project document (Eritrean Relief Association 1985).

The Rora Habab IRDS, then, is a comprehensive project aimed at improving social welfare and developing a stronger agricultural base from which farmers can make efforts toward self-sufficiency in food production. Moreover, the Scheme has important implications for future restoration efforts, notably by involving local people in planning and implementing soil conservation, tree planting, and water conservation projects.

CHAPTER 2

PHYSICAL GEOGRAPHY AND AGRICULTURE IN ERITREA AND ON THE RORA HABAB PLATEAU

The purpose of this chapter is to examine the context of my research with respect to the physical geography and agriculture of Eritrea and of the Rora Habab study area. The soil and vegetation survey and the experiments discussed in subsequent chapters, were designed in this context. Data presented in this chapter indicate how representative the geology, climate, vegetation, and agricultural systems of the Rora Habab study site may be of other areas in Eritrea, or elsewhere in East Africa. Any attempt to generalise the results of this research to other areas should take account of the particular physical geography and agricultural practices of Eritrea and of this site, as well as the political, economic and social factors discussed in Chapter 1.

GEOLOGY AND CLIMATE

Eritrea

Geology

Whilst the Red Sea coast has been reasonably well surveyed (Mobil Petroleum Ethiopia Inc. 1964, 1968), the geology of the northern inland areas of Eritrea is virtually unknown (Drury et al 1991). Studies by workers from the Open University, U.K. and the EPLF Construction Department using satellite remote sensing and large format photographs, are in progress but at an early stage (Drury et al 1991, Seife Berhe and S. Drury, Open University, U.K., personal communication). The most detailed geological maps available (1:250,000 and 1:100,000) were compiled by Mobil Petroleum Ethiopia Inc.

mostly from early Italian sources. Although Eritrea's geology is locally variable, especially in areas of continuing uplift and faulting, the present account must rely on rather general sources which refer in the main to Ethiopia. The following information is summarised mostly from Mohr (1961:186-93, 1987:721, 729), Last (1961:194-202, 1962:82-102) and Westphal (1975:1-17).

In common with most of Africa, the Paleozoic in the Horn of Africa marks an era of denudation represented only by an unconformity between the roots of eroded Precambrian mountains and the beginnings of Mesozoic sediments. Subsequent deposition has covered most of the Basement Complex in Eritrea, but it is exposed in some areas of highly variable geology, for example around Nacfa (Fig. 1.2). Here I found foliated rocks which were suggestive either of close proximity to a fault zone or of old gneiss (M.F. Thomas, Department of Environmental Science, University of Stirling, Scotland, personal communication); some larger samples were evenly foliated for several centimetres.

The dominantly sandstone Mesozoic sediments were deposited as a result of epeirogenic sinking and marine transgression across the Horn during the Triassic and Jurassic. The Adigrat Sandstone facies of Ethiopia thin to the north, merging with the Wollega and Eritrean Sandstones north of Asmara. Subsequent Upper Sandstone (littoral) facies have not been recorded as far north as Eritrea.

During the Tertiary (Miocene) sandstones and limestones were formed along the Eritrean coast, lagoons being established in the present day salt plain region around Afar in southeast Eritrea. The extensive, thick lava flows of the Trap series (Oligocene in the north, Miocene further south in Ethiopia) which cover much of the inland area are subdivided into the Ashangi Group (basalts) and the later, more felsic Magdala Group (trachyites and andesites inter-bedded in the basalts). The Magdala Group reportedly is absent up to 2 600 m (Mohr 1961:188). Mohr suggests that tension, associated with > 5 000 m upward flexion of the Basement Complex, is probably responsible for the extrusion of the Trap series. Moreover, "... the little denudation in Eritrea and Tigre between emergence in the Upper Jurassic and extrusion of the Trap series ... indicates that the land was low lying till just before formation of the Trap series" (Mohr 1961:189). The Ethiopian rift valley does not extend into Eritrea but geological events in the rift may still be affecting plateau uplift adjacent to it. According to Mohr (1987:721), slices of lithosphere in décollement zones accommodate diapiric injection of asthenosphere and this interaction of asthenosphere and lithosphere dictates the pattern of uplift in adjacent plateaux.

Quaternary sediments associated with uplift and subsidence have been exposed as raised beaches and coral reefs along the coast. In highland Eritrea, tectonic activity has been associated with further intrusive igneous material and much faulting whilst in the lowlands aeolian and fluvial deposits may have been significant since the beginning of the Quaternary. Volcanic activity associated with the rift system in the Arabian peninsula -- the Afar triple junction -- (Mohr 1987:721) may have occurred locally also in Eritrea and it seems probable that some of the tuffaceous sediments in the Eritrean highlands are of Quaternary rather than Tertiary age. The region as a whole remains subject to complex tectonic and locally, volcanic activity (Mohr 1987).

Topographically Eritrea is divisible into three general zones: the low-lying plains of the Red Sea coast, a rapid rise in elevation to the central highland plateaux, and a slightly gentler fall of the western escarpments toward the lowlands of Barca province and the eastern Sudan. These marked changes in elevation have a major impact on the climate of Eritrea.

Climate

Reliable climatic data for Eritrea have not been generally available for about 15 years and earlier records are usually included in documents which refer principally to Ethiopia. Until more recent data can be located and collated, we must rely on a few general references which use data collected between World War Two and the mid-1970's. Five stations provide reasonably comprehensive long-term data: Agordat (western lowlands), Adi-Ugri and Asmara (highlands), Ghinda (eastern escarpment) and Massawa (eastern lowlands). I have so far been unable to locate any long-term data for the north of Eritrea. This account refers mainly to the climate of the Eritrean highlands.

Altitude rather than latitude is the major determinant of regional scale climatic features in Eritrea. Bethke (1976) suggests six basic zonal rainfall patterns for the Ethiopia and Eritrea, whilst Westphal (1975:18-27) citing the work of Delliquadri and others, describes six rainfall and eight climatic regimes. It is important to note that there are marked differences in rainfall over even a few kilometres. Bethke's map (1976:99) excludes much of the higher plateau of Eritrea from any of the six rainfall classes, concentrating on the eastern and western slopes. Griffiths (1972) provides more comprehensive data but the absence of information on radiation and evaporation creates serious difficulties, especially where locally prevalent orographic cloud increases total precipitation and reduces losses from evapo-transpiration.

Between December and February northeasterly flow dominates. This is associated with high pressure over the Sahara and a ridge extending southwest over Arabia from an extensive high pressure area over central Asia (Griffiths 1972:370). Cyclonic storms occur over the eastern slopes of the highlands and the coastal areas when low pressure centres migrate from the Mediterranean but the dry, subsiding air from the two high pressure areas produces mostly dry weather from October to March (Kebede 1964:30).

From about the middle of March, the Saharan High weakens and moves north while the Arabian High also weakens and moves toward the Indian Ocean. Frontal precipitation (the "small rains") can occur, as warm, moist, unstable air from the Indian Ocean converges with stable, dry air of the

Saharan High. At this time, the wind veers to give a predominantly easterly airflow in the north (Delliquadri, cited in Westphal 1975:19).

During the summer months (June, July, August), the Inter-Tropical Confluence (ITC) moves to a position just north of Eritrea (Helldén and Eklundh 1988). Two processes combine to make July and August the period of greatest rainfall in the highlands. Convergence of dry, continental, high pressure air masses from the north, and cooler, moister, maritime air from the Indian Ocean marks the boundary of the ITC with the monsoonal low pressure area over India creating a pressure gradient from east to west (Delliquadri, cited in Westphal 1975:19). Secondly, heating of the Eritrean plateau creates convective instability and this, according to Griffiths (1972:370), is responsible for a high percentage of the rainfall. As the rains pass through Ethiopia toward Somalia they weaken in intensity. The ITC brings a second precipitation peak to southeastern Ethiopia and Somalia toward the autumn months, the rains generally terminating in Eritrea by October (Workineh 1987:24).

The processes described above give rise to three main seasons. In much of the literature, these are described by their Amharinia names, Kiremt (main rains), Bega (dry season), and Belg (small rains) (Kebede 1964, Workineh 1987). In the Eritrean Highlands, these seasons correspond roughly to the following months; June to mid-September (Kiremt), mid-September to late-March (Bega) and late-March to mid-April (Belg).

The above description refers to events on a regional scale which generally hold true from year to year. It becomes harder to typify deviations from regional patterns even where reliable data exist. For example, the prevailing summer winds in Addis Ababa, Adi Ugri and Asmara are reported as southerly, westerly and northeast- northwesterly respectively (Griffiths 1972:384, 387-8). Thus it appears that within the highlands north of Asmara, as elsewhere in the region, a heavily dissected landscape gives rise to marked local differences in microclimate, the implications of which are discussed below.

The FAO/UNESCO/WMO study of agroclimatology in East Africa noted the importance of local information and concluded that generalisations about climate in the Ethiopian highlands should be avoided (cited in Bethke 1976:97).

Figure 2.1 shows mean monthly rainfall, cloud cover, temperature and relative humidity at Asmara, 120 km south of the Rora Habab plateau. Asmara is at the same elevation as the Rora Habab study site and is the nearest reliable meteorological station with long-term records.

Local classification of climate is based upon elevation. Three zones are typically distinguished and referred to as 'agro-climatic regions'. These are, in Amharinia, a) Dega; cool climate, high altitude (>2 400 m), b) Woina Dega; moderate temperature, intermediate altitude (1 800 to 2 400 m), and c) Kola; arid to semi-arid, low altitude (< 1 800 m). Pankhurst (1957:306) and Ullendorff (1973:25) give slightly different elevation ranges. Within these three categories a number of agricultural systems are found.

The Rora Habab Study Site

Geology

Since it is adjacent to rift zones which extend from East Africa along the Red Sea to Israel, Rora Habab, in common with the rest of the Eritrean highlands, is in an area of tectonic uplift (Mohr 1987). However, the geomorphological processes in the area of tectonic activity known as the Afar triangle, of which Rora constitutes a northern part, are poorly understood with at least two theories competing to explain them (Mohr 1987, Seife Berhe, Open University, U.K. personal communication).

The sub-strata consist of Precambrian rocks associated with pyroclastic volcanics and occasional dolerite dikes (Eritrean Relief Association 1985). The surface volcanics consist of acid to intermediate rocks, dominantly andesites, trachyites and welded tuffs. I have found these rocks throughout the plateau,

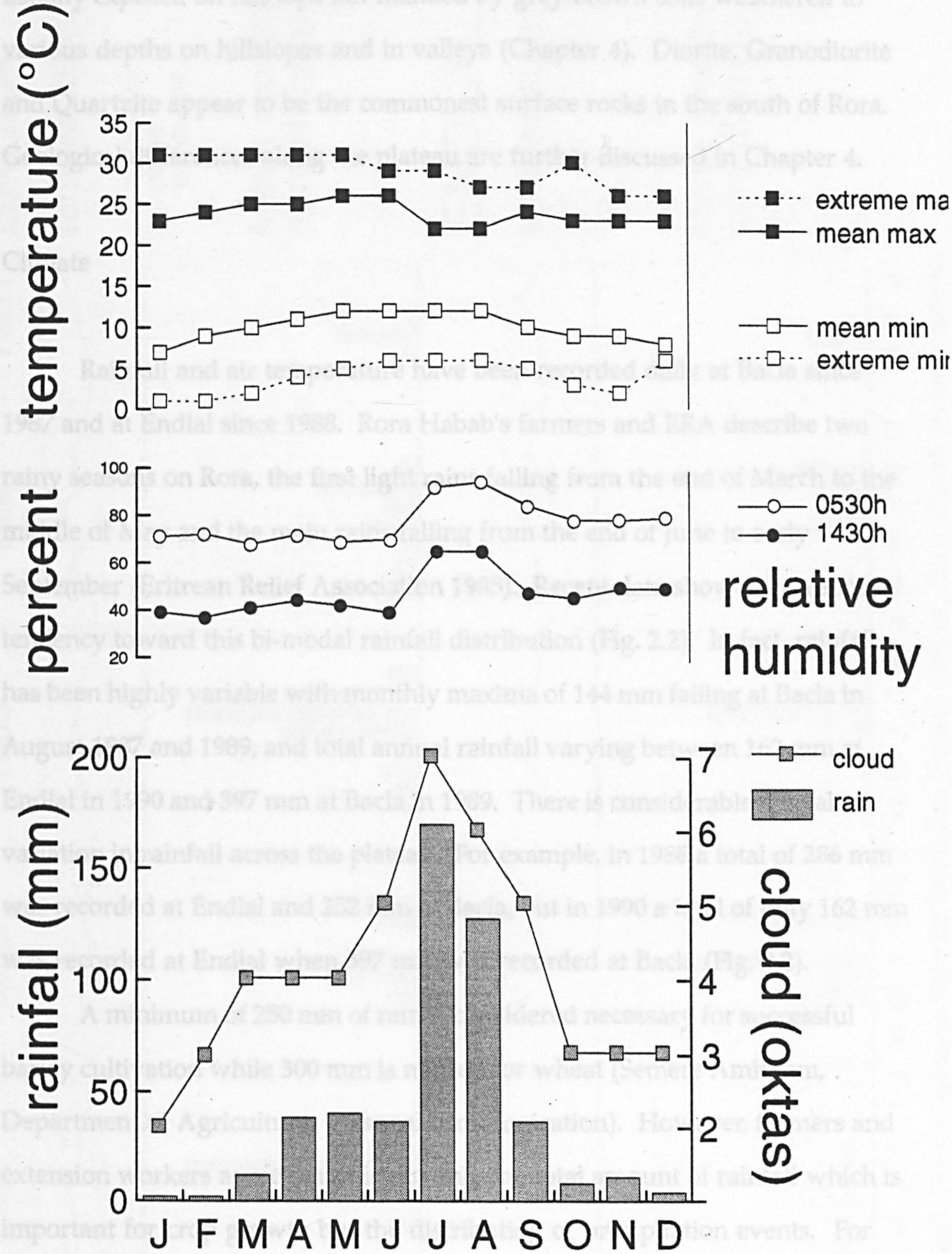

Fig. 2.1. Mean monthly climatic data for Asmara, Eritrea. Data are from Griffiths (1972) and Bethke (1976), averaged over 25 years (temperature), 7 years (relative humidity), 29 years (rainfall), and 8 years (cloud cover).

usually exposed on hill tops but mantled by grey-brown soils weathered to various depths on hillslopes and in valleys (Chapter 4). Diorite, Granodiorite and Quartzite appear to be the commonest surface rocks in the south of Rora. Geological differences along the plateau are further discussed in Chapter 4.

Climate

Rainfall and air temperature have been recorded daily at Bacla since 1987 and at Endlal since 1988. Rora Habab's farmers and ERA describe two rainy seasons on Rora, the first light rains falling from the end of March to the middle of May and the main rains falling from the end of June to early September (Eritrean Relief Association 1985). Recent data show only a slight tendency toward this bi-modal rainfall distribution (Fig. 2.2). In fact, rainfall has been highly variable with monthly maxima of 144 mm falling at Bacla in August 1987 and 1989, and total annual rainfall varying between 162 mm at Endlal in 1990 and 397 mm at Bacla in 1989. There is considerable spatial variation in rainfall across the plateau. For example, in 1988 a total of 286 mm was recorded at Endlal and 252 mm at Bacla, but in 1990 a total of only 162 mm was recorded at Endlal when 397 mm was recorded at Bacla (Fig. 2.2).

A minimum of 250 mm of rain is considered necessary for successful barley cultivation while 300 mm is needed for wheat (Semere Amlesom, Department of Agriculture, personal communication). However, farmers and extension workers agree that it is not only the total amount of rainfall which is important for crop growth but the distribution of precipitation events. For example, the total rainfall in Bacla in 1988 was 252 mm with 119 mm falling in a fairly even temporal distribution by mid-July (Fig. 2.2). However, the total absence of rain in late July and for the entire month of August led to crop failure for many farmers I spoke with at that time.

Mean monthly temperatures at Bacla ranged from 14.5°C for November 1988 and January 1990, to 23°C for July 1990; at Endlal the range was 12.7°C for

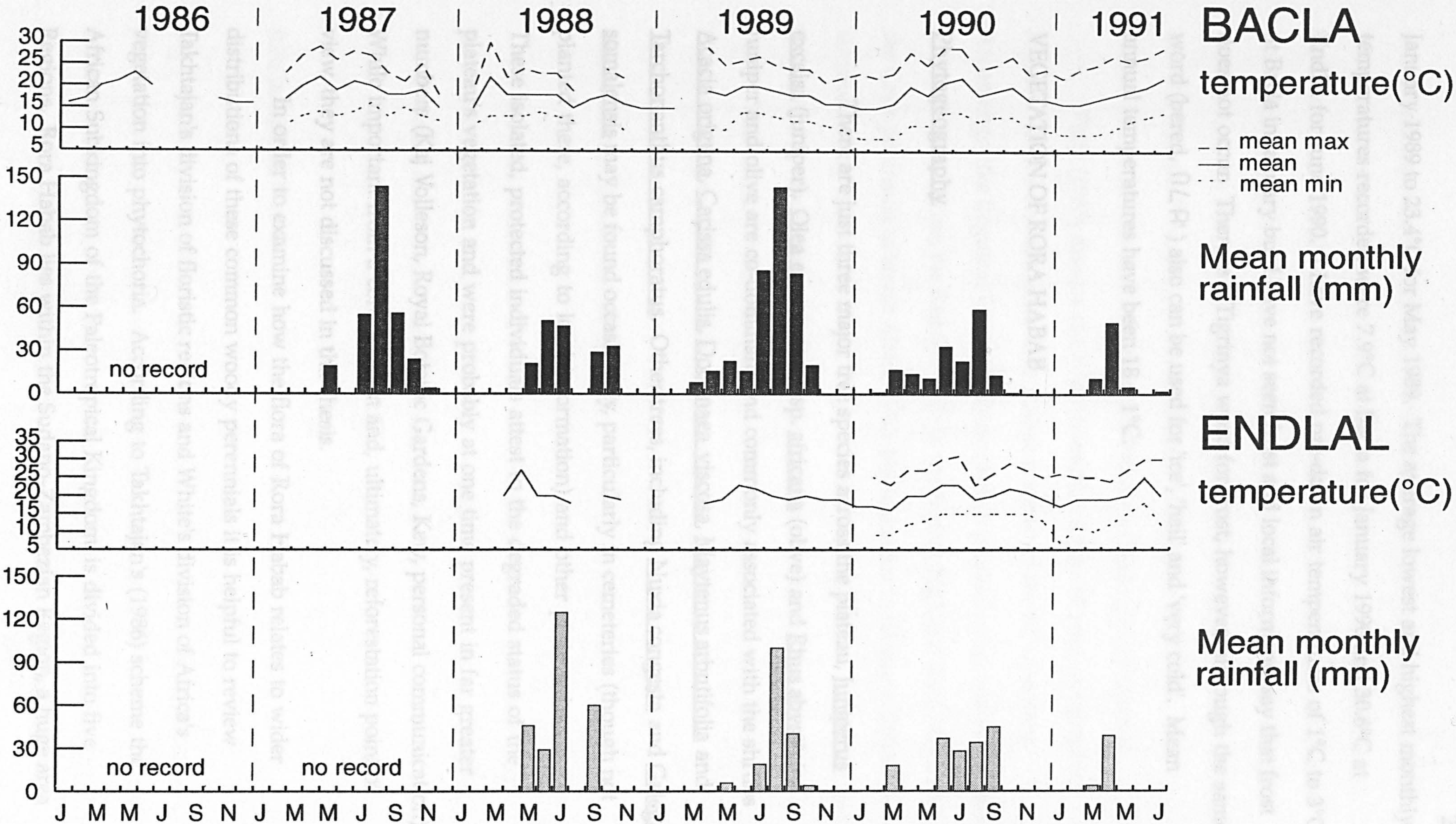

Fig. 2.2. Mean monthly rainfall and temperature data for Bacla and Endlal villages, Rora Habab plateau, Eritrea. From EPLF Department of Agriculture, northern zone statistics.

January 1989 to 23.4°C for May 1989. The average lowest and highest monthly temperatures recorded were 7.9°C at Bacla for January 1990 and 30.6°C at Endlal for June 1990. I have recorded pre-dawn air temperatures of 1°C to 3°C at Bacla in January but I have not seen frost and local informants say that frost does not occur. There is a Tigrinya word for frost, however, although the same word (bered, በረድ) also can be used for 'ice', 'hail' and 'very cold'. Mean annual temperatures have been 18 ± 1°C.

VEGETATION OF RORA HABAB

Phytogeography

There are just three major tree species across the plateau, Juniperus excelsa (juniper), Olea europaea subsp. africana (olive) and Rhus abyssinica. Juniper and olive are co-dominant and commonly associated with the shrubs Acacia origena, Carissa edulis, Dodonaea viscosa, Maytenus arbutifolia and Tarchonanthus camphoratus. Other trees, including Nuxia congesta and Galega somalensis may be found occasionally, particularly in cemeteries (though not planted there, according to local information) and other protected areas. These isolated, protected individuals attest to the degraded status of the plateau's vegetation and were probably at one time present in far greater numbers (Kaj Volleson, Royal Botanic Gardens, Kew, personal communication). While important from a conservation and, ultimately, reforestation point of view, they are not discussed in this thesis.

In order to examine how the flora of Rora Habab relates to wider distributions of these common woody perennials it is helpful to review Takhtajan's division of floristic regions and White's division of Africa's vegetation into phytochoria. According to Takhtajan's (1986) scheme the African Subkingdom of the Paleotropical Kingdom, is divided into five Regions. Rora Habab lies within the Sudano-Zambezian Region, a huge area which encompasses most of central southern Africa, eastern Africa, a band about 1 600 km north to south across the Sahel, tropical parts of the Arabian peninsula, Iran, Pakistan and northwestern India. This Region is subdivided into three Subregions, namely the Zambezian, the Sahelo-Sudanean and the Eritreo-Arabian Subregions. The Eritreo-Arabian Subregion is further divided into the Somalo-Ethiopian, South Arabian, and Socotran Provinces. Rora Habab lies within the Somalo-Ethiopian Province (Takhtajan 1986:206-8).

White (1983) divides the African mainland into 18 phytogeographic regions. In this classification, Rora Habab is a part of the Afromontane Archipeligo-like Regional Centre of Endemism, a phytochorion which includes parts of Sierra Leone, the Red Sea Hills in the Sudan, highland East Africa and the Cape peninsula in South Africa. This phytochorion in northern Eritrea is surrounded by the Somali-Masai Regional Centre of Endemism to the east and south, and by the Sudanian Regional Centre of Endemism to the west and north. This classification is broken down within Regional Centres into Vegetation Types, such as forest, woodland, and grassland.

Major Woody Species and their Uses

Table 2.1 summarises the local uses for the seven commonest woody perennials found on Rora, together with the plants' local names and families. These species are discussed in more detail below. Appendix 2 lists of all plants which I have collected and the local names which I have so far confirmed.

Acacia origena Hunde

I have previously erroneously referred to this species as Acacia seyal (Jones 1989:222), based on several specimens without fruits or flowers which I collected from Rora in 1987-8 and checked against the reference collection at Kew Gardens. A. seyal does occur on slopes adjacent to the Rora plateau. I

Table 2.1. Names and local uses of the seven commonest tree and shrub species on the Rora Habab plateau, Eritrea, including the principal synonyms and common English names.

Name of plant				
Latin	Tigre	Tigrinya	English	Uses
Acacia origena Hunde [LEGUMINOSAE]	Cha'a! ጫዓ	Cha'a! ጫዓ		browse, dead fencing, fuelwood (rarely).
Carissa edulis Vahl. [APOCYNACEAE]	Agam ዓጋም	Agam ዓጋም		browse, berries eaten during famine, construction poles (rarely).
Dodonaea viscosa Jacq. [SAPINDACEAE]	Tasas ታሳስ	Tahsas ታሕሳስ		firewood (rarely), leaves used as a steam 'sauna' by women, roofing, toothbrushes, brooms.
Juniperus excelsa Bieb. (syn. J. procera Hochst. ex Endl.) [CUPRESSACEAE]	Nardet ናርደት	Ts'hdi ጽሕዲ	(East) African pencil cedar	firewood, horizontal beams in house construction, roofing, windbreaks, dead fencing, shade.
Maytenus arbutifolia (Hochst. ex A. Rich) Wilczek [CELASTRACEAE]	Ergitté እርግቴ	Argudi ዓርጉዲ		browse, construction poles (rarely), dead fencing.
Olea europaea L. subsp. africana (Mill.) P.S. Green (syn. O. africana Mill.) [OLEACEAE]	Wogre ወግሬ	Auwlie! ኣውሊዕ	African olive (also applied to other olive species in Africa)	firewood, charcoal (rarely on Rora but often elsewhere in Eritrea), shade, upright supports in house construction, dry season animal fodder, plough handles, mattock handles and other agricultural implements, herding sticks, ornaments, kitchen and household utensils, toothbrushes.
Rhus abyssinica Hochst. ex Oliv. [ANACARDIACEAE]	Shamot ሻሞት	Shamot ሻሞት	African sumac	firewood (rarely), water freshener, dry season animal fodder, shade.

collected further specimens with flowers and pods from the same plants in 1989. These have been identified as A. origena Hunde, a species endemic to Eritrea, Wello and Yemen (Hunde 1982, identifications by J. Blewett, Royal Botanic gardens, Kew). A. origena is a tree which is closely related to A. abyssinica and A. negrii. It typically reaches 5 to 11 m in height and occurs in upland woodland grassland between 1 900 and 2 600 m elevation (Hunde 1982). In Rora, I have not found any plants taller than 2 m and I have rarely seen them in flower or fruit, probably because they are very heavily browsed. This together with their stunted form makes identification difficult and Hunde (1982) reports that A. origena previously has been published as A. abyssinica, A. abyssinica var. arabica, A. negrii, and A. menachensis .

Many Acacia species are known to occur in Ethiopia and Eritrea. Two of these, A. abyssinica and A. senegal, are used as a source of gum arabic (Westphal 1975:204, Heywood 1985:152). In some parts of Eritrea, Acacia spp. are used in construction, though not on Rora (Heruyi Asgedom, Department of Agriculture, personal communication). On Rora, A. origena is browsed by livestock and sometimes used for fuelwood. Plants may be cut off at the base for fencing material and do not seem to be protected from this or from browsing despite their relative scarcity.

Carissa edulis Vahl.

C. edulis is a common shrub usually reaching no more than 3 m in height when growing in isolated situations. Blundell (1987:142) reports that one example in Nairobi National Park reached 18 m as a climber and I found one plant 6 m in height in Bacla village on Rora Habab which was growing as a climber up the stem of an O. europaea subsp. africana tree. In East Africa C. edulis reportedly occurs from sea level to about 2 000 m but I have not so far found any examples in Eritrea below 1 500 m, perhaps because of lower rainfall in Eritrea than in other mid-altitude locations in East Africa (Blundell 1987:142).

The species occurs in four of the floristic regions described by White and it is a common component of termite mound thickets in Zambia, in Sudanean scrub forest, on inselbergs on the Jos plateau, Nigeria, in northern Kenya, Uganda and Burundi, and throughout the Ethiopian and Eritrean highlands (White 1983:98,109,114,121,129,182; Andrews 1952:390).

In Ethiopia, C. edulis roots reportedly are used to cure snake bites, toothache and stomach ache (Jansen 1981:263). The Nyamwesi in Tanzania, who call the plant Mfudje-anje, use the roots to relieve "chest complaints" (Bally 1938:21). Its small, edible black berries are eaten by children on Rora and when food is scarce or during famine, they are eaten by adults. The berries also are eaten in Ethiopia (Selinus 1971:24).

Dry wood from dead shrubs is used as fuelwood but the plant is not specifically cut for this purpose. The leaves provide year-round fodder for livestock which are allowed to browse freely on the plant. Although C. edulis seems to be strongly favoured by livestock, the plant is not cut to bring leaves to livestock, as is the case with olive, probably because its low branches are easily reached by animals and because, unlike olive, it has spines. Taller shrubs occasionally are used as non-structural building and plants of any size may be used as dead fencing material.

Dodonaea viscosa Jacq.

D. viscosa is a shrub which is locally common over much of Africa. Its range covers the Seychelles, the Cape Verde Islands, and mainland Africa west to the Jos plateau, Nigeria, as far as northern Sudan, and south beyond the Orange River (White 1983:109,115, 140, 251,257). Exell et al (1963:542) reported its occurrence in Rhodesia, Nyasaland and Moçambique. Westphal (1975:45,48) reports that D. viscosa is a common component of montane evergreen thicket and juniper forests in east Africa.

Along Rora Habab, D. viscosa also is locally common, seemingly confined to rocky slopes and often in association with other species. Andrews (1952:339) suggests that the plant may reach 8 m in height, though more usually it reaches 2 to 4 m. None of the shrubs I measured on Rora exceeded 5 m.

In Ethiopia the leaves are used as a wound dressing, a febrifuge and to cure sore throats (Jansen 1981:267). On Rora too, D. viscosa leaves are valued for their medicinal properties. A common skin disease in cattle, known locally as Wayeh (ወየሕ) may be cured after a few treatments involving mixing the leaves with milk and rubbing the mixture directly onto the sores. The leaves also are used by women in a steam and smoke 'sauna'. Leaves are burned in a shallow pit and left to smoulder while a woman wraps herself in a blanket and takes what is locally referred to as a 'steam bath'. D. viscosa is rarely used for firewood and not at all in major construction, although branches sometimes are spread over the roofs of houses and it may be used as dead fencing material.

Juniperus excelsa Bieb.

Juniperus excelsa Bieb. (Cupressacae) is a tree which grows at an altitude of 1 750 to 2 500 m, reaches 30 to 37 m in height and 1.2 to 1.5 m in diameter and has a range in Africa from N. Eritrea to N. Zimbabwe (Hall 1984; Rendle 1969). According to Lewis (1960), J. procera Hochst. ex Endl. sometimes has been regarded as a variety of J. excelsa Bieb. differing only in having smaller fruits. African and Arabian populations formerly were distinguished as J. procera, but Hall (1984) considers J. excelsa to be the taxonomically acceptable name. However, a revision of the species is underway and Adams (1990), based on his analysis of volatile leaf oils, states that merging the taxa is not acceptable, arguing that J. procera should be maintained at the specific rank. In this thesis I refer to the plant as J. excelsa, following Hall (1984).

Forests of J. excelsa previously were extensive in East Africa (White 1983) with about 200,000 ha existing in Ethiopia in 1955 (Huffnagel 1961).

However, it appears that the species is in decline, especially at the extremes of its range in Africa (Hall 1984), and perhaps also in Saudi Arabia (Abulfatih 1979), Pakistan (Chaudhry and Wali-ur-Rehman 1979) and Crimea (Larina 1980). The reasons for this decline in northeast Africa could include a change in climate towards reduced and less regular rainfall, land clearance for agriculture, and fuelwood cutting. Where weakened, the trees seem susceptible to fungal and insect attack (Chaudhry and Wali-ur-Rehman 1979; Jansen 1981).

In Ethiopia J. excelsa is a major and often the dominant component of woodlands which represent a cultural resource as well as being economically and ecologically important. In Eritrea J. excelsa is especially valued for fuelwood, house construction and shade. As an evergreen species it also is valuable for watershed protection especially at the onset of the rainy season when little ground cover is present.

All parts of the tree except the roots have been reported as having medicinal uses in Ethiopia, ranging from the prevention of 'camel itch' (the young branches) to alleviating hepatic disorders (the resin) (Jansen 1981:214). Cufodontis (1953, cited in Jansen 1981:214) observed that the fruits are used as a sudoriferum and as an emenagogue. None of these medicinal uses are known on Rora according to my informants. In response to specific questions about medicinal uses for the fruits, all informants responded that they are not used "..except by birds" -- presumably a means of seed dispersal.

Commercial uses for J. excelsa have included construction, telegraph poles, pencils, flooring and furnishings (Hall 1981:26). On Rora Habab, one major use for J. excelsa is in construction but it almost never is used as upright supports in houses. Local informants said that the reason for this is its lack of strength and the fact that the wood splits easily. As a construction timber it is prized for its resistance to termites and the ease with which it can be worked using hand axes and small mattocks. Jansen (1981:215) also notes the tendency of the wood to split and the fact that the heartwood, though not the sapwood, is termite resistant.

Homes on Rora are entirely constructed from local materials with J. excelsa used to make horizontal beams over doors, window frames and, especially, horizontal supports for the flat roofs. In roof building, smaller (8 to 15 cm in diameter) J. excelsa trunks or branches are laid closely together across a framework of larger (15 to 25 cm) ones. The roofs are insulated by filling in the gaps with small branches, twigs and earth. Further layers of twigs and earth may then be laid on top of this until the structure is sufficiently insulated and leakproof.

J. excelsa also is used on Rora Habab for fuelwood although whole trees no longer are cut specifically for this purpose. Villagers on Rora say that they prefer olive for fuelwood because the wood from J. excelsa is smoky and burns more quickly. Smaller branches and leafy twigs may used as fencing material around small gardens, though thorny species seem to be preferred for this purpose.

Rora Habab has the most northerly remnant of J. excelsa woodland in Africa, except for an un-surveyed, small and declining population 80 km further north. The distribution of J. excelsa along Rora Habab now is patchy and restricted to the north of the plateau where it is cut by villagers and subject to drought.

Maytenus arbutifolia (Hochst. ex A. Rich) Wilczek

This common, bushy shrub which reaches a height of 1.8 m and is found throughout east and central Africa between 1 500 m and 2 350 m elevation (Blundell 1987:126). The species is common on the Rora plateau where it is up to 3 m tall. It was not possible to identify some specimens collected from Rora with absolute certainty beyond the genus level. A comparison of collected specimens with the entire Maytenus reference collection at Kew led to M. arbutifolia as the most likely species in nearly all cases. However, M. arbutifolia is mentioned in only one of the floras I have searched, although a closely related species, M. senegalensis, is mentioned in several floras. Discussions of the variability of M. senegalensis and closely related species can be found in Andrews (1952:281-3), Westphal (1975:45,50) and White (1983:195,344). Although it appears that M. arbutifolia is the only Maytenus species on Rora, a more complete collection of specimens from this genus is needed.

According to Bally (1938) the east African genus Gymnospora (now renamed Maytenus, (Exell et al 1963:358)) has medicinal properties. Jansen (1981:273) reports that leaves from M. senegalensis are used in Ethiopia to treat diarrhoea in animals and that M. undatus (undulata) leaves are used as a stimulant, but he gives no further details. Informants on Rora say that M. arbutifolia does not have medicinal uses. As with C. edulis, taller shrubs rarely are used as non-structural building material but all plants may be used as dead fencing material. The fruits reportedly are not eaten by people on Rora. Goats browse on the leaves but other animals apparently are put off by the long thorns and generally avoid M. arbutifolia.

Olea europaea L. subsp. africana (Mill.) P.S. Green

O. europaea subsp. africana is a common tree of the Eritrean and Ethiopian Highlands, occurs in seven of the eighteen African mainland floristic regions described by White (1983:115,121-2, 129, 135, 167, 182, 193-5, 201,224) and often is associated with J. excelsa (Jansen 1981:213, Takhtajan 1986). The tree reaches 7 to 10 m, though occasionally 15 m in height (Dale and Greenway 1961:346) and often has two or more stems. There are several olive species in Africa and this means that describing precise boundaries for the geographical range of O. europaea subsp. africana is difficult. The Amharinia name "woyra" (ወይራ) appears to refer to a number of Olea species. Selinus (1971:30), for example, refers to O. chrysophylla as woyra but in the opinion of one ethnobotanist his descriptions probably refer to O. europaea subsp. africana (J. Mercier, Royal Botanic Gardens, Kew, personal communication). At least twenty names previously identified O. europaea subsp. africana. The present combination, using the sub-specific rank africana, was published by Green and Kupicha (1978: 69-75) who provide a full synonymy.

O. europaea subsp. africana is co-dominant with J. excelsa across most of Rora Habab but isolated trees, remnants of a much larger population (Saleh Ahmer, farmer, Laba village, personal communication) can be found along the hills and drainages almost down to Nacfa (1 770 m). The species is present on very steep slopes along the eastern escarpment of Eritrea, from 16° to 14°50 ' N, between about 900 and 2 500 m where at the higher elevations it may be found in association with J. excelsa. It is abundant along the escarpment east of Ad Teklezan in an area called Semienawi Bahri (15° 40 'N, 38° 50 ' E). Here, it is the dominant species in the only relatively undisturbed natural forest in Eritrea that I have seen. The woodlands of this area may have survived because the slopes are very steep or possibly because the area has been heavily mined by the Ethiopian army. Dale and Greenway (1961:348) also note that in Kenya O. europaea subsp. africana is associated with J. excelsa and has an elevation range from 760 to 2 900 m.

On Rora, O. europaea subsp. africana has many uses (Table 2.1), most of which are related to the hardness of the wood. A principal use for the trunks is for the upright supports in house construction. Local informants give several reasons for this; the timber is strong and does not split easily, it is termite-resistant and relatively rot-resistant even under ground in warm, moist conditions, and it easily supports the horizontal beams and roofing made from J. excelsa. According to informants, olive branches are not used as roofing material because the tree is heavy, difficult to work and more valued for other uses than J. excelsa, the only other species large enough and sufficiently abundant to be used routinely in house construction. Dale and Greenway (1961:348) state that in East Africa, the durability of the species has led to its extensive use as a building material where subterranean poles are needed and that it is a superlative firewood used in ".. very large quantities .. in Kenya for railway fuel".

Eritrea's O. europaea subsp. africana woodlands have been extensively cleared to make way for agriculture. Olive trees have many uses in Eritrea and are regarded as providing the best wood for use as a fuel. Further south in Eritrea, but not on Rora, olive is commonly used for making charcoal. This is a further reason for its decline in those areas. Although living trees no longer are cut for fuelwood on Rora, villagers say that olive trees were cut extensively for fuelwood in the past. O. europaea subsp. africana is the principal species used in the manufacture of plough handles, ox yokes, herding sticks, mattock handles and other agricultural implements (Table 2.1). Twigs between one and two years old are used as toothbrushes, selling in towns for 10 centimes (3 pence) per twig in August 1991. A small woodworking industry in Asmara produces ornaments, plates, tables candlesticks and other manufactures from olive wood harvested in Eritrea.

Perhaps the most important reason why this species is particularly threatened on Rora is that its foliage is the principal green fodder crop in the dry season and during drought. Farmers know that the practice of stripping leafy branches ultimately kills the trees but they face a dilemma; either they chop the olives to feed their animals or else the animals die. This points to the need for range management and forage research. A further consequence of this practice is that trees rarely get a chance to flower and set fruit. Despite exploring many kilometres on foot and checking hundreds of olive trees, I have only found three plants that have set fruit in any quantity. Two of these were in cemeteries.

O. europaea subsp. africana, then, is a valuable, multi-purpose tree on Rora Habab and in much of Eritrea. However, its survival is threatened as a consequence of the factors mentioned above. Regeneration of the tree is hampered by two further problems: it has proved difficult to germinate, and those plants which do germinate often do not escape the grazing pressure of animals.

Rhus abyssinica Hochst. ex. Oliv.

According to Exell et al (1963:591) there may be as many as 130 Rhus species in Africa. R. abyssinica is a tree which was collected by Schimper from Adowa, 250 km south of Rora, in 1837 and it has been described by Andrews (1952:349-50) and mentioned by Westphal (1975:47) as a component of 'montane savanna'. R. abyssinica is not among the 27 Rhus species mentioned by White (1983:350) nor is it among the 37 Rhus species described by Exell et al (1963:590-615). Exell et al (1963:600, 603) note that the genus hybridises frequently and that the range of many species is restricted. The distribution of R. abyssinica may be limited to the Sudan Hills, Eritrea and Ethiopia (R. Polhill, Royal Botanic Gardens, Kew, personal communication) although it also may occur in the highlands of Yemen and southwestern Saudi Arabia. On Rora, the species is found along river banks and at the foot of slopes but only rarely on more exposed or steeper slopes with shallower soils. Most plants on Rora are 4 to 6 m high and are found in close association with other species, especially O. europaea subsp. africana.

In Ethiopia the leaves are used as a treatment for influenza and the root is used to treat "udder disease" (Amare Getahun 1976, cited in Jansen 1981:276). Elsewhere in Africa, R. natalensis also is reported as useful in the treatment of influenza (Bally 1938:20). Informants on Rora said that R. abyssinica had no medicinal uses they knew of. However, villagers do use the plant to improve the taste of water which is stored in goatskin containers, called harbi (ሓርቢ) locally. The powdered leaves of R. abyssinica are rubbed onto the inner surface of these containers to keep them soft and to prevent the taste of the animal skin from tainting the water. Leaves are harvested for this purpose and for use as dry-season fodder and one may sometimes see donkeys laden down with leafy twigs cut from R. abyssinica trees.

The wood is soft and, according to local information, easily destroyed by termites. For these reasons and because of its small size, R. abyssinica rarely is used in house construction. Although local people value the tree as a source of fuelwood, it is less often used for this purpose than olive or juniper because it is much rarer than these species and it has uses which commoner trees do not. The small, brown fruits reportedly have been eaten in times of famine.

AGRICULTURAL SYSTEMS AND LAND TENURE

Agricultural Systems in Eritrea

Eritreans are among the poorest people in the world. About 80% of the population live in rural areas and rain-fed subsistence agriculture or animal husbandry are the principle economic activities.

Four agricultural systems are distinguished in Ethiopia and Eritrea by Westphal (1975:88-173): the seed-farming complex, the ensat (Ensete ventricosum, 'false banana') farming complex, shifting cultivation and the pastoral complex. There is also a plantation sector producing cash crops such as coffee (Coffea arabica) and cotton (Gossypium spp. and hybrids). Cultivation of ensat is restricted to southwestern Ethiopia and shifting cultivation is limited to the western and southwestern Ethiopian highlands and to part of Sidamo province in Ethiopia (Westphal 1975:123). The following discussion, then, is limited to the pastoral complex and the seed-farming complex, which are practised in Eritrea.

Pastoralism

Pastoralism is virtually restricted to Muslim peoples in the lowland areas of Eritrea. Large herds of goats are kept together with a number of camels and a few cattle. Dogs also are kept by many families.

It is not possible to generalise about a pastoral way of life in Eritrea for here, as elsewhere in Africa, the words 'pastoralism' and 'nomadic' encompass a variety of lifestyles and activities (Gulliver 1975). Moreover, for a number of reasons, the customary lifestyle of many nomadic groups is under threat.

In the eastern lowlands, the relative autonomy of the 'Afar who customarily rely on vegetation sources related to the seasonal flooding of the Awash river, has been threatened by large scale agricultural development in the Awash valley since the 1960's, and by several major droughts (Flood 1976, Kloos 1982, Teferra-Worq and Harbeson 1978). In the western lowlands war and drought have proved disruptive for customary migrations. The related tribes of Sudan/Eritrea border areas have found it necessary to live as refugees in the Sudan several times in recent years (Eritrean Relief Association 1984).

Customary economic and social relationships between settled highland communities and nomadic groups also have changed. The history of relations between these groups is not clear and probably were changed over the decades of Italian influence (Barnett 1983). It seems clear, though, that the nature of economic exchanges is related to differences in wealth and bargaining power. For example, wealthier, powerful nomads may be in a position to exchange animals for grain while those without a surplus of livestock may only be able to exchange their labour for grain (Barnett 1983). These relations are dynamic and subject to variations through time as well as between different communities. On Rora, the Habab have at different times relied mainly on animal husbandry or on cereal cultivation for their livelihood (discussed further below).

A further significance of nomadism is that nomadic people, as well as travelling merchants, are a major source of communication between settled agriculturalists in highland villages where the the seed-farming complex is the dominant agricultural system.

The Seed-Farming Complex

The seed-farming complex is found solely in the highlands. Considerable variation in species cultivated is summarised in Westphal (1975:87-9, table 3). The major cereal crops grown are taff (Eragrostis abyssinica, similar to millet but with grains less than 1 mm in diameter), sorghum, wheat, millet, barley and maize. Niger seed (Guizotia abyssinica) and groundnuts are the most common cash crops, potato the commonest tuber crop, and cabbage, tomatoes and capsicum peppers the commonest vegetables. Many different pulses are grown and in some areas, notably in the highlands south of Keren (Fig. 1.1), citrus fruits are grown, although most of the commercial orchards I saw in August 1991 were destroyed or abandoned during the last ten years of the Ethiopian occupation.

In addition to growing crops, most farmers keep a few oxen, cows and goats. The number of animals kept by farmers varies according to wealth, need and preference. Poorer farmers who do not own oxen may need to hire these animals for ploughing although oxen also may be shared between a number of families. I witnessed families sharing oxen in a number of villages during famines in 1984 and 1991. Several informants in villages at my research site said that there, as elsewhere in Eritrea, it is customary to share scarce resources in times of difficulty. A few camels are kept in the highland areas but their ownership generally is restricted to people who migrate to the lowlands or to the Sudan.

Seasonal migration is common in the northern highlands. Some families are transhumant for part of the year (Barnett 1983) while in some cases only male family members will travel. Such journeys are undertaken to graze stock in more favourable locations, to buy or sell livestock at distant markets, or to obtain money in the Sudan or in Eritrean cities through sale of animals or cash employment. This income provides some flexibility in times of poor harvest enabling the purchase of extra food, and may be used to purchase manufactures such as clothes, household items and agricultural tools.

Migration to lowland areas and the Sudan is common in the northern Eritrean highlands where it is an important feature of the seed-farming system. The term seed-farming complex is a general one encompassing several systems which are distinguished according to the crop grown and whether a hoe or plough is used. The agricultural system of Rora Habab thus can be referred to as the grain-plough complex (Westphal 1975).

The Highland Grain-Plough Complex

Characteristic of the grain-plough complex are the broadcast sowing of seeds and the use of a plough to prepare a seed bed and cover the seeds. In contrast to other types of seed farming, fruit trees, tuber crops and most green vegetables are virtually absent (Westphal 1975:83) and the cultivation of pulses is rare in some areas. The plough used (Plate 2.1) has no mould board so that there is minimal incorporation of plant residues and animal manure into the soil. Frequent cross-ploughing often is necessary to prepare a good seed bed (Committee for the World Atlas of Agriculture 1976:88).

Although the plough does not turn the soil over it is able to break up larger soil aggregates and probably assists in improving surface drainage and aeration. Normally two oxen are used to pull the plough although donkeys or cows may be used if no oxen are available (Plate 2.1).

Even within the grain plough complex there are variations between regions and villages. The different farming systems are practised within a variety of land tenure arrangements.

Land Tenure in Eritrea

Land tenure arrangements continue to have a great impact on the ability and desire of villagers to manage natural resources and to plant or remove trees. In order for land restoration and reforestation to be effective, an understanding of property rights is essential, as Fortmann has noted; "Agroforestry depends on people's rights to plant and use trees, rights that in turn depend on the prevailing systems of land tenure and tree tenure." (Fortmann 1988:16). Land tenure is therefore briefly discussed below and the notion of tree tenure, as it affects the restoration of Rora's woodlands is discussed in Chapter 7.

The two commonest forms of land tenure in the grain-plough complex of the Eritrean highlands are diesa and risti. Diesa is best described as communal or village ownership (Houtart 1980:84). Risti refers to private ownership by individuals or, more commonly, by a kinship group (Ullendorff 1973:181).

Diesa

The major principle of diesa is the redistribution of land every few years. Redistribution takes place at intervals of three to seven years and is intended to take account of families' changing needs (Barnett 1983) and permit equitable distribution of land according to local differences in soil fertility. There are three major difficulties which may lead to departures from the egalitarian principles of the diesa system. These relate to absentee farmers, land improvement, and to local politics governing the redistribution process.

Rights to use land do not require the physical presence of every villager and absentee land 'users' (e.g. urban workers) may make arrangements with relatives to look after plots allocated to them. According to Houtart (1980:87) this practice " .. has been the basis of the social and economic differentiation of the peasantry." A second difficulty concerns the low incentive many farmers feel to improve land that is used by them only for a limited period. In some cases this problem extends to maintenance of terraces, fences and application of organic amendments to the soil. Thirdly, control over land redistribution in the diesa system rests with male village elders. These people often are in a position to use the system to their own advantage. The power of the elders is such that redistribution may be delayed or cease altogether; this reportedly has happened in several areas (Heruyi Asgedom, Department of Agriculture, personal communication). In such circumstances, diesa may come to resemble something more like the risti system of land tenure.

Risti

The risti land tenure system is based on the " .. permanent and inalienable possession of land" (Ullendorff 1973:181). Three features characterise the range of land-holding principles that are encompassed by the term risti: ownership of land is absolute, hereditary, and derived from " .. the historical right of a first possession by some remote ancestor" (Nadel 1946:7). The 'original' family members who own the land are known as the restegna and only members of their extended family have rights to the risti land of that family. Land cannot be sold without the consent of all family members. In some areas, risti and diesa systems operate side by side (Nadel 1946:14).

Villages where the risti system operates are largely controlled, politically and economically, by the richer members of the restegna. The authority of certain restegna families was further enhanced during Italian rule through their appointment as headmen in charge of sub-districts. Such structural change in Eritrean society yielded benefits for the local restegna and the colonial government at the expense of poorer communities or people farming under the diesa system who were living adjacent to risti areas. (Houtart 1980:86-7).

Structural changes in land tenure were not always undertaken in favour of the restegna. For example, in 1935 the Italian government expropriated a large area of land around the southern town of Senafe to build an aerodrome, abolishing private ownership of land in order to do so. The old risti rights were over-ridden and all land became communally held (Nadel 1946:14).

During the 1980's the Ethiopian government nationalised all land in areas of Eritrea which it controlled. According to farmers I have spoken with, this led most families to fell the remainder of their trees to ensure that they, and not the government, received the money from the sale of their trees for fuelwood and construction. As a result, the few remaining native trees in the highlands were removed. When I drove north from the Ethiopian border via Asmara to Keren in August 1991, the plateau was almost completely devoid of trees.

In the early 1970's the EPLF initiated land reform in several areas, reinstating the primacy of the diesa system and modifying existing arrangements to achieve a more equitable distribution of land. Today, as the provisional government, the EPLF is undertaking a nationwide survey of land tenure arrangements and agricultural productivity. It seems likely that some form of private ownership of land and trees will prevail under their governance (Issaias Afwerki, General Secretary, EPLF; Stefanos Seyoum, Head, Agricultural Commission, personal communications), although the details of future tenure laws and land rights are not yet known.

Agriculture on the Rora Habab Plateau

Crops

An estimated 3 093 ha of land are potentially cultivable across Rora of which 2 167 ha was suitable for cultivation in 1985 (Eritrean Relief Association

1985). Table 2.2 shows the area of land actually and potentially cultivable per family for Bacla, Berige and Laba and for the plateau as a whole.

Table 2.3 shows the 1988 yields of three crops from three areas of Rora Habab. The main crops grown are wheat and barley. Rarely and only in some locations, beans, sorghum and maize are grown. Since 1987 potatoes also have been supplied by EPLF extension officers and have been grown with great success by farmers who choose to plant them. The high potato yield was one reason why many farmers had a food surplus in 1987, the first for fifteen years. In that year, many farmers were even able to sell some of their surplus, a fact which further enhanced the positive relationship between villagers and the Agriculture Department. In general, though, wheat and barley may be regarded as the staple foods, and they certainly are the crops which for the last 100 years at least have influenced soil characteristics and land use.

Wheat and barley sometimes are rotated with each other from year to year. More usually the same crop is grown in the same area every year according to how farmers judge the land's suitability. Local people point out, for instance, that wheat requires more water and they plant wheat on the flatter and lower slopes where the soils generally are deeper and runoff from adjacent hillslopes accumulates.

Preparations for sowing take place in the dry season and into the summer months. In common with virtually all farmers in Eritrea, the villagers of Rora do not have access to machinery so that agricultural tasks are undertaken manually with oxen used to pull ploughs. The land is ploughed, usually twice, between January and April. Ploughing is described as either deep (25 to 30 cm) or shallow (8 to 20 cm, depending on soil type). Animals are grazed on plant residues for some time to manure the land and then moved to another area. The first ploughing is deep and aims to incorporate this manure and remaining plant residues into the soil. Second and any subsequent cross-ploughings are shallow and may also be done after manuring by animals. Seeds are broadcast by hand into shallow furrows at the

Table 2.2. Cultivable land and population in 1985 in Bacla (north), Berige (central), and Laba (south) villages on Rora Habab plateau, Eritrea. Calculated from data of Eritrean Relief Association 1985.

Village	Potentially cultivable area (ha)	Suitable for cultivation (ha)	No. of families	Population	Potentially cultivable area per family (ha)	Potentially cultivable area per person (ha)
Bacla	265	186	242	1452	1.1	0.18
Berige	70	49	76	456	0.9	0.15
Laba	298	209	215	1290	1.4	0.23
TOTAL[1]	3093	2167	2090	12540	1.5	0.25

1 Total is for all 13 villages on Rora Habab

Table 2.3. Yields of wheat, barley and potatoes (Tonnes ha^{-1}) in 1988 from three areas of Rora Habab, Eritrea. Numbers are means (± 1 SD), maximum and minimum. Data are from EPLF Dept. of Agriculture, northern zone, 1988 statistical records. The numbers of fields from which means were obtained varied by crop and village. Village locations are shown in Fig. 1.2.

	mean yield	max.	min.
WHEAT			
Bacla	1.92 (0.17)	3.04	1.26
Meriet	2.30 (0.27)	3.34	1.43
Endlal + Berige	1.76 (0.11)	1.95	0.57
BARLEY			
Bacla	2.14 (0.02)	2.46	1.82
Meriet	1.45 (0.12)	1.74	1.14
Endlal + Berige	1.70 (0.11)	1.85	1.48
POTATOES			
Bacla	24.33 (2.39)	41.67	10.67
Meriet	28.64 (2.46)	43.59	13.69
Endlal + Berige	22.63 (1.97)	38.40	17.50

beginning of the rains. A final ploughing aims to cover these seeds. No irrigation is undertaken except in small gardens close to reservoirs, where hand-watering sometimes is done.

Chemical fertilisers are not used although wood ash reportedly may be brought to the fields as a fertiliser. Cattle dung is preferred to goat manure since the latter, according to local information, tends to "burn" the land. Goat manure, therefore, generally is mixed with cattle dung or else not intentionally used at all.

January to April also is the time for maintenance and repair of the low stone walls which function as terraces around fields on sloping land. Primarily designed as a means of soil erosion control, farmers also say they build them to channel runoff water into adjacent fields and capture surface water to increase water infiltration depth behind them. However, it seems that they are easily broken by the relatively fast overland flow which can occur during big storms and their usefulness is limited.

Since 1985, villagers working with extension officers from the Agriculture Commission have terraced much more than the 600 ha goal of the IRDS (Semere Amlesom, Department of Agriculture, personal communication). These are stronger structures than the stone walls, typically about 0.75 m high and wide, with foundations and facing stones buried in the soil. In between the facing stones villagers place boulders and smaller rocks. None of these new structures has yet broken even in torrential rain. Unfortunately, there are no estimates of soil erosion before the terraces were built but Plate 2.2 shows an area of Laba terraced in 1986 which was previously subject to severe surface erosion and where overland flow now is much reduced.

After sowing the main tasks in the field are weeding and protecting crops from damage by birds and livestock. Weeding is done by hand with a small scythe-like knife (Plate 2.3). Animals for the most part are removed from the cultivated areas of the plateau during the summer months to graze on the slopes of Rora or in valleys and on hillsides further afield.

Harvesting takes place between 90 and 120 days after germination, depending on the crop, seed variety and rainfall distribution. Yields at harvest (late September to early November) are highly variable but are often insufficient for the average family's yearly need. In times of famine, when crop failure is extensive, the following year's wheat and barley seed may be eaten; this has happened three times since 1984. ERA then had to obtain seed for the next years crop from outside the area.

Although the agricultural cycle briefly described above may be regarded as "normal", farming routine has been disrupted by drought and by the war. Usually, animals would provide something of a fall-back in the event of partial or complete crop failure, either to be consumed directly or else sold for cash to buy grain. Prices for animals can fall dramatically during a drought or famine year and the danger of aerial bombardment made migration to regional markets in Eritrea and the Sudan hazardous for the past two decades. Nevertheless, animals remain a major part of the economy of Rora Habab.

Livestock

A census of the domesticated animal population was carried out by ERA in 1983 and 1984 and livestock numbers from this census are given in Table 2.4. However, the animal population apparently declined greatly during the census, increased during the late 1980's and declined in 1989 and 1990. Therefore the figures can be regarded only as a rough estimate of the number of animals today.

Cattle, goats and sheep primarily are kept for their milk. Oxen are used in ploughing although, as noted above, donkeys or cows may be used if oxen are unavailable. Goats are useful for meat and their skins are used to make water containers, floor and bed coverings, drums and other items. Sheep are a source of meat, skins and wool. Camels and donkeys are used principally as pack animals, camels being best suited to long, dry-season journeys and

Table 2.4 Estimated livestock numbers in 1984, for the thirteen villages on the Rora Habab plateau , Eritrea, and for the villages of Bacla, Berige and Laba. Data are calculated from Eritrean Relief Association 1985. The number of families per village are given in Table 2.2.

	Cattle	Goats	Sheep	Donkeys	Camels
Bacla					
Total	1318	3114	912	245	58
per family	5.4	12.9	3.8	1.0	0.2
Berige					
Total	482	841	67	138	44
per family	6.3	11.1	0.9	1.8	0.6
Laba					
Total	1076	1565	667	305	42
per family	5.0	7.3	3.1	1.4	0.2
All Rora					
Total	15000	36000	4800	3200	1100
per family	7.2	17.4	2.3	1.5	0.5

Notes: 1) Pastoral people in the lowlands have more camels and goats, and fewer cattle, sheep and donkeys than families on Rora.
2) Mnzava (1980) reports a ratio of 11:1 cattle to people in Dodoma, central Tanzania, where farmers also practise agriculture together with animal husbandry.

donkeys more suited to transport of people, water, fuelwood, grain etc. over shorter distances.

A number of diseases affect these animals, the most important of which are anthrax, trypanosomiasis, rinderpest, and a variety of ecto- and endo-parasites (Semere Amlesom, Department of Agriculture, personal communication). A veterinary clinic now has been established in Bacla as a base from which to conduct a vaccination programme for all animals in the IRDS area.

Apart from grazing on crop residues, animals are led to graze and browse on common land and on uncultivated, precipitous hillslopes, usually by children between 8 and 15 years old. The relative importance of animal husbandry with grazing over wide areas, versus settled agriculture probably has fluctuated over the centuries. It appears, though, that when the Habab moved to Rora they were able to develop trade with the coast in live animals and animal skins and that crop cultivation rapidly became less prominent in their economy from perhaps the middle of the 17th century (Anthony d'Avray, British administrator for Sahel province 1943-6, personal communication). Today, both cereal cultivation and animal husbandry are important in Rora's mixed farming system, with some farmers preferring settled farming with few animals, and others relying mainly on their animals.

CHAPTER 3

VEGETATION SURVEY

INTRODUCTION AND OBJECTIVES

Eritrea has been described as having juniper woodlands over a large area and the Rora Habab plateau has been mapped as Juniperus procera (syn. J. excelsa) forest (White 1983). However, during my visits between 1984 and 1986 it became clear that Rora's woodlands had a patchy distribution and that many trees were dead. J. excelsa is apparently in decline at the extremes of its range in Africa (Hall 1984) and several elderly farmers have told me that much of the plateau's woodland has disappeared over their lifetimes. However, the vegetation of Rora has never been surveyed and the species composition of the woodlands and the potential for restoring them has not been studied.

The purpose of the vegetation survey was to examine the spatial distribution and status of the woodlands on Rora, particularly with respect to the two dominant tree species, Olea europaea subsp. africana and Juniperus excelsa. The major part of the survey was conducted in the middle of the rainy season for three main reasons. Firstly, it would be possible by July to observe flowering and/or fruiting on all tree and shrub species. Secondly, many annual and perennial grasses and herbs are in flower by this time, making their identification easier than at other times. Lastly, any very young tree seedlings which germinated from the previous year's seed fall would be fairly easy to find two or three months after germination, which I assumed to coincide with the beginning of the rains. Moreover, because many livestock are removed from the plateau during the rainy season when crops are growing (Chapter 2), animal densities are at their lowest and losses of seedlings due to grazing would be at their lowest.

METHODS

Preliminary Survey

Prior to detailed study, preliminary reconnaissance of Rora Habab was undertaken by means of ground surveys and the study of false colour composite images generated from satellite data. This initial work revealed a diversity of vegetation cover and species distribution which appeared to be only partly related to differences in elevation, aspect and human activity across the plateau.

Ground Survey

Initial ground reconnaissance was undertaken during three visits to Rora between 1984 and 1986 in the months June to August, and November to January. During these visits, I interviewed farmers about their approach to land management and uses for plants, in the villages of Bacla, Shamotet, Muni, Endlal and Berige (Fig. 2.1). Interviews were undertaken near people's houses and also while walking with farmers in order to facilitate plant collection and recording of species distributions.

Between December 1985 and January 1986, I undertook a pilot survey of soils and vegetation in a 0.9 km^2 watershed (Abhaklu ኣብሃኽሉ, Fig. 3.1) in the village of Bacla. This survey was designed to guide further research and had two purposes; to investigate the spatial variation of soil chemical and physical characteristics on eroded and less eroded soil, under different vegetation, and on farmed and un-farmed land, and secondly, to examine the distribution and relative densities, by size class, of the common woody perennials. To do this, four transects between 200 m and 400 m long were laid out perpendicular to the main channel of the watershed. All trees ≥ 10 cm at

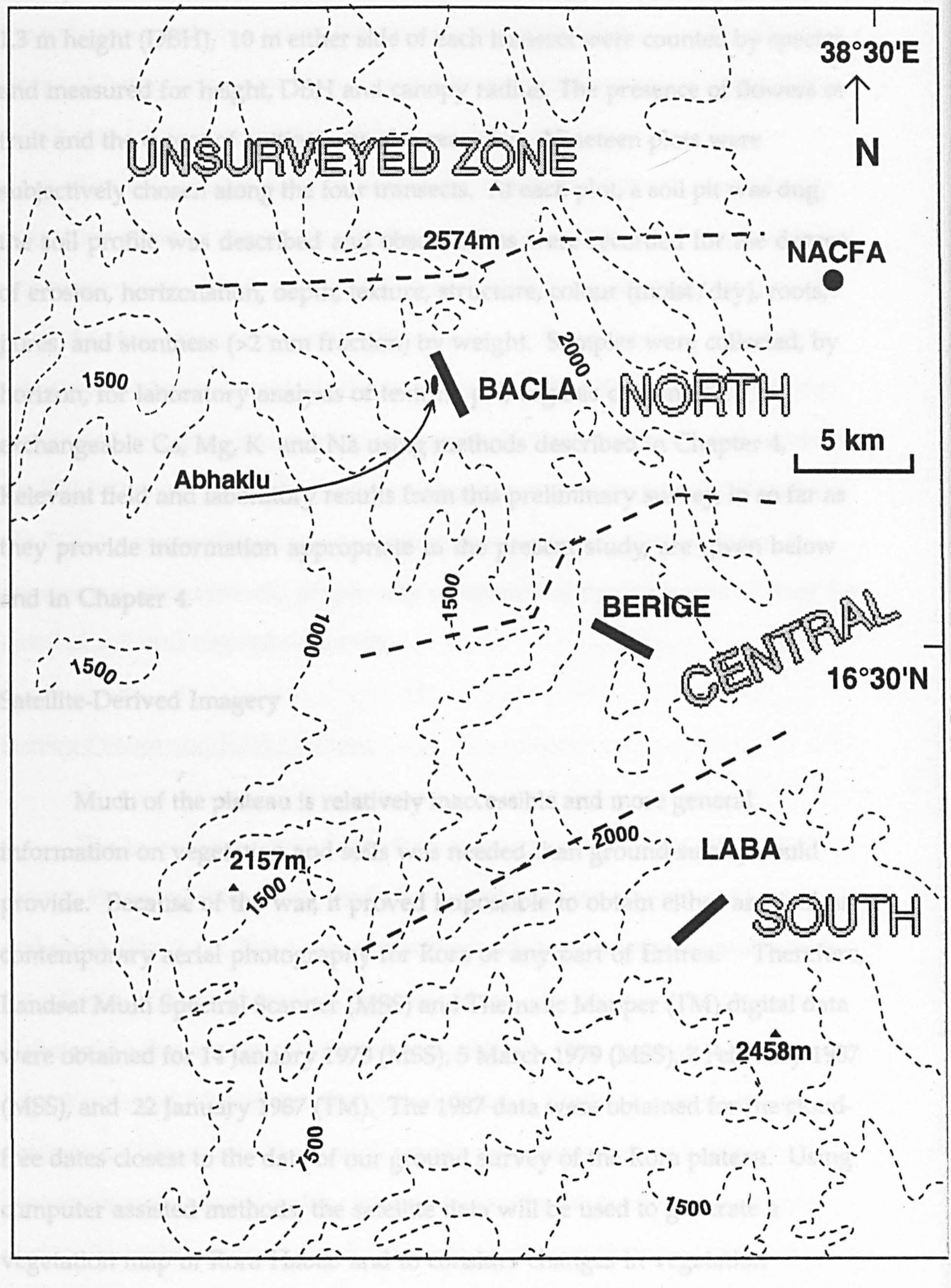

Fig. 3.1. Study site on the Rora Habab plateau, northern Eritrea. Dashed lines demarcate the vegetation zones, determined from ground survey and study of false-colour-composite satellite images (see text). Solid bars show the locations of the transects used for vegetation and soil survey in the villages of Bacla (north), Berige (central) and Laba (south). Solid oval shows the location of the Abhaklu watershed which was surveyed in 1985.

1.3 m height (DBH), 10 m either side of each transect were counted by species and measured for height, DBH and canopy radius. The presence of flowers or fruit and the extent of cutting was also recorded. Nineteen plots were subjectively chosen along the four transects. At each plot, a soil pit was dug, the soil profile was described and observations were recorded for the degree of erosion, horizonation, depth, texture, structure, colour (moist/dry), roots, pores, and stoniness (>2 mm fraction) by weight. Samples were collected, by horizon, for laboratory analysis of texture, pH, organic carbon and exchangeable Ca, Mg, K and Na using methods described in Chapter 4. Relevant field and laboratory results from this preliminary survey, in so far as they provide information appropriate to the present study, are given below and in Chapter 4.

Satellite-Derived Imagery

Much of the plateau is relatively inaccessible and more general information on vegetation and soils was needed than ground survey could provide. Because of the war, it proved impossible to obtain either archival or contemporary aerial photography for Rora or any part of Eritrea. Therefore, Landsat Multi Spectral Scanner (MSS) and Thematic Mapper (TM) digital data were obtained for 14 January 1973 (MSS), 5 March 1979 (MSS), 7 February 1987 (MSS), and 22 January 1987 (TM). The 1987 data were obtained for the cloud-free dates closest to the date of our ground survey of the Rora plateau. Using computer assisted methods, the satellite data will be used to generate a vegetation map of Rora Habab and to consider changes in vegetation between 1973 and 1987. For our initial purposes, however, false colour composite (FCC) images were obtained to enable visual examination of plant community distributions on the plateau and surrounding slopes. The FCC images were constructed from digital data by assigning each of three bands to the red, green and blue colour guns on a monitor and displaying the resulting image. Photographs were then obtained by saving the image as a digital file which was converted to a negative.

The FCC images were processed, by colour assignment, to emphasise vegetation cover of perennials which was possible because all images were for dry season dates. Study of the FCC images confirmed observations from the ground survey that some parts of Rora had a moderate cover of trees while others were almost devoid of woody perennials. The Rora plateau has been partitioned into four areas, based on topography and extent of tree cover, by the EPLF Department of Agriculture. These four areas appeared different on the FCC images and during ground reconnaissance and they provided an appropriate and relatively simple way of stratifying the landscape of Rora for detailed soil and vegetation survey.

Survey Design and Field Methods

The boundaries between the four areas into which Rora can be divided are not sharp but may conveniently be described as northwest, north, central, and south (Fig. 3.1). The north area is the most densely wooded and includes the villages of Bacla, Shamotet, Zagir and Muni. The south, which includes Hahot and Laba has almost no woody perennials. The northwest (including Rora Keyeh and Mariet) and the central (Ketanit, Endlal, Berige) areas are characterised by sparse cover with woody perennials largely confined to cemeteries and seasonal water courses. Following interviews with villagers during the preliminary survey, further information on their uses for local plants was obtained in the course of 60 follow up interviews. These were conducted as formal interviews at people's houses and informally on walks with villagers during which we examined, recorded and collected specimens. Uses for common woody perennials are given in Chapter 2.

Once the plateau had been stratified into four areas based on vegetation cover and extensive reconnaissance had been completed, transects were laid out to further investigate plant and soil distributions.

Location and Description of Transects

Three of the four areas were studied in detail. Because of transport and logistical difficulties, the northwest area could not be included in this study. Three 2.6 km-long transects were laid out in the villages of Bacla (north), Berige (central) and Laba (south) (Fig. 3.1). The north and central transects were surveyed in July to August 1987. The south transect was surveyed in early January 1989. The locations of these transects were subjectively chosen as representative of each of the three areas. Each transect then was laid out as a random, non-aligned grid with thirteen 200 x 200 m grid squares running the length of the transect on alternating sides (Appendix 3). One 20 m radius plot was randomly located in each grid square. Representative soil pits were dug at the centre of each plot for profile description and sample collection.

An additional plot at Shamotet, not on the transects (Fig. 2.1) was surveyed. This plot was in an area identified by village elders as having the densest woodland on Rora and had an area of 0.0625 ha, half the area of the 39 plots on the transects. Also, an additional 4 junipers and 21 olives adjacent to plots 4, 6 and 7 at Bacla were measured.

Soils methods and results from the soil survey are presented in Chapter 4. For each plot the following were measured and recorded in the field:

<u>Plot characteristics</u>:

elevation, topography, slope, aspect, land use, erosion.

<u>Trees ≥ 10 cm at 1.3 m (DBH)</u>:

location, dead trees and stumps, height (HT), DBH, canopy radius (CR), numbers of dead leaves, branches and branchlets (all living, < 10% dead, 10 to 50% dead, > 50% dead), presence of abundant hanging lichen (<u>Usnea articulata</u> (L.) Hoffm.) in the canopy, presence of canker on boles and branches (none, < 5 lesions, 5 to 20 lesions, > 20 lesions), condition of the top of the tree (living or dead), occurrence of stripped bark on the base of trees (bark intact, < 25% stripped, 25 to 50% stripped, > 50% stripped to a height of 1.5 m), presence of flowers or fruit, and the extent of cutting.

<u>Trees <10 cm at 1.3 m:</u>

A count of tree seedlings/saplings less than 50 cm and greater than or equal to 50 cm tall.

<u>Shrubs</u>:

percent cover, by species.

<u>Herbs and grasses</u>:

percent cover, (not done at Laba [south transect], which was surveyed in the dry season, 17 months after the north and central zones).

Elevation, slope and aspect were recorded using an ERA project map for Rora, an altimeter, clinometer and compass. Topography was recorded as summit, upper slope, midslope, footslope, terrace or valley bottom, and as either uniform (even) or complex following Faniran and Areola (1978:101-3). Complex slopes were designated as concave, convex or terrace. The boundaries between land use categories were unclear and plots often had more than one use. Therefore, the major land use was recorded (woodland, grazing or field) together with other features of the plot, and features of adjacent land (Table 3.1). These categories were determined by visual examination and from discussion with farmers living near to each plot.

An approximate indication of the degree of soil erosion at each plot was estimated subjectively and categorised as 1) slight, 2) moderate, or 3) severe (Table 3.1). To do this, I noted the character of the soil surface, the depth of the A horizon, and compared the level of the soil with adjacent trees. For example, numerous rills running through a red surface soil was categorised as moderate erosion. If, in addition, the exposed soil profile was primarily saprolite (as opposed to saprolite that had been transported downslope by erosion) the same soil was categorised as severely eroded. The presence of soil particles entrained in the bark of a tree, or the significant exposure of roots was taken as additional evidence of the lowering of the soil surface (Biot 1990).

The location of each tree ≥10 cm at 1.3 m was recorded on a diagram made of each plot. Most dead trees had been cut to stumps < 50 cm high. The number of dead trees and stumps were counted, and the species was identified where this was possible. Tree height was calculated trigonometrically from tape and clinometer measurements using the equation $\mathbf{H} = \mathbf{h_o} + \mathbf{D_h} \tan \mathbf{q}$ where $\mathbf{H}$ = height, $\mathbf{h_o}$ is the height of the clinometer, $\mathbf{D_h}$ is the horizontal distance between the tree and clinometer and $\mathbf{q}$ is the angle of elevation between clinometer and the top of the tree (Tovey 1982:336-7). The canopy radius (CR) was taken as the average of three randomly oriented distance measurements from the trunk to the edge of the canopy, plus the radius of the bole.

Plants formed a continuum between those that were clearly vigorous and thriving and those which appeared near to death. Therefore, a subjective assessment was made of five features (amounts of dead leaves, branches and branchlets, canker and bark stripped from the base of tree trunks) which were commonly observed in many plots and which were indicative of stress or disease. An additional four features were noted as occurring or not occurring.

Table 3.1.a. Major characteristics of plots along three transects on Rora Habab plateau, Eritrea.

NORTH TRANSECT (Bacla village)

Plot no.	Aspect (°)	Slope (°)	Major Land Use	Other features	Features of adjacent land	Erosion
1	W	29	woodland	grazing	woodland	moderate
2	NE	9	woodland	grazing	woodland	severe
3	SW	12	grazing	field	field, woodland	moderate
4	N	5	field	grazing	field, woodland	slight
5	NW	4	field	grazing	field, grazing	slight
6	N	3	field	gully	field, grazing, fuelwood	slight
7	S	2	field	grazing	field, grazing	moderate
8	S	6	field	terrace, fuelwood, grazing	field, grazing	moderate
9	SW	9	grazing	fuelwood, rocks	field, grazing	severe
10	NE	15	grazing	abandoned terraces, fuelwood	grazing, fuelwood	severe
11	SW	14	grazing	abandoned fields, fuelwood	fuelwood, abandoned fields, grazing	moderate
12	--	0	grazing	--	grazing, fuelwood	moderate
13	SW	21	grazing	woodland	grazing, woodland	severe

Table 3.1.b. Major characteristics of plots along three transects on Rora Habab plateau, Eritrea.

CENTRAL TRANSECT (Berige village)

Plot no.	Aspect (°)	Slope (°)	Major Land Use	Other features	Features of adjacent land	Erosion
1	E	2	field	grazing	field	slight
2	N	14	field	grazing, fuelwood, terrace	field, grazing, fuelwood	severe
3	NW	18	grazing	field	field, grazing, fuelwood	severe
4	W	18	grazing	swale, bare rock	field, grazing	moderate
5	N	2	field	grazing, bare rock	field, fuelwood	slight
6	E	11	grazing	rocks	field, grazing, cemetery	severe
7	E	9	grazing	threshing area, old terrace	rocky hillslope, grazing	severe
8	W	33	grazing	fuelwood	abandoned fields	severe
9	NE	15	field	grazing, terrace	field, grazing, fuelwood	severe
10	NE	4	field	footpath	field, grazing	slight
11	W	16	grazing	road, field	field, grazing	severe
12	SE	2	field	grazing	field, grazing	slight
13	--	0	field	grazing	field, grazing	moderate

Table 3.1.c. Major characteristics of plots along three transects on Rora Habab plateau, Eritrea.

SOUTH TRANSECT (Laba village)

Plot no.	Aspect (°)	Slope (°)	Major Land Use	Other features	Features of adjacent land	Erosion
1	NW	13	grazing	fuelwood	grazing	moderate
2	NW	19	grazing	fuelwood, abandoned field & house	grazing	severe
3	NW	28	grazing	fuelwood	grazing	severe
4	W	29	grazing	fuelwood	grazing	severe
5	NW	19	grazing	fuelwood	field, grazing	severe
6	S	5	field	fuelwood	field, grazing	slight
7	SW	4	field	footpath	field	slight
8	SW	7	field	terrace	field	slight
9	W	5	field	terraces	field	slight
10	SE	6	field	terraces	field	slight
11	W	7	field	--	field, terraces	slight
12	N	2	field	terrace, foot-path, fallow	field, fallow	slight
13	W	8	field	terrace, rock outcrop	field, swale	slight

These were the death of the tops of a tree, hanging lichen (Usnea articulata (L.) Hoffm.), flowers and fruit.

Many of the junipers and Rhus on Rora and nearly all of the olives had been cut by villagers for fuelwood, fodder, house construction and other uses (Table 2.1). Cutting sometimes produced plants whose form and dimensions made their status as trees ambiguous. In some cases the cutting involved selectively lopping branches but in others the whole tree was felled. Trees were felled at various heights from 10 cm to 2 m or more above the ground. Many of these felled trees had died but others remained alive with branches growing from the stumps. On some stumps a few branches had been left intact and occasionally new stems were found growing vertically from the stump. Other stumps which survived merely had a few leafy twigs growing from them. This range of conditions for felled trees created some difficulties with respect to classification, since even tall stumps with vertical stems were clearly different in form and growth habit from intact trees or trees which only had one or two branches removed.

Trees which had been felled but which were still living were therefore divided into two categories. If a tree had been felled below 1.5 m and had no vertically growing stems >10 cm dbh, it was classified as a living stump. A total of 22 junipers, 16 olives and 10 Rhus fell into this category (Table 3.2). Some of these plants had branches growing laterally up to 3 metres from the stump while others had branches which had assumed vertical growth and were, effectively, new trunks. In some cases, these plants had significant amounts of foliage and were influential in that they imposed nutrient, water and light demands on the area they occupied. Also, they were clearly capable of continued growth if left uncut, with the potential to become trees again, and some had flowers or fruits. Therefore, these plants were included in measures of density but not cover , basal area or height, and the presence of

Table 3.2 Numbers of living Juniperus excelsa, Olea europaea subsp. africana, and Rhus abyssinica trees and living stumps in the plots where they occurred (out of forty surveyed) on Rora Habab plateau, Eritrea. Felled stumps had been cut below 1.4 m and had no vertical stem ≥10 cm DBH surviving. Felled trees had been felled below 1.4 m but had at least one vertical stem ≥10 cm DBH surviving. The area of the plot at Shamotet was 0.0625 ha. All other plots were 0.125 ha.

	JUNIPER				OLEA			RHUS		
Plot	felled stump	felled tree	uncut tree	total	felled stump	uncut tree	total	felled stump	uncut tree	total
Sham -otet	0	0	13	13	0	2	2	0	0	0
north										
1	1	5	8	14	1	2	3			
2	0	1	8	9						
3					0	6	6	0	1	1
4					0	1	1			
5					0	6	6			
6					0	3	3			
7					0	2	2			
8	0	0	4	4	0	8	8	1	2	3
9	1	4	3	8	0	3	3			
10	0	0	3	3	2	6	8	0	3	3
11	6	0	2	8	2	1	3	2	0	2
12	3	0	0	3	4	2	6	2	0	2
13	7	3	1	11	5	4	9	3	0	3
central										
1					0	1	1			
2					0	5	5	0	1	1
3					0	5	5	0	2	2
4					0	6	6			
6	1	0	0	1						
7	0	1	0	1						
8					0	4	4			
9					0	2	2			
11					0	4	4			
13					0	1	1	1		1
south										
1	2	1	0	3	1	2	3	1	0	1
3	1	0	0	1	1	0	1			
7					0	1	1			
Extra [1]	0	0	4	4	0	21	21			
Total	22	15	46	83	16	98	114	10	9	19

1 additional plants surveyed growing just outside plots 4, 6 and 7 in the north.

flowers or fruit was noted but not dead leaves, branches or branchlets, canker, dead tops, lichen or stripped bark.

The second category included plants which had been felled at a height of 1.5 m or greater and had foliage, and plants which had been felled below 1.5 m but had a vertical stem ≥10 cm dbh. For example, one juniper tree in plot north 1 which had been felled at 0.5 m had a single stem growing from the stump which had a dbh of 20 cm and was 9.6 m tall with a canopy cover of 17.1 m^2. A total of 15 junipers fell into this category (Table 3.2.). These felled plants were considered as trees and all measurements and observations described above were made on them.

A count of seedlings and saplings of J. excelsa, O. europaea subsp. africana, and R. abyssinica was made. Plants in ≥ 50 cm tall and < 50 cm tall categories were counted. The percent cover of shrubs was estimated for each species using Bauer's line intercept method (Barbour et al 1987:198) with one 40 m line randomly oriented across the diameter of each plot. The percent cover of herbs and grasses was estimated by line intercept with one 20 m line randomly oriented as a radius from the centre of each plot.

RESULTS

General Characteristics of Transects and Plots

The total area of the plateau, to the boundaries illustrated in Fig. 3.1 (including the unsurveyed northwest zone), and above 1 900 m elevation, is about 420 km^2. The area of the forty plots surveyed, including the smaller plot at Shamotet, was just over 5 ha, about 0.01% of the plateau.

Tables 3.1 a, b and c summarise the major characteristics of the thirteen plots along the northern (Bacla), central (Berige) and southern (Laba) transects. The degree of heterogeneity, both within and among plots, is principally due to the topography of the plateau, and the land management practises of the last seventy years, but perhaps earlier (Chapter 2).

Rora Habab is called a plateau because it rises so prominently above the Anseba valley to the west and the Nacfa plain to the east. However, Rora is not flat but has gently rolling terrain punctuated by a few fairly steep hills and small hill ranges (Fig. 3.1). Therefore, the slopes for the plots varied between 0° and 33°. Similarly the aspect of the plots was variable and faced all directions except E and SE in the north , S and SW in the central zone, and SW, NE and E in the south (Tables 3.1a,b and c).

The heterogeneity of land use results from the fact that land is not zoned by the Habab people into discrete areas for cultivation, grazing and woods. Rather, as Plate 3.1 illustrates, fields, uncultivated land and trees may all be found close together, such as when a field is terraced, bordered by trees, and adjacent to thin or rocky soils more suited to grazing than cultivation. Also, trees are sometimes left within fields for shade purposes and fields left fallow or abandoned are grazed by domestic animals. Thus, it was not uncommon for our plots to include land with multiple uses as shown in Tables 3.1 a, b, and c.

Despite the heterogeneity within some plots, there are some important slope, land use, and erosion features which distinguish certain plots and transects from others. The least heterogeneous landscape was in the south (Plate 3.2, Table 3.1c). Here, slopes of 13° or more were moderately or severely eroded and used only for grazing and fuelwood collection (plots 1 to 5), while slopes of 8° or less were all slightly eroded fields (plots 6 to 13) (Table 3.1 c). At plot 2 in the south, which had severely eroded slopes of 19°, there were the remains of an abandoned house and field. It was not possible to determine whether this house and field were in use prior to the severe erosion evident today.

The landscape in the central zone (Plate 3.3, Table 3.1 b) was only slightly more heterogeneous than that in the south. Although small clumps of trees were found along seasonal water courses and in cemeteries, none of these fell in our plots. The slight increase in complexity was due not to additional features in the plots, but to the fact that two cultivated plots (2 and 9) were on steep, eroded slopes. There also was evidence in the central zone village of Berige of abandoned fields on very steep terrain (close to plot 8) and our transect traversed several such areas. Five of the six plots in which grazing was the major land use were severely eroded (plots 3, 6, 7, 8 and 11) and the other, plot 4, was moderately eroded.

The landscape at Bacla, in the north, was the most heterogeneous of the three zones surveyed, principally due to the presence of woodlands in plots 1 and 2 (Plate 3.4, Table 3.1 a). The soils of the woodland in northern plot 1 were moderately eroded and those of woodland in plot 2 were severely eroded. Of the six plots where grazing was the major land use, three were moderately eroded (plots 3, 11 and 12) and three were severely eroded (plots 9, 10 and 13). Abandoned fields were found on steep slopes at Bacla between plots 10 and 12, and in several areas within 500 m of the transect. Abandoned terraces also were found at plot 10 (15° slope) although it was not clear whether these indicated the presence of now-abandoned fields.

In summary, the major land use of all plots was either grazing or field, except from plots 1 and 2 in the north which were located in woodland. These two plots had no fields close by but were heavily grazed. Almost all fields were on slopes of ≤8° and had slight or moderate erosion, while grazed or woodland plots were on slopes of >8° and had moderate or severe erosion (Table 3.3). The exceptions to this were the severely eroded fields in central zone plots 2 and 9, which have slopes of 14° and 15° (Table 3.1 b), and the moderately eroded, but flat grazing land at plot 12 in the north which was on the nose of a ridge surrounded by steep grazed slopes (Table 3.1 a). These results conform with farming practices on Rora where cereal cultivation is practised in valleys and on shallow slopes.

Table 3.3 Numbers of plots according to average hill-slope, major land use, and erosion categories for thirty-nine plots on Rora Habab plateau, Eritrea.

Slope	Major Land Use	----- Erosion category ----- slight	moderate	severe	total
≤8°	field	15	3	0	18
	grazing	0	1	0	1
>8°	field	0	0	2	2
	grazing*	0	5	13	18
total		15	9	15	39

* Includes plots 1 and 2 in the northern zone whose woodlands had other uses (e.g. cutting, medicinal plants) in addition to grazing.

The foregoing brief description of the plots and landscapes along and adjacent to the three transects provides a background against which to examine vegetation and soils in more detail.

Vegetation

The most striking features of vegetation revealed by our survey were the differences in density, percent cover, and basal area of junipers and olives among plots and between transects, and the large number of trees which were either dead or had dead above-ground parts. Even in the densest and most species-rich plot there were clear indications of management, with grazing and tree cutting strongly evident throughout the plateau. In fact, no part of the plateau could be described as undisturbed although there were a few locations where grazing and cutting seemed slight. These less disturbed sites were found only in Bacla and Shamotet in the north of the plateau (Fig. 3.1), where they occupied up to 3 km^2. We surveyed one such area in Shamotet, the results of which are given below. Before considering the quantitative floristic measurements made at each plot, some general features of J. excelsa and O. europaea subsp. africana on the Rora Habab plateau will be presented.

A total of 61 junipers and 98 olives ≥ 10 cm dbh were found in the forty plots surveyed. This included felled trees which had stumps >1.5 m high, or ≥10 cm dbh, trees in the plot at Shamotet, and 25 trees (4 juniper and 21 olive) which were growing just outside plots 4, 6 and 7 in Bacla. Table 3.4 shows the percentage of these plants which had dead leaves, branches or branchlets, canker on the boles and branches, dead tops, bark stripped from the base of boles, significant amounts of hanging lichen in the canopy, and flowers or fruit. Many living trees of both species had significant numbers of dead leaves, branches and branchlets, in excess of what might be considered "normal"

Table 3.4 Field observations on the condition of Juniperus excelsa and Olea europaea subsp. africana trees from Rora Habab plateau, Eritrea. Data are percent of trees ≥10 cm dbh and >2 m tall.

Plant part	Condition	Juniperus (%) (n=61)	Olea (%) (n=98)
Leaves	all living	45	93
	<10% dead	32	7
	10-50% dead	10	0
	>50% dead	13	0
Branches	all living	70	76
	<10% dead	18	15
	10-50% dead	4	6
	>50% dead	8	3
Branchlets	all living	26	84
	<10% dead	15	9
	10-50% dead	13	3
	>50% dead	46	4
Canker	none	16	na
	<5 lesions	28	na
	5-20 lesions	25	na
	>20 lesions	31	na
Top of tree	dead	15	1
Bark[1]	intact	99	62
	<25% stripped	1	10
	25-50% stripped	0	8
	>50% stripped	0	20
Lichen[2]	present	55	61
Flowers	present	24	20
Fruit	present	24	2

1 On bole of tree to 1.5 m height.
2 Usnea articulata (L.) Hoffm.

mortality for evergreen trees. This mortality appeared to be unrelated to wounds from cutting or to grazing damage.

Dead leaves were found in moderate(10 to 50% dead) or numerous (>50% dead) amounts on 23% of junipers, but no olives had more than a few dead leaves. More than 10% of the branches were dead on 12% of junipers and 9% of olives. More than 10% of the branchlets were dead on 59% of junipers, but on only 7% of olives. Canker was found on 84% of the junipers surveyed, and 56% of the surveyed junipers had more than 5 lesions. The tops of the trees were dead in 15% of the junipers but only in 1% of the olives. Only 1% of the junipers but 38% of the olives had bark stripped from the trunk. Over half of the junipers and olives surveyed had Usnea articulata lichen hanging from the canopy. Flowers were found on 24% of the junipers and 20% of the olives. J. excelsa is dioecious (Hall 1981) and the flowers of O. europaea subsp. africana are bisexual (Heywood 1985:226). Fruit was also found on 24% of the junipers (not necessarily the same plants that were flowering) but only on 2% of the olives (Table 3.4).

Species Distribution and Density

The distribution of vegetation shows several important trends from north to south along the plateau and within each of the three transects. These will be discussed by tree species, and then for smaller plants.

Trees

Density

The area of the plots was 0.125 ha, except the plot at Shamotet which was 0.0625 ha. The numbers of trees per hectare, therefore, may be estimated by multiplying by 8 plots per hectare (16 for Shamotet). The density of total living trees was much greater in the north of Rora than in the central or southern zones, ranging between 1 and 23 trees per plot in the north, and 0 to 7 trees per plot in the central and southern zones (Table 3.5). This pattern was similar for the density of seedlings which, for seedlings < 50 cm tall, ranged from 0 to 134 in the north, 0 to 27 in the central zone, and 0 to 30 in the south of the plateau. However, there were more dead trees in the central zone than in the north or the south, although plot 13 in the north had the greatest number of dead trees (27).

The greater number of junipers in the north is particularly striking. Seven of the plots in the north had living juniper trees, with plot 1 having 14 junipers, whereas only two of the 26 plots in the central and southern zones had living junipers and the maximum number was 3 trees (plot 1 south, Table 3.5). Eleven plots in the north had juniper seedlings >50 cm tall with plots 1 and 2 having 70 and 75 seedlings >50 cm tall. These two plots also had the greatest numbers of juniper seedlings <50 cm tall (10 and 63) although all other northern plots had either none or few seedlings <50 cm tall. There were almost no juniper seedlings in the central or southern zones of the plateau. Two plots in the central zone and one in the south had 1 seedling >50 cm tall, while no juniper seedlings <50 cm tall were found in any central or southern plots. There were no dead junipers in the central or southern zones but 5 plots in the north had between 2 and 17 dead junipers.

The average number of living olive trees in the north was the same as the average number of living juniper trees although the evenness of the distribution of olives along the northern transect was greater than for junipers, ranging from 0 to 9 trees (Table 3.5). The central zone of the plateau had between 0 and 6 living olive trees and living olives were present in 8 of the 13 central zone plots. Living olives were scarce in the south of the plateau with between 1 and 3 trees found in only 3 plots. There were more olive seedlings in the north of the plateau than in the central zone, which in turn had more olive seedlings than the southern zone. In the north, plot 8 was the only

Table 3.5 Numbers per plot of living (L) and dead (D) Juniperus excelsa, Olea europaea subsp. africana and Rhus abyssinica trees ≥10 cm at 1.3 m high, and numbers of seedlings <50 cm and ≥50 cm tall along three transects and at Shamotet on the Rora Habab plateau, Eritrea. The area of the plots was 0.125 ha, except Shamotet which was 0.0625 ha.

Plot	Juniperus				Olea				Rhus				Total			
	L	D	<50	>50	L	D	<50	>50	L	D	<50	>50	L	D	<50	>50
Sham -otet	13	1	4	34	2	0	3	0	0	0	0	0	15	1	7	34
north																
1	14	2	10	70	3		29	12					17	2	39	83
2	9	9	63	75			71	32					9	9	134	107
3					6			1	1				7			1
4			1		1		2	1					1		3	1
5				1	6		6	4					6		6	5
6				1	3		4	2					3		5	3
7				1	2		7	1					2		7	2
8	4			4	8				3				15			4
9	8		3	9	3		22	2					11		25	11
10	3			3	8		11	3	3				14		11	6
11	8	2	1	7	3	1	18	8	2				13	3	19	15
12	3	6		5	6	2	43	33	2				11	8	43	38
13	11	17		6	9	10	10	7	3				23	27	10	13
Median	3	0	0	4	3	0	10	3	0	0	0	0	11	0	10	6
Mean	4.6	2.8	6.0	14.2	4.5	1.0	17.2	8.2	1.1	0	0	0	10.2	3.8	23.2	22.2
central																
1					1		2						1		2	
2					5	21			1		2		6	21	2	
3				1	5	12	5		2		1		7	12	6	1
4					6	10	5	3					6	10	5	3
5							1								1	
6	1					11	27	5					1	11	27	5
7	1			1		3	12	2			1		1	3	13	1
8					4	16	2	1			1		4	16	3	1
9					2	12	16	10	1			1	3	12	16	11
10																
11					4	2	10	9					4	2	10	9
12						4								4		
13					1	5	12	9				1	1	5	12	10
Median	0	0	0	0	1	5	5	1	0	0	0	0	1	5	5	1
Mean	0.2	0	0	0.2	2.2	7.4	7.1	3.0	0.3	0	0.4	0.2	2.8	7.4	7.5	3.2
south																
1	3			1	3	1	17	7	1				7	1	17	8
2						2	30	12		1				3	30	12
3	1				1	2	11	1					2	2	11	1
4						3	2	1						3	2	1
5						2	6	2						2	6	2
6						6								6		
7					1	9							1	9		
8																
9						3	1							3	1	
10																
11						1								1		
12						3								3		
13								1								1
Median	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0
Mean	0.3	0	0	0.1	0.4	2.5	5.2	1.8	0.1	0.1	0	0	0.8	2.5	5.2	1.9

plot which had no olive seedlings. The density of olive seedlings <50 cm tall was greater than the density of olive seedlings >50 cm tall, in contrast to juniper where the reverse situation was found.

The distribution of dead olive trees was different from that of living olive trees. Living olives were found in 12 of the 13 northern plots but dead olives were present in just 3 plots. In only one of these, (plot 13) did the number of dead olives exceed the number of living olives (Table 3.5). In contrast living olives were found in 8 central and 3 southern plots but dead olives were found in 10 plots at both these sites. Moreover, the number of dead olives was greater than the number of living olives in all but 2 central plots and 1 southern plot.

The density of Rhus trees, living or dead, and Rhus seedlings, is strikingly less than for either olive or juniper (Table 3.5). The number of living Rhus trees is greater in the north of the plateau, ranging from 0 to 3 trees, than in the central zone, which in turn has more living Rhus than the southern zone. Rhus seedlings were not found in the north or the south of the plateau but a few were found in six plots in the central zone. No dead Rhus trees were found in the north or central zones but plot 2 in the south had 1 dead Rhus.

In addition to the differences in density between trees and among sites there were differences in cover, height, and basal area between juniper and olive among zones and within zones. These differences will be examined first in relation to plots (Table 3.6) and then in relation to species averages (Table 3.7).

For plots, percent cover was calculated by summing the cover of the individual trees and by dividing by the area of the plot (1256.6 m^2), and basal area was calculated on a per hectare basis (m^2 ha^{-1}) by summing the basal area of individual trees and multiplying by the number of plots per hectare (7.958).

Table 3.6. Percent cover and basal area, by plot, of Juniperus excelsa, Olea europaea subsp. africana and Rhus abyssinica trees along north, central and south transects on Rora Habab, Eritrea. Major land use; G = grazing, F = field, W = woodland. Plots 2 to 6, and 8 to 13 in the south had no trees, excepting the living stumps shown in Table 3.5.

		JUNIPERUS		OLEA		RHUS		TOTAL	
PLOT	land use	cover (%)	basal area (m^2 ha^{-1})	cover (%)	basal area (m^2 ha^{-1})	cover (%)	basal area (m^2 ha^{-1})	cover (%)	basal area (m^2 ha^{-1})
Sham -otet	G,W	35.2	9.4	1.0	0.6	0	0	36.2	10.0
north									
1	G,W	31.7	8.0	0.1	0.5	0	0	31.8	8.5
2	G,W	6.7	2.6	0	0	0	0	6.7	2.6
3	G	0	0	5.9	10.6	1.7	0.6	7.6	11.2
4	F	0	0	0.3	3.6	0	0	0.3	3.6
5	F	0	0	9.0	17.1	0	0	9.0	17.1
6	F	0	0	2.8	8.2	0	0	2.8	8.2
7	F	0	0	3.0	4.6	0	0	3.0	4.6
8	F	13.2	8.9	10.2	14.2	8.1	2.1	31.5	25.2
9	G	8.9	4.7	0.2	2.1	0	0	9.1	6.8
10	G	12.2	6.5	1.5	3.0	4.8	2.6	18.5	12.1
11	G	6.1	2.7	0.5	1.7	0	0	6.6	4.4
12	G	0	0	0.1	0.8	0	0	0.1	0.8
13	G	1.6	1.3	1.3	2.4	0	0	2.9	3.7
Median		**1.6**	**1.3**	**1.3**	**3.0**	**0.0**	**0.0**	**7.0**	**6.8**
Mean		**6.2**	**2.7**	**2.7**	**5.3**	**1.1**	**0.4**	**10.0**	**8.4**
central									
1	F	0	0	3.3	2.5	0	0	3.3	2.5
2	F	0	0	2.7	3.4	0.8	0.3	3.5	3.7
3	G	0	0	2.5	3.4	1.1	0.7	3.6	4.1
4	G	0	0	2.9	3.6	0	0	2.9	3.6
5	F	0	0	0	0	0	0	--	--
6	G	0	0	0	0	0	0	0	0
7	G	0.1	0.5	0	0	0	0	0.1	0.5
8	G	0	0	0.3	2.3	0	0	0.3	2.3
9	F	0	0	0.4	1.1	0	0	0.4	1.1
10	F	0	0	0	0	0	0	--	--
11	G	0	0	2.1	2.4	0	0	2.1	2.4
12	F	0	0	0	0	0	0	--	--
13	F	0	0	0.2	0.1	0	0	0.2	0.1
Median		**0.0**	**0.0**	**0.2**	**1.1**	**0.0**	**0.0**	**0.3**	**0.5**
Mean		**<0.1**	**0.4**	**1.1**	**1.4**	**0.1**	**0.1**	**1.2**	**1.6**
south									
1	G	0.1	0.1	0.01	0.4	0	0	0.11	0.5
7	F	0	0	0.1	0.7	0	0	0.1	0.7
Median		**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Mean		**<0.1**	**<0.1**	**<0.01**	**0.1**	**--**	**--**	**<0.1**	**0.1**

Table 3.7 Numbers of trees, mean canopy cover, mean basal area and mean height for individuals of Juniperus excelsa and Olea europaea subsp. africana in the twenty-five plots with living trees (of the forty plots surveyed) on Rora Habab plateau, Eritrea. Numbers are means (±1SD) of the number of trees of that species given in column labelled N. The area of the plot at Shamotet was 0.0625 ha. All other plots were 0.125 ha. The large standard deviations reflect the great differences in tree size, particularly noticeable in this small sample.

	JUNIPERUS				OLEA			
Plot	N	cover (m^2)	basal area (cm^2)	height (m)	N	cover (m^2)	basal area (cm^2)	height (m)
Sham -otet	26	17.0±8.2	449±177	11.6±2.6	4	3.2	204	3.8
north								
1	13	30.7±35.2	777±823	9.2±4.2	2	0.6	345	4.9
2	9	9.3±6.1	363±136	7.1±2.2	0	--	--	--
3	0	--	--	--	6	12.3±6.6	2228±951	9.3±2.3
4	0	--	--	--	1	3.8	4510	9.4
5	0	--	--	--	6	18.9±11.6	3588±2043	8.6±1.7
6	0	--	--	--	3	11.7±4.7	3423±800	11.4±4.4
7	0	--	--	--	2	18.6	2915	8.2
8	4	41.5±18.7	2800±388	13.2±1.7	8	16.1±14.4	2380±2229	8.1±2.1
9	7	15.9±4.8	839±477	5.5±2.4	3	0.7±0.4	887±489	4.1±1.2
10	3	51.2±34.3	2722±1223	8.2±2.8	6	3.2±2.1	640±371	5.2±1.5
11	2	38.3	1671	9.8	1	6.8	2140	3.1
12	0	--	--	--	2	0.9	525	4.3
13	4	5.0±6.6	410±413	4.3±3.9	4	4.2±4.9	748±208	4.3±0.9
mean	46[1]	26.1±26.6	1146±1042	8.4±3.9	65[2]	10.0±10.9	2452±2429	7.9±3.0
central								
1	0	--	--	--	1	41.5	3140	9.5
2	0	--	--	--	5	6.8±5.2	843±449	7.6±2.6
3	0	--	--	--	5	6.4±3.7	858±446	5.1±0.5
4	0	--	--	--	6	6.0±4.6	763±696	3.0±1.0
7	1	0.8	659	2.5	0	--	--	--
8	0	--	--	--	4	1.0±0.6	690±461	3.1±0.8
9	0	--	--	--	2	2.5	715	3.4
11	0	--	--	--	4	6.7±4.1	743±425	5.3±2.3
13	0	--	--	--	1	1.4	220	3.4
mean	1	0.8	659	2.5	28	6.5±8.0	843±641	4.8±2.4
south								
1	1	0.5	121	2.2	2	0.1	280	2.3
7	0	--	--	--	1	1.7	890	5.5
mean	1	0.5	121	2.2	3	0.6±0.9	483±366	3.3±1.9

[1] Number includes 4 junipers growing just outside plots 4 and 7 north, see text.

[2] Number includes 21 olives growing just outside plots 4, 6 and 7 north, see text.

The averages for the vegetation zones are simple means of the plot values (N=13 for each zone).

For species averages, mean cover (m^2), mean basal area (cm^2), and mean height (m) were calculated by summing the respective values for all trees of each species in that plot and dividing by the number of trees in the plot. The averages for the vegetation zones were computed by summing the respective values for all trees of each species and dividing by the number of trees in that zone.

Cover, basal area and height, by plot

The trend between transects with respect to density of the three tree species is reflected in the decline in percent cover of living trees from north to south along the plateau (Table 3.6). In the north of Rora, the total percent cover of trees ranged from 0.1% to 31.8%. In the central zone, percent cover fell to between 0% and 3.6%, and in the south the maximum cover of tree species in any plot was 0.11%. The maximum cover of juniper was 31.7% (plot 1, north), of olive was 10.2% (plot 8, north), and of Rhus was 8.1% (plot 8, north).

The total basal area of the plots in the north transect ranged from 0.8 m^2 ha^{-1} (plot north 12) to 25.2 $m^2 ha^{-1}$ (plot north 8) (Table 3.6). In the central zone the range of basal areas was narrower, with several plots having no trees or less than 0.1 $m^2 ha^{-1}$ and a maximum of only 4.1 $m^2 ha^{-1}$ (plot central 3). In the south of the plateau, basal area was 0.5 $m^2 ha^{-1}$ and 0.7 $m^2 ha^{-1}$ in plots 1 and 7 but less than 0.1 $m^2 ha^{-1}$ or zero in all other plots. The maximum basal area was 8.9 $m^2 ha^{-1}$ for juniper (plot north 8), 17.1 $m^2 ha^{-1}$ for olive (plot north 5), and 2.6 $m^2 ha^{-1}$ for Rhus (plot north 10) (Table 3.6).

Trends in the density, percent cover, and basal area reflect difference in the size structure of sampled populations of living junipers and olives between species and transects. There were more olives with large basal area than junipers (Fig. 3.2). There were more large junipers, olives and Rhus in the north than in the central or southern zones (Fig. 3.2).

At the plot level, the relationship between density of trees and percent cover is not a simple one. The canopy cover of trees normally is independent of density but correlated with basal area (Smith 1986:120, Barbour et al 1987:192). In our survey, for data averaged by plot, canopy cover and density were not correlated but mean cover, mean basal area, and mean height were correlated for both juniper and olive (Fig. 3.3 a,b, and c). However, when data for cover, basal area and height were examined for individual trees, there was either no relationship or only a weak one between them (Fig. 3.3 d,e, and f).

In summary, the density of living trees and seedlings of juniper, olive, and Rhus decreased from north to south, but there were more dead than living olives in the central and southern zones of the plateau, and these zones had more dead olives than the northern zones. The mean percent cover and mean basal area of living junipers, olives and Rhus also decreased from north to south (Fig. 3.2, Fig. 3.4, Table 3.6).

Cover, basal area and height, by species

Between-species comparisons were only possible in the north of the plateau because only two junipers ≥ 10 cm dbh were found in the central and southern zones. In the north, mean cover and mean height were greater for junipers (26.1 m^2 and 8.4 m) than for olives (10.0 m^2 and 7.9 m), but the mean basal area in the north was lower for junipers (1146 cm^2) than for olives (2452 cm^2). Where there were trees, the per-plot average cover of junipers ranged from 5.0 to 51.2 m^2 and that for olive ranged from 0.6 to 18.9 m^2. The per-plot average height of junipers ranged from 4.3 to 13.2 m and the height for olive ranged from 3.1 to 11.4 m. The per-plot average basal

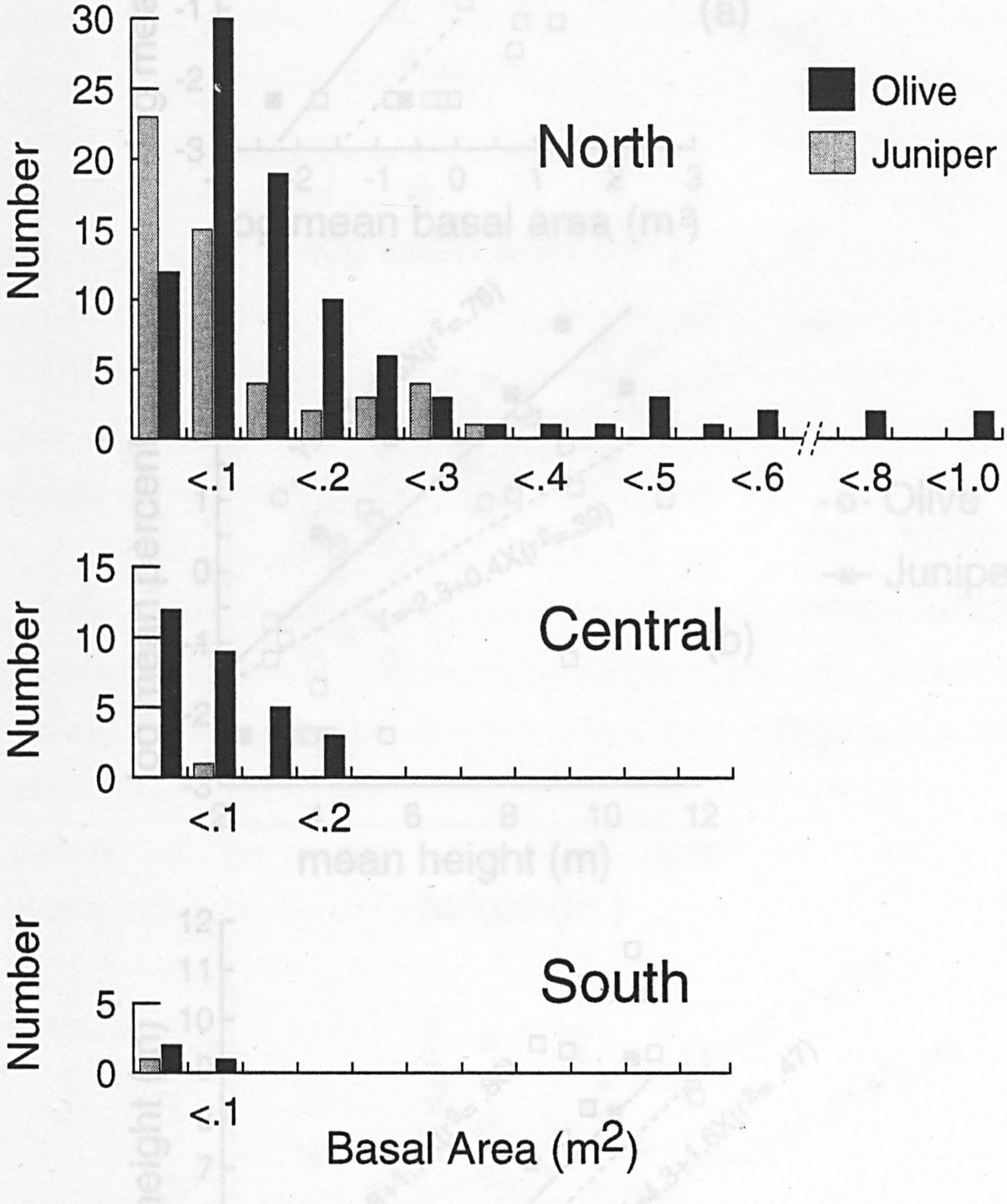

Fig. 3.2. Numbers by basal area of *Olea europaea* subsp. *africana* (olive) and *Juniperus excelsa* (juniper) greater than 10 cm in diameter at breast height along north, central, and south transects on the Rora Habab plateau, Eritrea.

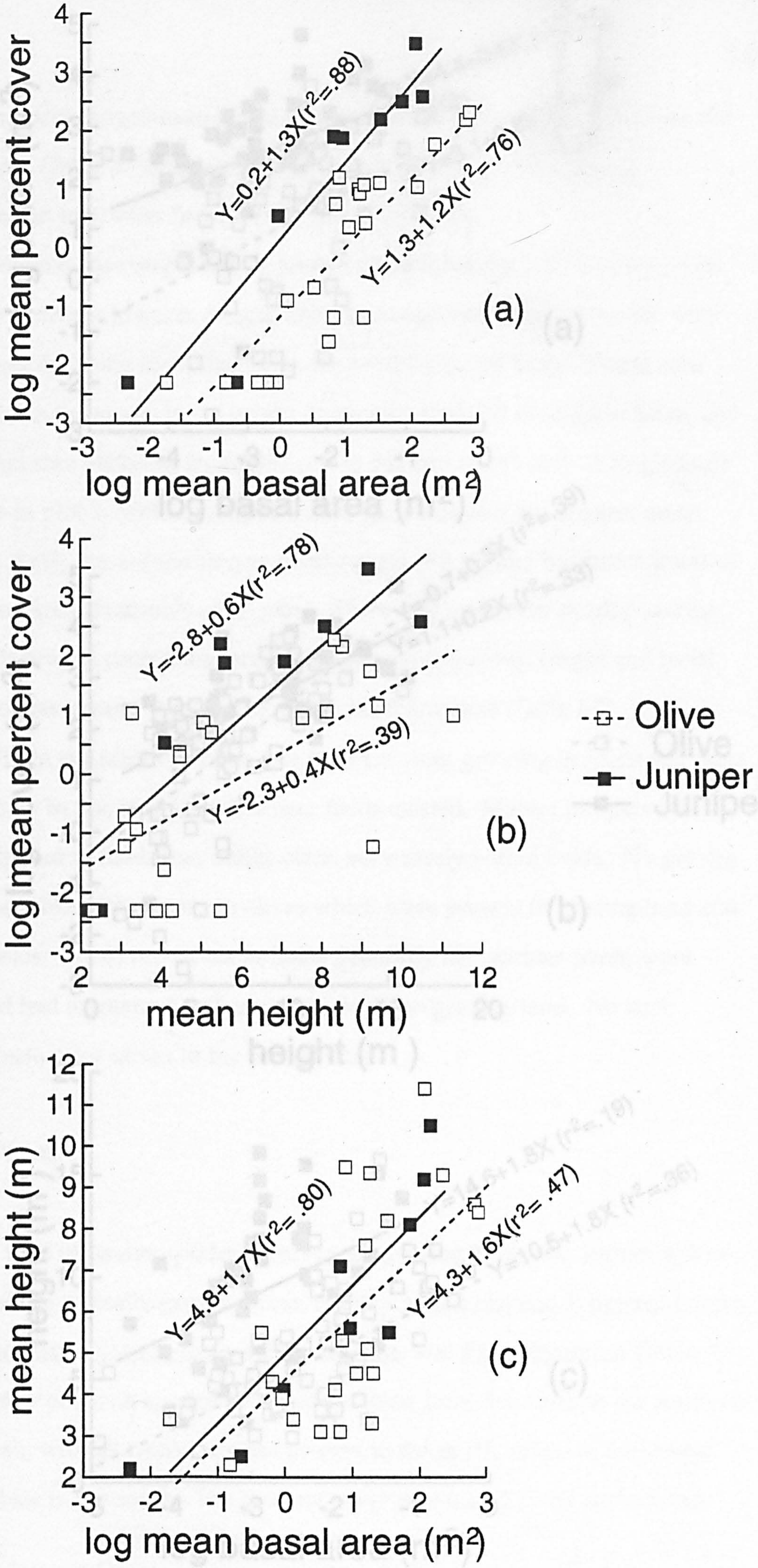

Fig. 3.3. Relationship between mean cover, mean basal area, and mean height by plot for *Juniperus excelsa* and *Olea europaea* subsp. *africana* on the Rora Habab plateau, Eritrea.

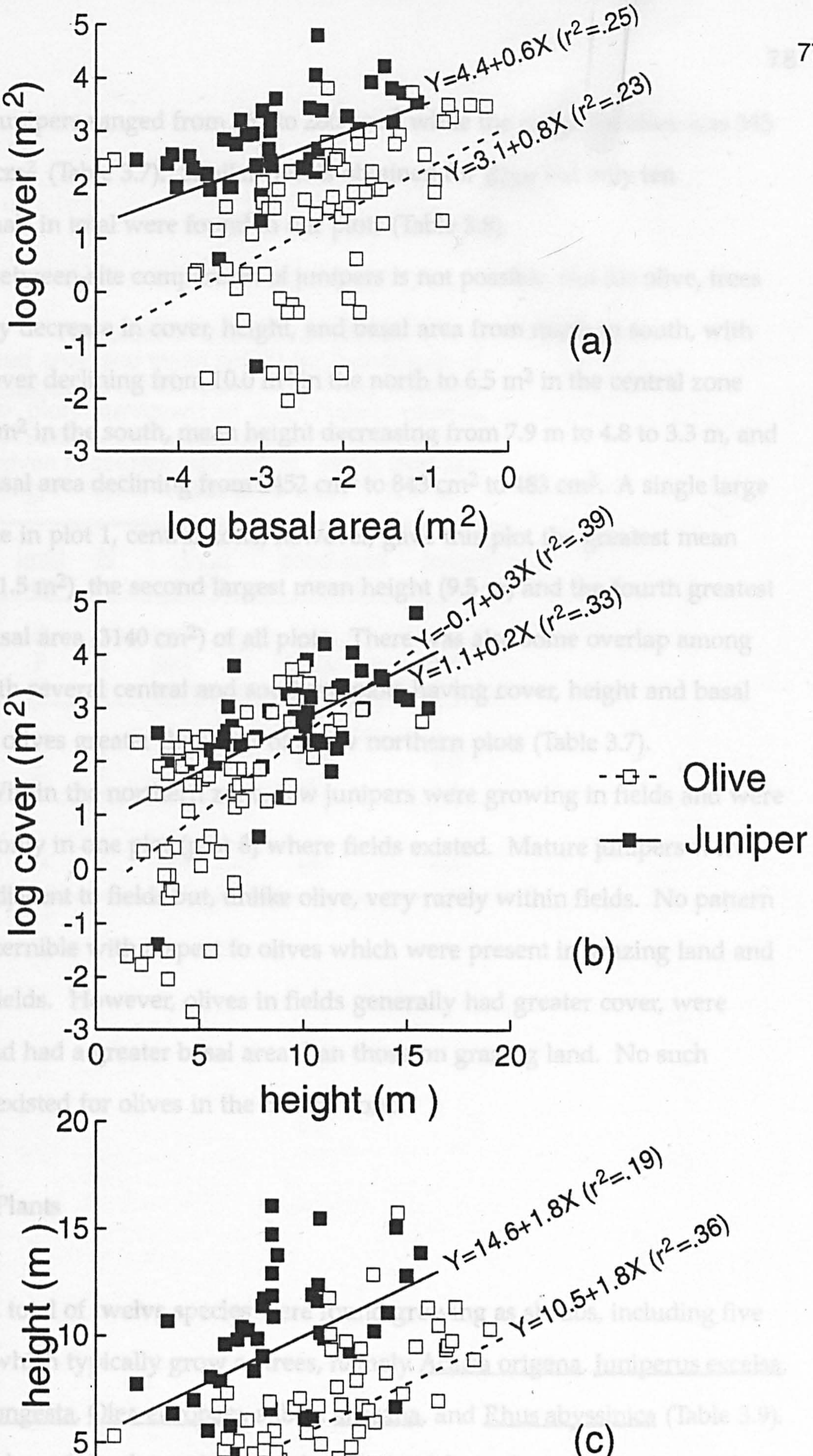

Fig. 3.4. Relationship between cover, basal area,and height for individuals of *Juniperus excelsa* and *Olea europaea* subsp. *africana* on the Rora Habab plateau, Eritrea

area of junipers ranged from 363 to 2800 cm^2 while the range for olive was 345 to 4510 cm^2 (Table 3.7). Similar trends obtained for Rhus but only ten individuals in total were found in our plots (Table 3.8).

Between-site comparison of junipers is not possible, but for olive, trees generally decrease in cover, height, and basal area from north to south, with mean cover declining from 10.0 m^2 in the north to 6.5 m^2 in the central zone and 0.6 m^2 in the south, mean height decreasing from 7.9 m to 4.8 to 3.3 m, and mean basal area declining from 2452 cm^2 to 843 cm^2 to 483 cm^2. A single large olive tree in plot 1, central zone, however, gave this plot the greatest mean cover (41.5 m^2), the second largest mean height (9.5 m) and the fourth greatest mean basal area (3140 cm^2) of all plots. There was also some overlap among plots with several central and southern plots having cover, height and basal area for olives greater than that of a few northern plots (Table 3.7).

Within the northern zone, few junipers were growing in fields and were present only in one plot (plot 8) where fields existed. Mature junipers were found adjacent to fields but, unlike olive, very rarely within fields. No pattern was discernible with respect to olives which were present in grazing land and within fields. However, olives in fields generally had greater cover, were taller, and had a greater basal area than those on grazing land. No such pattern existed for olives in the central zone.

Smaller Plants

A total of twelve species were found growing as shrubs, including five species which typically grow as trees, namely Acacia origena, Juniperus excelsa, Nuxia congesta, Olea europaea subsp. africana, and Rhus abyssinica (Table 3.9). The number of shrub species recorded declined from the north to the south of the plateau, with all twelve species present in the north, seven in the central zone and six in the south. The greatest cover was found in the north where

Table 3.8 Numbers of trees, mean canopy cover, mean basal area and mean height for individuals of Rhus abyssinica in the six plots with living trees (of the forty plots surveyed) on Rora Habab plateau, Eritrea. Numbers are means (±1SD) of the number of trees given in column labelled N. Major land use; G = grazing, F = field. These plots were 0.125 ha.

Plot	land use	N	cover (m^2)	basal area (cm^2)	height (m)
north					
3	G	1	20.7	436	7.9
8	F	2	50.7	1293	8.6
10	G	3	20.3±10.5	1095±268	4.6±0.6
central					
2	F	1	9.4	436	4.0
3	G	2	6.9	457	3.3
south					
1	G	1	0.5	121	2.2

Table 3.9 Percent cover of shrubs and herbs along north, central and south transects and at Shamotet on the Rora Habab plateau, Eritrea. Species are labelled alphabetically by the first initial of genus and specific epithet: Acacia origena, Carissa edulis, Dodonaea viscosa, Jasminum abyssinicum, Juniperus excelsa, Maytenus arbutifolia, Nuxia congesta, Olea europaea subsp. africana, Psiadia punctulata, Rhus abyssinica, Solanum schimperianum, Tarchonanthus camphoratus.
In the south, the herb layer was not estimated and plots 7 to 13 had no shrubs.

Plot	Shrub species													Herb
	Ao	Ce	Dv	Ja	Je	Ma	Nc	Oa	Pp	Ra	Ss	Tc	**Total**	**Total**
Sham-otet			10.8		25.2	0.1		0.2					36.3	15.8
north														
1		1.3	30.4		12.3	0.5			4.0		0.5	5.8	54.8	26.8
2			0.9		7.0	0.6		0.9			1.0		10.4	10.0
3													0	10.6
4													0	64.3
5						0.4							0.4	7.0
6													0	7.3
7													0	54.8
8		3.5			7.9	15.5					0.1		27.0	18.8
9	0.6		2.8		9.3		0.5	0.5					13.7	14.2
10		1.8			2.6								4.4	14.5
11			0.9		4.9	0.4		0.4		0.6			7.2	28.4
12	0.3	2.4		0.4		4.4		0.3		0.3			8.1	13.3
13		4.4	0.2			2.6						1.0	8.2	25.0
median													**7.2**	**14.5**
mean													**10.3**	**22.7**
central														
1		0.5											0.5	27.2
2						4.0							4.0	15.1
3	1.9					3.7							5.6	7.3
4		5.6				0.8							6.4	29.0
5													0	26.8
6	0.8		0.1			0.1		0.3					1.3	4.3
7													0	13.2
8	1.3					1.5			1.8	0.4			5.0	5.6
9	1.0					2.3			0.5				3.8	27.5
10													0	61.9
11						1.0			0.1				1.1	15.0
12													0	47.0
13			0.6										0.6	9.5
median													**1.1**	**15.1**
mean													**2.2**	**22.3**
south														
1		0.3			0.3	0.5		1.4					2.5	na
2	1.3		0.8			0.4		0.4					2.9	na
3			9.1		1.1								10.2	na
4			5.1			0.5							5.6	na
5			8.4					0.1					8.5	na
6			1.0										1.0	na
median													**0.0**	
mean													**2.4**	

shrubs were present in nine of the thirteen plots, ranging from 0.4% to 54.8% cover. In the central zone, shrubs were also found in nine plots but their cover was lower, ranging from 0.5% to 6.4%. In the south of the plateau, shrubs were found in only six plots and in these, cover ranged 1.0% to 10.2% (Table 3.9).

In the north, four species had greater than 5% cover as shrubs in at least one plot. These were Dodonaea viscosa, Juniperus excelsa, Maytenus arbutifolia and Tarchonanthus camphoratus. In the central zone only Carissa edulis had greater than 5% cover in any plot (plot 4) while in the south, only Dodonaea viscosa had greater than 5% cover in any plot (plots 3,4 and 5).

The most frequently encountered shrub was Maytenus arbutifolia, found in seven northern and seven central zone plots, and in three plots in the south. The cover of this species was less than 5% in all plots except plot 8 in the north where its cover was 15.5%. Dodonaea viscosa was the second most frequently encountered shrub species, occurring in five plots each in the northern and southern zones and in two plots in the central zone. In three plots in the south, this species had greater than 5% cover and in plot 1 in the northern zone, its cover was 30.4%.

All other species were recorded in only eight or fewer plots of the forty surveyed throughout the plateau. Two species, Jasminum abyssinicum and Nuxia congesta, were present in only one plot and one species, Tarchonanthus camphoratus, was found in only two plots, and all three of these species were recorded only in the northern zone (Table 3.9).

The percent cover of herbs was very similar between the northern and central zones, the only two zones for which data were obtained. Herbs and grasses were present in all plots. In the north, cover ranged between 7.0% and 64.3% and in the central zone, the range was 4.3% to 61.9%. Cover was greater than 25% in five northern and six central zone plots, and greater than 10% in all but two northern and all but four central zone plots (Table 3.9).

In summary, the inter-plot differences in vegetation density and species composition were large, particularly in the north and central zones (Tables 3.5 and 3.9, Fig. 3.5). There were also marked differences between zones. The total density, cover, basal area and height of living juniper olive and Rhus trees declined from the north to the south of the plateau, coincident with a decline in the number of juniper and olive seedlings and in the percent cover of shrubs. There were no dead junipers and almost no living junipers south of Bacla village.

There were a large number of dead trees across the plateau. The distribution of dead olives is particularly interesting with more dead olive trees in the central zone than in the south, which in turn had more dead olives than the northern zone. Furthermore, there were more dead olive trees than living ones in the central and southern zones, in contrast to the pattern for olives in the northern zone, and all zones for juniper and Rhus.

There were many juniper and olive seedlings in the north and many olive seedlings in the centre and south of the plateau. However, the high numbers are mostly accounted for by a few plots and 14 plots have 8 seedlings ha^{-1} or less (Table 3.5).

Tree Cores from Junipers at Three Sites

In order to determine the age of trees on the plateau, to relate tree age to tree diameter, height and volume, and to attempt to relate annual ring widths to rainfall records for northern Eritrea, I cored a number of trees to inspect growth rings to assess their suitability for dendrochronological analysis. I anticipated that growth rings would be clear and annual because of the pronounced unimodal distribution of rainfall at Rora (Chapter 2) where a long dry season is likely to lead to periods where cambial activity ceases. In temperate areas where winter dormancy is related to cold temperatures and trees are deciduous, tree ring analysis has proven very successful in climate

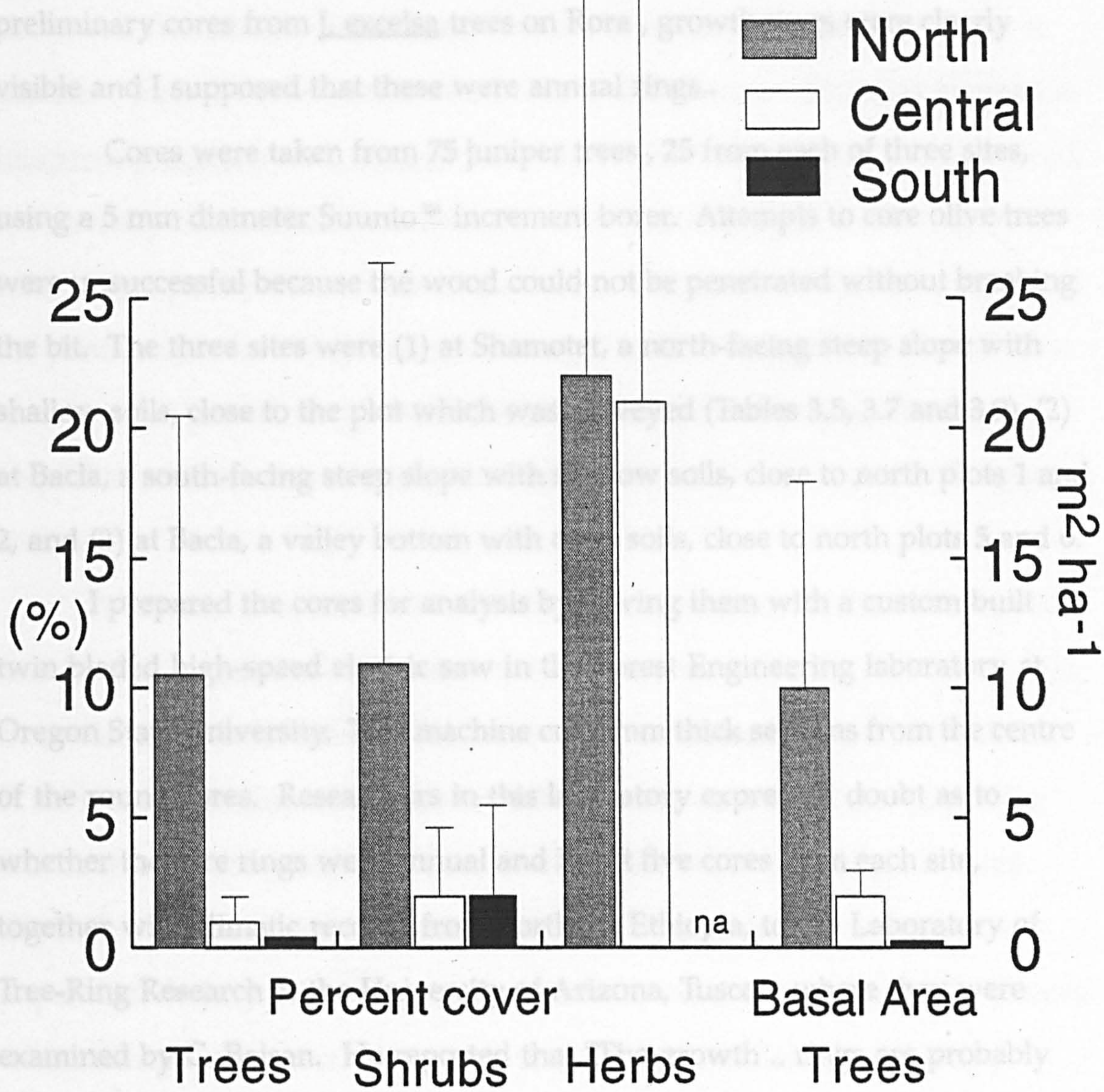

Fig. 3.5. Percent cover of trees, shrubs, and herbs and basal area of trees along north, central and south transects on the Rora Habab plateau, Eritrea. Herbs were not surveyed in the south (na). Vertical bars are + 1 SD above the means from thirteen 20 m radius plots at each transect.

studies (Pilcher and Gray 1982). In East Africa tree ring isotope records from Juniperus excelsa have been used to aid palaeoclimatic reconstruction (Krishnamurthy and Epstein 1985) and J. excelsa annual rings have been used to determine the relationship between growth rate and size (Kigomo 1985). In preliminary cores from J. excelsa trees on Rora , growth rings were clearly visible and I supposed that these were annual rings.

Cores were taken from 75 juniper trees , 25 from each of three sites, using a 5 mm diameter Suunto™ increment borer. Attempts to core olive trees were unsuccessful because the wood could not be penetrated without breaking the bit. The three sites were (1) at Shamotet, a north-facing steep slope with shallow soils, close to the plot which was surveyed (Tables 3.5, 3.7 and 3.9), (2) at Bacla, a south-facing steep slope with shallow soils, close to north plots 1 and 2, and (3) at Bacla, a valley bottom with deep soils, close to north plots 5 and 6.

I prepared the cores for analysis by sawing them with a custom-built twin bladed high-speed electric saw in the Forest Engineering laboratory at Oregon State University. This machine cut 1 mm thick sections from the centre of the round cores. Researchers in this laboratory expressed doubt as to whether the core rings were annual and I sent five cores from each site, together with climatic records from northern Ethiopia, to the Laboratory of Tree-Ring Research at the University of Arizona, Tuscon, where they were examined by C. Baisan. He reported that "The growth .. rings are probably not annual layers in many cases but represent changing conditions over varying lengths of time. .. It is not possible .. to definitively age these specimens nor relate layers from one tree to another (even though) .. variation in the width of the layers .. (is) the result of ... probably climatic variability" (C. Baisan, personal communication). Following C. Baisan's suggestions, I will examine successive cores from the same trees and search for more favourable microsites. C. Baisan gave approximate ages for three trees of between 80 and 120 years ± 20%.

DISCUSSION

Results from this survey suggest that the wooded area of Rora has decreased dramatically over recent decades and that woodlands continue to decline. Trees are now absent over much of the plateau which was mapped as Juniperus procera (syn. J. excelsa) forest by White (1983). Trees, living or dead, are virtually absent from the southern portion of the plateau and living trees have only a patchy distribution in the north. The north and central portions of the plateau also have large numbers of dead trees. We cannot be certain why, or over what period, Rora's woodlands have become so degraded but it is helpful to consider two obvious potential reasons: human activity, and climate change.

A number of observations from this survey support the idea that human activity has contributed to woodland disappearance on Rora. Almost all dead trees had been cut or felled; there were very few standing dead trees. Areas of surviving woodland were patches which occurred where cutting, grazing and cultivation are prohibited, such as in cemeteries, in places where steep slopes and/or shallow soils make cultivation impossible, and in areas of low population density. For example, there were several cemeteries on the plateau where canopy cover was 100% (Plate 3.5). Survival of the densest juniper forest, at Shamotet, has been attributed to the low population density there (G. Makkonen, Department of Agriculture, northern zone, personal communication).

The highest densities of seedlings and saplings of juniper and olive occurred under surviving patches of woodland, while few or no seedlings were found near cultivated fields. Grazing appeared to have stunted the growth of many observed olive seedlings, which had juvenile foliage and distorted shapes, in a fashion similar to that noted for olive seedlings grazed by goats in Greece (Porlingis and Therios 1976). These authors have reported that heavily grazed olive trees remain dwarf and juvenile for more than 50 years, a point worth considering in Rora where I have classified many plants as "seedlings" on the basis of their small size and juvenile leaves.

There is some evidence to support the idea that long term climate change has contributed to woodland disappearance on Rora, although the absence of long-term records means that the role of climate cannot be answered definitively. Naldini (1916:240) stated rainfall and orographic cloud was probably adequate for two harvests per year on Rora; today many areas cannot provide one reliable harvest per year. Villagers' accounts of climate change did not always agree, with some elders saying that less rain was falling these days, and other saying that there have always been dry years and wet years. There is also the confounding issue of a perceived climate change being related to the removal of trees, for if trees were as abundant as elders and Italian visitors report, they would certainly have added a good deal of moisture to the warm, rising air flows from the Anseba valley. This would have contributed to fog formation, if not to locally increased precipitation. The presence of hanging Usnea articulata lichen (Table 3.4) was noticeably related to areas of orographic cloud and fog drip from tree canopies.

In the tree cores, the fact that growth layers are not discernable as annual rings but indicate a response to changing conditions over varying time periods suggests that water, and not temperature, nutrients, or some other factor, is the primary variable limiting growth. The pattern of growth rings also suggests that J. excelsa can respond rapidly to changes in water availability.

Studies on J. occidentalis in the high desert of eastern Oregon (where temperature and moisture both limit growth seasonally) have shown that this species is not water use efficient and that water was lost from stomates which were further open than was needed for adequate carbon uptake (Miller 1990).

Other studies have shown that J. occidentalis crowns capture water very effectively, concentrating rainfall, via stem flow, to a dense root mat at the base of the trunk, and that the species has an extensive root system extending far beyond the canopy (L. Eddleman, Department of Rangeland Resources, Oregon State University, personal communication). These studies and the growth rings in the juniper cores from Rora indicate the necessity for further study on the water relations, root morphology, and water capture mechanisms of J. excelsa. They also suggest that on Rora, it may be helpful to consider other species for use in climate studies.

The disappearance of Rora's forests may have occurred gradually over several centuries, but what evidence we have suggests that it has been rapid since 1900 in the south of the plateau, and very rapid in the past one or two decades in the centre of the plateau. The accounts of villagers and of Italian visitors indicate that closed-canopy forests existed in the south at the turn of the century, but there are almost no trees or tree stumps there now. Stumps probably were removed by villagers for fuelwood, so that in an area where trees apparently were common, stumps have disappeared within six or seven decades, despite the relative aridity of the plateau. In contrast to the south, stumps outnumber living trees (olives) by as much as five to one in the centre of the plateau. On the argument just made, these trees probably have been felled in the past ten to thirty years. In the north, where woodlands are most intact, living trees greatly outnumber stumps or dead trees. Thus, of the three zones along the plateau, the rate of forest disappearance seems most difficult to gauge in the north, the only remaining area of woodland.

It is difficult to account for the different distributions of olives, which are found throughout the plateau, and junipers, which are restricted to the north. Elderly farmers in Laba and Endlal report that junipers have never been found in the south and Naldini (1916:288-9) reported that while olives dominated the Laba area earlier this century, juniper woodland became more frequent moving north from Berige (Fig. 1.2). As yet unclear local differences in climate or geology could account for this. Much of Laba is 100 m or so lower in elevation than Bacla but the higher ground there is the same elevation as Bacla. The absence of trees and associated woodland vegetation in the south makes the question moot for now. However, I will be addressing these questions experimentally over the next few years following outplanting of olive and juniper seedlings in several sites along the plateau. Future studies will also focus on soil properties, another factor which may be influential in the north-south differences in vegetation.

CHAPTER 4

SOIL SURVEY

INTRODUCTION AND OBJECTIVES

Results from my 1985 preliminary soil survey of the 0.9 km^2 Abhaklu watershed in Bacla village showed that a number of soil chemical, physical and morphological characteristics were highly variable over even short distances. The variability was principally due to differences between eroded and less eroded sites, and to differences among different land uses. In general, soils at eroded sites were shallower, lighter in colour, and had higher pH, Na, Ca and Mg, but lower P and organic carbon than soils at less eroded sites. Soils where woody perennials were relatively common and those used for cultivation were generally deeper, darker in colour and slightly lower in pH than the soils of grazing land.

In any restoration programme on Rora Habab, it will be important to have some understanding of soil characteristics and soil spatial variability. The major objectives of the survey conducted in summer 1987 and January 1989, therefore, were to investigate soil variability over a wider area and to identify more precisely those soil characteristics which were associated with eroded and less eroded soils, and with different land uses. A further objective was to investigate whether specific soil characteristics were associated with certain topographic and vegetation features across the plateau.

It is important to note that the soil survey was not designed as a mapping exercise or with soil or land management concerns in mind. Therefore, areas for survey were not delineated *a priori* on the basis of erosion, land use, topography or vegetation classes but sampled in stratified random fashion along transects as described in Chapter 3.

METHODS

Survey Design and Field Methods

Soils were examined along the same three transects and in the same plots which were sampled for vegetation on the Rora plateau (Chapter 3). Each of the 2.6 km long transects had thirteen 200 x 200 m grid cells running the length of the transect on alternating sides with one 20 m radius plot randomly located within each grid square. The transects were subjectively chosen as representative of the three areas being studied, namely north (Bacla), central (Berige), and south (Laba) but the location of the soil pits within the plots took no account of within-plot variability. For profile description and sample collection, a relatively intact soil was chosen as close to the centre of each plot as vegetation and bare rock permitted.

Since soils were sampled in a variety of sites under different conditions, an attempt was made to analyse soils according to four categories: erosion, land use, topography and vegetation. However, it was not possible to derive meaningful classes for erosion, topography or vegetation for the following reasons. Firstly, there was a marked correlation of severely eroded soils with grazing land, and slightly eroded soils with fields (Table 3.1). With land use and erosion categories reduced to two classes each (field, and grazing + woodland; slight, and moderate + severe), there were still no profiles in the slightly eroded, grazed + woodland class, and only five profiles in the moderate + severely eroded, field class. Therefore, much of the information concerning erosion was contained within the land use category.

Secondly, topographic variability with respect to morphological slope divisions, slope angle and aspect was so great that a meaningful classification would have resulted in many classes, each being represented by only one profile (Table 3.1, Appendix 4). Lastly, vegetation was absent in many of the plots so that meaningful classes for relating vegetation information to soil characteristics could not be derived. However, some of the information that would have been contained in vegetation classes also is contained in the land use categories.

In order to analyse soils by several categories, a different survey design would be needed in which categories and classes were defined *a priori* and sampling was undertaken with those in mind.

Soil profiles were sampled and described by horizon rather than by depth, although where soils had minimal horizon differentiation and boundaries between horizons were gradual, samples were less representative of discrete horizons because they may have been taken from transitional layers. One exception to this was a second profile dug at central (Berige) plot 10 which was sampled in 10 cm increments to 80 cm depth.

For each soil profile the following were measured or recorded in the field: degree of erosion, land use, horizonation, depth, texture, structure, colour (moist and dry), roots, pores, and stoniness (>2 mm fraction by weight). Soil erosion and land use at each plot were categorised according to criteria described in Chapter 3, except that prior to statistical analysis of soils data by land use, the two "woodland" plots in the north (Table 3.1 a) were combined with the "grazing" class to give just two land use classes for the whole plateau, i.e. field and grazing. Field observations of soil horizons, depth, texture, structure, colour, roots, pores and stoniness were made following guidelines in the USDA Soil Survey Manual (Soil Survey Staff 1980), Birkeland (1984:353-60) and Landon (1984). Soil pits were dug to a depth of at least 1 m or to the lithic or paralithic contact, whichever was shallower. Soils were classified to the Family level according to the USDA Soil Taxonomy (Soil Survey Staff 1975).

Laboratory Analyses

The following data were obtained on air-dried < 2 mm soil fractions:

(1) soil particle size (percent sand, silt and clay);
(2) pH in water and 1 M KCl;
(3) dichromate-oxidisable organic carbon;
(4) total N and total P;
(5) total K, Ca, Na and Mg;
(6) exchangeable K, Ca, Na and Mg;
(7) Cation Exchange Capacity (CEC);
(8) available P (bicarbonate extractable);
(9) electrical conductivity; and
(10) soluble salts.

Most analyses were conducted on all soil samples by horizon but CEC and available P were determined on a subset of samples consisting of all 39 surface horizon samples and 3 samples from the Cr horizons of north profile 2, central profile 12 and south profile 11. Electrical conductivity and soluble salts were determined on ten samples: three surface horizons from the north, two from the central zone and three from the south, and on two Cr horizons, one central and one south.

Soil particle size was determined for 50 g samples using the simplified hydrometer method (Gee and Bauder 1986). Soil pH was determined as the average of two replicate 30 g samples using a glass electrode in 1:1 soil:water and 1:1 soil:1 M KCl. Organic carbon was determined as the average of two replicate 0.5 g samples using the Walkley-Black method (Walkley 1947, Nelson and Sommers 1982).

Total N, P, K, Na, Ca and Mg were determined from a 0.5 g sample digested in H_2SO_4 and H_2O_2 with $LiSO_4$ and Se as catalysts (Setaro and Jones, unpublished 1989). Total N and total P in the acid digests were determined using a modified Indophenol assay for NH_4 and an ammonium molybdate-ascorbic acid assay for PO_4 (Setaro and Jones, unpublished 1989, Dorich and Nelson 1983, Scheiner 1976). Total Na and total K in the acid digests were determined by atomic absorption spectrophotometry (AAS) using an air-acetylene flame (Knudsen et al 1982); total Ca and total Mg were determined by AAS using an N_2O-acetylene flame (Lanyon and Heald 1982:257).

Five internal N standards were included in each of the four digestion runs: one blank tube (distilled water), two tubes with 224.4 μmole NH_4Cl, and two tubes with 224.4 μmole urea (organic N). In combination with external standards for N, these internal standards were used to assess: (1) the accuracy of predicted absolute N values, (2) the recovery of organic N in each digest run, determined by dividing the predicted urea (organic N) by the predicted NH_4Cl (inorganic N) values, and (3) variations between digest runs. Results indicated that predicted N values were 120, 117, 81 and 130 percent of actual N in the first, second, third, and fourth digests. Thus there is some indication that reported data on total N, P, K, Na, Ca and Mg for the samples from the north and south, and profiles 1 to 7 in the central zone may be higher than their actual values, while those from central profiles 8 to 13 may be lower. However, organic N recovery was 105, 101, 100, and 102 percent, varying little between digests, which suggests that there may be some other reason for the apparent differences between digest runs. For example, the external standards used for determining N colorimetrically also varied with each digest run.

Exchangeable cations were extracted with 1 M NH_4COOCH at pH 7.0 (Thomas 1982). Extracts were spiked with lanthanum (Lanyon and Heald 1982:257). Exchangeable Ca, Mg, Na, and K were determined by AAS using an air-acetylene flame (Knudsen et al 1982:231,239, Thomas 1982:160).

For all surface samples and three subsurface samples, available P was extracted from a 2.0 g sample with 0.5 M $NaHCO_3$ using a modification of the procedure of Olsen and Sommers (1982) where the ammonium paramolybdate solution contained HCl to neutralise $NaHCO_3$, a colorimeter tube was used rather than a volumetric flask, and stannous chloride was used as the reducing agent instead of ascorbic acid. Electrical conductivity was determined in a saturated paste extract using a 30 g to 50 g sample following the method of Rhoades (1982) for a subset of ten samples. The concentrations of K, Na, Ca, and Mg in the soil solution were determined from the saturated paste extract using AAS. For surface samples and three subsurface samples, CEC was determined from a 10 g sample using saturation of the soil with 1 M NH_4COOCH and replacement of the NH_4 with 0.1 M HCl following the procedure of Schollenberger and Simon (1945) with determination of NH_4-N by spectrophotometry rather than by Kjeldahl distillation and filtration.

RESULTS

Soil Formation

It is instructive to consider the characteristics of the soils on the Rora plateau in relation to the five soil forming factors described by Jenny (1941). The factors are usually written as an equation, s = *f* (cl, o, r, p, t) where a soil is a function of the climate, biota, relief, parent material and time which have exerted an influence upon it. Some argue that where these factors can be treated as independent variables, solving for one function at a time permits a reasonable, partly quantitative treatment of the soil system which has predictive value, an approach which has been reviewed and critiqued by Birkeland (1984: 162 et seq). For our purposes the factors will be considered separately to provide a conceptual framework to assist in understanding the soils of the plateau, while acknowledging that they are interdependent.

Climate

In the present day climate of Rora Habab about 75% of the 150 to 350 mm annual rainfall usually falls between late June and late August. There is a six to seven month period in which surface soils are dry and a three to four month period in which soils are dry at depth. Air temperatures vary between about 2°C and 30°C during the year but typical day-time temperatures throughout the year reach 15 to 23°C (Fig. 2.2). The lower limit for frost in Eritrea and the northern Ethiopian province of Tigre has been given as 2 500 to 2 600 m (Hövermann, cited in Messerli et al 1980:109), elevations which agree with villagers' statements that frost does not occur on Rora Habab. During the rainy season, high intensity storms normally bring flash floods on several occasions, wetting or re-wetting the soil to a depth of several centimetres. Orographic cloud, which reduces evapo-transpiration and moderates high soil temperatures, is fairly persistent across parts of the plateau during the rainy season and can occur at other times of the year.

Rora's past climate is unknown but from the historical evidence discussed in Chapter 1, and from information provided by elderly villagers and Italian archives, it seems likely that total rainfall was once greater, that the duration of the rains may have been longer and that orographic cloud was influential over a greater area for more days of the year. In eastern Africa as a whole, it is clear that climate has been varied greatly during the Quaternary and since the last glacial maximum (post-18 000 B.P.), with at least two moist periods in the past 10 000 years, but there are also climatic fluctuations whose periodicity is unclear (Flohn and Nicholson 1980, Gasse et al 1980, Hamilton 1982, Williams 1982, Nicholson 1989). The question of whether the soils we see today actually formed under today's climatic conditions therefore remains an open one but it is reasonable to suggest that many were at least partly formed under a wetter climate.

Biota

Present day biota on Rora consists of a mosaic of relict juniper - olive evergreen woodlands, cultivated fields, and grazing land, which are all managed or at least extensively used by people. The relatively open woodlands have an understory of between three and ten evergreen shrub species and several dozen grass and herb species. Woodlands are restricted to the north of the plateau where their distribution is patchy. Land that is used for grazing sometimes supports a few trees and shrubs but is mostly bare or has less than 20% cover of grasses and herbs. Most of the flatter areas of the plateau are cultivated for wheat and barley production. In these areas, isolated trees and shrubs may be found at the margins of fields or within fields in the northern portions of the plateau. Livestock, principally goats and sheep, are grazed freely in most areas but their access to cultivated land is restricted during the crop growing season. The large numbers of animals which are ranged as flocks and herds may influence soil compaction locally and certainly increase erosion on unstable hillslopes where I have often seen livestock displace soil aggregates and rocks, causing them to fall downslope.

Soil fauna on Rora need to survive prolonged drought. I have found, but not counted, nematodes and body parts from small arthropods using a microscope but have only rarely found larger soil fauna such as termites, ants and beetles in whole soils. The influence of soil fauna on soil development on Rora is unknown but presumably fluctuates in relation to soil moisture, with a surge in microbial populations following the first rains and increasingly limited microbial activity as the dry season progresses.

From the evidence of elderly farmers, Italian archives and old maps (Chapters 1 and 2), it seems that Rora Habab had very extensive juniper-olive woodlands until about seventy years ago. How much of the plateau was relatively undisturbed until the Italian colonial period is not known but since deer, wild pigs and even leopards have been recorded as living on Rora until early this century, it is likely that some portions of the plateau had little human activity until fairly recently. Many of Rora's soils, then, probably formed under conditions in which evergreen, open woodland was the dominant vegetation, domestic animals had less impact on the landscape than they now do, and where greater vegetation cover probably made soil erosion a less significant factor than it is today.

Relief

Most of the Rora plateau exceeds 2 000 m in elevation, where winds are generally less strong and precipitation is higher than in the surrounding lowlands. In these circumstances water is mainly responsible for the removal and transport of sediment (Messerli et al 1980:91). On the eastern and western flanks of Rora, however, strong updrafts from the Inkema and Anseba drainages may make wind erosion a significant factor locally.

The topography of Rora is characterised by rolling terrain with slopes of 1° to 20° and occasional steep hills which have slopes of 30° or more. Slopes faced all compass directions (Table 3.1). In many of the shallow valleys, which are up to 0.5 km wide, flood waters flow across the soil surface at moderate speeds, fanning out across fields or infiltrating the soil behind recently built terraces. In steeper areas, runoff is faster and rills and small gullies may be found. In these drainages, seasonal streams frequently overtop their banks, creating erosional surfaces on steeper slopes and depositional surfaces and increased moisture infiltration on gentler slopes. Elderly farmers report that the speed of overland flow and the frequency with which seasonal streams flood have increased in their lifetime, probably as a consequence of reduced vegetation cover. Much of the rainfall received on the plateau is lost via waterfalls to the Anseba and Inkema drainages.

Parent Material

The parent material for most of Rora's soils is andesite and trachyite (Eritrean Relief Association 1985). However, four surface rock samples I collected at Laba, which appeared to be the commonest rock types there, were identified by Prof. A. Grunder at the Department of Geosciences, Oregon State University as phonolite, diorite, granodiorite, and quartzite. Granodiorite arguably is likely to dominate the parent material for Laba soils because it has a coarser grain size and weathers more rapidly than the other rock types (A. Grunder, personal communication). For some depositional soils in valleys, the parent material consists of buried soils or sediments. In some areas, rock has weathered to saprolite a metre or more in thickness.

Time

Most soil forming processes are very slow and their effect is time-dependent (Birkeland 1984). For example, soil properties associated with organic matter occur more rapidly (10^{1} to 10^{3} years) than those associated with the weathering of primary minerals (10^{4} to 10^{6} years) (Birkeland 1984:165, 194, 198). Mollisols and Aridisols with cambic horizons could form in 1 000 to 2 000 years whilst those with argillic horizons would take 10^{4} years or more (Birkeland 1984:224).

According to Birkeland (1984) the time taken for soil A horizons to reach a steady state can vary from 200 to 10 000 years while the time needed for the development of a Bt (argillic) horizon would take 40 000 to 140 000 years. Birkeland (1984:197,198) also provides data from the Sierra Nevada in California which show that more than 200 000 years is needed for small clasts of andesite to weather to the core, and from Mt. Rainier in Washington State where the weathering rinds on andesite reach 3 mm in 300 000 years.

There are many sites on the Rora plateau where andesite clasts of a centimetre or more in diameter have weathered to the core. Weathering rinds of 1 to 2 mm on exposed rocks and small pebbles on soil surfaces are common across Rora. Whether these clasts and rocks were once covered by soil or have been exposed for millenia is not known. Where they have not been transported, they indicate that soils found in situ in some sites could be very old, or that old soils may once have mantled parts of the Rora plateau, as they still do today in small areas of the Arussi and Bale mountains in Ethiopia (Hamilton 1982:152 et seq).

In some areas of the plateau soils have been eroded recently or are still eroding. Elsewhere, soils have formed comparatively recently or are still being formed by erosion processes. Indeed, the presence of buried soils in some valleys may suggest cycles of erosion and deposition (Birkeland 1984:30) in response to fluctuations in climate or, more recently, vegetation clearance. One such soil may be found in the Abhaklu watershed at Bacla (Fig. 3.1).

Summary

In summary, the soils of Rora have developed and are developing in response to many interdependent factors. Recent land-use changes, notably vegetation clearance and/or climatic change may have profoundly altered the pattern of soils and the degree of soil development which can be found today. Soils on moderate or steep slopes where vegetation has been cleared are presently eroding, apparently very rapidly, but may once have been thicker with horizons that were more developed. In valleys where gradients are gentle, soils often are depositional, receiving sediments from eroding upslope surfaces. Soils in valleys where gradients are steeper may once have been depositional or, where vegetation was dense, they may have formed in situ, but now are eroding.

If the foregoing summary characterises the general situation across the plateau there are in addition small areas on slopes where erosion is less severe or where soils are perhaps receiving sediments from higher up. Such areas are associated with small depressions where water and sediments accumulate, and on flat terraces which have a dense cover of vegetation, particularly low lying shrubs and perennial grasses and herbs.

In characterising the soils of Rora with respect to soil forming factors, the most important factor about which we have some knowledge is vegetation, the clearance of which has had clear effects on soil formation and stability. The most important factor about which we know very little is climate, which may be fluctuating with an unclear periodicity or may be gradually trending toward hotter, drier conditions (Flohn and Nicholson 1980, Lamb 1988, Nicholson 1988). Vegetation changes are taking place on a scale of decades whilst climatic fluctuations may be occurring across several temporal scales.

- Soil Chemical and Physical Properties

The most interesting aspect of surface soil characteristics on the Rora plateau were a) the large range of values of most soil properties and the inter-correlation among them, b) the differences between soil properties in the north of Rora compared to the south, and c) the unexpected relationships between certain soil properties among erosion and land-use classes. These will be considered in turn. The Booker Tropical Soil Manual (Landon 1984) has given guidelines on nutrient quantities related to soil fertility for the tropics and I use these as a basis for discussion in the following sections.

Overview of Properties and Correlations among them

Many important soil properties on the plateau are correlated with one another. Exchangeable Ca, the sum of bases, CEC and total N are strongly positively inter-correlated ($r >= 0.70$), and negatively correlated with sand (Table 4.1). Organic carbon is strongly positively correlated with the sum of bases, CEC and total N, and weakly correlated with exchangeable Ca.

Table 4.1 Matrix of positive (+) and negative (Θ) correlations among selected A horizon soil properties from 39 soil profiles on Rora Habab plateau, Eritrea; + = correlation ≥ 0.55, ++ ≥ 0.70, +++ ≥ 0.85. Data from central zone profile no. 5 are excluded from the correlation matrix (see text). A family-comparison error rate of P < .03 was determined using Bonferroni-adjusted probabilities following Wilkinson (1989:67-8).

	avail -able P	TOTAL N	P	K	Na	Ca	Mg	EXCHANGEABLE K	Na	Ca	Mg	sum of bases	CEC	C	pH	sand
av. P																
tot. N																
tot. P																
tot. K																
tot. Na																
tot. Ca				Θ	+											
tot. Mg																
ex. K	+	+		+												
ex. Na				ΘΘ	+											
ex. Ca		++														
ex. Mg										+						
sum of bases		++								+++	++					
CEC		++								+++	+	+++				
C		++								+		++	++			
pH																
sand		ΘΘ		Θ					++	Θ		Θ	ΘΘ			
clay		+		+	Θ	Θ			ΘΘ	+		+	++			ΘΘΘ

Exchangeable Na is negatively correlated with clay content and positively correlated with sand (Table 4.1).

Organic carbon ranged from 2 to 30 g kg^{-1} with a mean of 12 g kg^{-1} (Table 4.2). This is in the low to very low range for organic carbon in most soils of the world (Landon 1984:140, Bohn et al 1985:136, Brady 1990:294). These values also are low by comparison to other woodland soils in East Africa. Lundgren and Lundgren (1972:236) report values of 133 g kg^{-1} under natural Olea woodland at 2 070 m elevation, and 146 to 159 g kg^{-1} under grassland at 1 980 m elevation on the east side of Mount Meru in Tanzania. Allen (1986:135) reports values of 55 to 77 g kg^{-1} under natural forest and Acacia, Eucalyptus and Cupressus plantations at 1 660 to 1 950 m elevation on the southwest side of Mount Meru, and 1860 m elevation in the Uluguru Mountains, Tanzania. The values for organic carbon on Rora also are lower than those reported by Bono and Seiler (1985) for surface samples from 35 profiles in the highlands of Shewa region, northern Ethiopia which range from 1 to 85 g kg^{-1}, with an average of 31 g kg^{-1}.

Total N in Rora's surface soils ranged from 0.7 to 7.6 g kg^{-1} with a mean value of 2.2 g kg^{-1} (Table 4.2). This is in the low to medium range for total N given by Landon (1984:138). Parton et al (1989:155) provides a figure of 1.5 g kg^{-1} as the mean total N of 61 surface soils from ".. the tropics ..". Lundgren and Lundgren (1972:236) report total N of 14 to 17 g kg^{-1} under Olea forest or grassland on Mount Meru. Bono and Seiler (1985) report that total N varies from 1 to 10 g kg^{-1} in surface soils from Shewa region.

C:N ratios on the plateau ranged from 2.3 to 7.8 with a mean of 5.3, excluding south profile no. 13 where the ratio was 30.3. This range, excluding south 13, is somewhat lower than C:N ratios reported elsewhere. For example, Brady (1990:292) states that the long-term C:N ratio of 10 or 12 is an average for humid sites, Parton et al (1989:155) report an average of 13.7 for 61 "tropical" surface soils, Lundgren and Lundgren (1972:236) report C:N ratios of

Table 4.2 Means, standard deviations, maximum and minimum values of 20 surface soil properties from Rora Habab, Eritrea. Organic C, total N, P, K, Na, Mg, and Ca in g kg^{-1}. Available P in mg kg^{-1}. Exchangeable K, Na, Mg, Ca and CEC in cmol kg^{-1}. Values for available P exclude central zone profile no. 5, where available P was ten times higher than the next highest value. Values for C:N ratio exclude south profile no. 13, where C:N was four times the next highest value.

	organic C	total N	C:N	available P[1]	pH
mean	12	2.2	5.3	9	6.9
std. dev.	7	1.5	1.4	6	0.4
maximum	30	7.6	7.8	30	7.6
minimum	2	0.7	2.3	2	6.1
	sand (%)	silt (%)	clay (%)	CEC	sum of bases
mean	35	36	29	17.0	17.8
std. dev.	13	4	11	6.0	6.9
maximum	63	43	48	30.5	45.0
minimum	14	27	9	6.1	7.8
	exch. Ca	exch. K	exch. Mg	Ca:Mg	exch. Na
mean	13.4	0.6	3.3	4.5	0.3
std. dev.	5.6	0.5	1.4	2.2	0.3
maximum	33.9	3.1	7.8	12.0	1.0
minimum	5.4	0.2	0.9	3.0	0.001
	total P	total K	total Na	total Ca	total Mg
mean	0.8	8.6	0.8	13.5	2.5
std. dev.	1.1	3.9	0.2	4.8	1.4
maximum	7.3	14.0	1.2	23.6	5.9
minimum	0.2	2.2	0.4	5.5	0.5

9.6 to 11.4 from Mt. Meru, and Bono and Seiler (1985) report ratios from Shewa region of between 4.6 and 35.4, with an average of about 12.

The generally low organic carbon values and C:N ratios for Rora Habab compared to soils from similar elevations further south in East Africa may be explained by the relative aridity of northern Eritrea. The climate at Rora Habab is drier than the sites of Lundgren and Lundgren (1972), Bono and Seiler (1985), or Allen (1986) and would be expected to produce less litter and have slower decomposition rates. Also, there may be differences in the species of soil organisms between the sites and more pronounced seasonal constraints on their activity which could account for the low C:N ratios of Rora's soils.

Available P in Rora's surface soils ranged from 2 to 356 mg kg^{-1} with a mean of 18 mg kg^{-1}. However, the available P at central zone profile no. 5 was an order of magnitude higher than the next highest observation which was 30 mg kg^{-1} (Table 4.3). Omitting this value, the mean value for available P fell to 9 mg kg^{-1}, which is considered to be adequate for crops such as grasses and cereals whose demand for P is low, but deficient for crops with high P demand, such as potatoes and sugarbeet (Landon 1984:135). This is a somewhat surprising result in one way because if available P was used as the sole indicator of fertility and projected crop growth, one would expect potatoes to grow poorly on many of Rora's soils when in fact they have produced high yields since potato growing began in 1987 (Table 2.2). The range of available P across Rora (excluding central zone profile no. 5) encompasses the entire range of values given in the Booker Tropical Soil Manual (Landon 1984) from levels which are deficient for even low P-demand crops (less than 4 mg kg^{-1}), to levels which are adequate for high P-demand crops (more than 21 mg kg^{-1}) .

Most of Rora's soils are near neutral in pH and P fixation by Fe, Al or Ca is likely to be limited. However, the high affinity of Ca ions for phosphate

Table 4.3 Major characteristics of surface soil horizons in 39 plots along three transects in the (a) northern, (b) central, and (c) southern zones on the Rora Habab plateau, Eritrea. Texture class from Brady (1990:99); sic = silty clay, cl = clay loam, l = loam, c = clay, sl = sandy loam. **(a) - Northern zone, Bacla.**

Property	1	2	3	4	5	6	7	8	9	10	11	12	13	Mn	Sx
horizon	A	A	A	Ap	A	Ap	Ap	A	A	A	A	A	A		
depth of A (cm)	6	5	26	11	5	6	16	4	5	11	20	19	22	12	8
total depth (cm)	28	114	55	85	37	80	93	72	20	36	66	44	93	63	29
gravel (%)	1	36	18	10	10	3	0	3	57	2	65	69	1	7	7
sand (%)	18	33	35	35	33	23	24	24	38	26	19	27	22	27	7
silt (%)	40	29	35	42	34	38	41	43	27	35	33	37	40	37	5
clay (%)	42	38	30	23	33	39	35	33	35	39	48	36	38	36	6
texture class	cl	cl	cl	l	cl	cl	cl	cl	cl	cl	c	cl	cl		
pH	7.6	7.2	6.9	6.7	6.5	6.4	6.1	6.6	7.2	7.3	6.7	6.4	6.8	6.8	0.4
organic carbon (g kg^{-1})	30	15	15	4	12	5	8	17	14	20	20	25	24	16	8
total N (g kg^{-1})	4.8	2.3	2.3	1.3	3.3	1.8	2.1	3.3	2.9	4.2	4.1	4.3	4.5	3.2	1.1
total P (g kg^{-1})	1.0	0.5	0.7	0.4	0.6	0.5	0.5	0.7	0.7	0.6	0.8	0.8	0.8	0.7	0.2
available P (mg kg^{-1})	17	9	12	7	10	10	8	16	30	10	7	14	11	12	6
total K (g kg^{-1})	9.9	6.9	13.1	12.7	12.6	12.5	8.4	12.4	14.0	12.5	10.1	11.4	12.7	11.5	2.1
total Na (g kg^{-1})	0.6	0.4	0.9	0.4	0.7	0.8	0.9	0.7	0.7	0.7	0.5	0.7	0.6	0.7	0.1
total Ca (g kg^{-1})	10.2	6.5	15.0	9.2	11.9	11.7	14.5	11.9	10.0	10.9	11.4	10.5	11.2	11.1	2.2
total Mg (g kg^{-1})	0.8	0.7	0.9	0.5	1.9	1.3	2.1	0.8	0.9	0.6	1.1	4.0	5.2	1.6	1.4
exch K (cmol kg^{-1})	0.6	0.6	0.9	0.3	1.2	0.7	0.3	1.4	1.1	0.8	0.4	1.5	0.5	0.8	0.4
exch Na (cmol kg^{-1})	0.2	0.2	0.2	0.1	0.1	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.2	0.1
exch Ca (cmol kg^{-1})	25.5	16.8	14.3	7.5	12.6	11.1	12.1	12.2	14.4	19.3	18.1	14.5	21.7	15.4	4.8
exch Mg (cmol kg^{-1})	4.4	2.7	1.2	1.4	3.0	3.6	2.9	2.4	3.4	3.7	4.9	4.4	4.1	3.3	1.1
sum of bases (cmol kg^{-1})	30.7	20.3	16.6	9.3	16.8	15.7	15.5	16.4	19.1	24.0	23.6	20.6	26.3	19.6	5.6
CEC (cmol kg^{-1})	30.2	19.2	17.5	9.9	17.9	16.0	16.2	17.3	18.3	23.4	25.1	22.1	25.5	19.9	5.2
base saturation (%)	102	106	98	94	94	98	96	95	104	103	94	93	103	98	5

Table 4.3 cont'd. **(b) - Central zone, Berige**

Property	1	2	3	4	5	6	7	8	9	10	11	12	13	Mn[1]	Sx[1]
horizon	Ap	A	A	A	Ap	A	A	A	A	Ap	A	Ap	A		
depth of A (cm)	35	30	13	20	10	13	18	22	17	11	14	12	7	18	8
total depth (cm)	35	78	35	86	27	13	18	112	45	93	26	85	44	54	33
gravel (%)	13	4	17	1	0	4	17	4	25	1	17	4	19	10	9
sand (%)	30	24	27	14	29	30	28	21	31	22	25	40	39	28	7
silt (%)	34	42	35	40	37	34	36	39	37	41	38	35	33	37	3
clay (%)	36	34	38	46	34	36	36	40	32	37	37	25	28	35	5
texture class	cl	cl	cl	sic	cl	cl	cl	cl	cl	cl	cl	l	cl		
pH	7.2	6.8	6.4	7.1	7.3	7.2	7.3	6.8	6.7	7.2	7.3	7.4	7.5	7.1	0.3
organic carbon (g kg^{-1})	11	13	14	13	21	5	5	17	12	13	8	7	5	10	4
total N (g kg^{-1})	2.0	2.8	1.8	2.0	7.6	1.0	1.1	2.5	1.8	1.7	2.6	1.3	0.8	1.8	0.6
total P (g kg^{-1})	0.5	0.6	0.5	1.4	7.3	0.4	0.6	0.6	0.6	0.9	0.6	0.6	0.4	0.6	0.3
available P (mg kg^{-1})	6	6	5	9	356	7	3	4	4	30	8	10	7	8	7
total K (g kg^{-1})	13.4	10.8	14.0	9.1	10.3	12.6	3.9	7.3	8.7	9.9	12.3	9.0	12.1	10.2	2.9
total Na (g kg^{-1})	0.5	0.9	0.6	0.7	0.6	0.8	0.5	0.6	0.9	0.7	0.9	0.8	0.6	0.7	0.2
total Ca (g kg^{-1})	5.5	11.0	5.8	12.1	21.3	13.7	18.4	8.4	12.8	15.3	12.3	17.6	6.6	11.6	4.4
total Mg (g kg^{-1})	3.1	4.4	3.7	4.8	4.6	2.8	2.5	4.0	3.4	2.7	5.9	2.6	3.4	3.7	1.0
exch K (cmol kg^{-1})	1.0	0.7	0.2	0.6	3.1	0.2	0.2	0.4	0.3	1.0	0.2	0.4	0.2	0.5	0.3
exch Na (cmol kg^{-1})	0.0	0.1	0.1	0.2	0.2	0.3	0.2	0.2	0.2	0.1	0.2	0.0	0.0	0.1	0.1
exch Ca (cmol kg^{-1})	9.0	15.0	12.9	20.2	33.9	12.1	9.0	15.7	11.8	11.6	21.3	10.0	8.0	13.0	4.3
exch Mg (cmol kg^{-1})	3.4	3.6	4.1	6.0	7.8	1.9	1.7	4.4	2.9	2.7	2.0	0.9	1.4	2.9	1.5
sum of bases (cmol kg^{-1})	13.4	19.4	17.3	27.0	45.0	14.7	11.4	20.7	15.2	15.4	23.7	11.3	9.6	16.6	5.3
CEC (cmol kg^{-1})	15.1	19.6	17.1	26.2	30.5	13.0	11.5	22.9	15.2	15.6	22.5	12.7	10.0	16.8	5.0
base saturation (%)	89	99	101	103	148	113	99	90	100	99	105	89	96	99	7

1 These means and standard deviations exclude the value from plot 5, whose C, N, P and exchangeable cations had been greatly increased because the soil sampling location was used as a grain threshing area.

Table 4.3, cont'd. (c) - **Southern zone, Laba**

Property	1	2	3	4	5	6	7	8	9	10	11	12	13	Mn	Sx
horizon	A	A	A	A	A	Ap	Ap	Ap	Ap	Ap	Ap	Ap	Ap		
depth of A (cm)	14	40	6	20	15	15	11	12	15	12	32	12	15	21	16
total depth (cm)	50	40	6	20	15	65	94	55	55	82	74	91	65	55	28
gravel (%)	74	24	49	23	7	8	0	27	25	4	6	2	22	20	21
sand (%)	42	49	57	44	48	45	30	57	58	63	62	46	57	51	9
silt (%)	36	31	32	32	37	34	42	32	29	28	28	39	31	33	4
clay (%)	22	20	11	24	15	21	28	11	13	9	10	15	12	16	6
texture class	l	l	sl	l	l	l	cl	sl	sl	sl	sl	l	sl		
pH	6.8	6.5	7.1	6.8	7.2	6.9	6.7	6.8	6.5	6.6	6.7	6.6	7.0	6.8	0.2
organic carbon (g kg^{-1})	14	11	4	9	11	8	9	4	3	2	3	6	23	8	6
total N (g kg^{-1})	2.3	2.0	0.7	1.7	1.4	1.1	1.4	0.7	0.8	0.9	0.7	1.0	0.8	1.2	0.5
total P (g kg^{-1})	1.0	0.6	0.2	0.4	0.5	0.5	0.6	0.4	0.6	0.7	1.0	0.9	1.7	0.7	0.4
available P (mg kg^{-1})	4	4	2	3	16	4	6	3	6	6	7	6	13	6	4
total K (g kg^{-1})	3.2	5.0	5.5	3.4	2.2	2.9	4.6	3.2	4.2	3.2	4.0	5.3	5.5	4.0	1.1
total Na (g kg^{-1})	1.2	1.0	0.8	0.8	0.9	1.0	0.9	0.9	0.9	0.9	0.9	1.0	1.0	0.9	0.1
total Ca (g kg^{-1})	17.2	10.0	9.5	9.7	18.9	14.8	15.4	23.6	16.0	18.2	23.6	19.6	22.5	16.9	5.0
total Mg (g kg^{-1})	2.0	1.3	0.7	1.3	1.1	1.8	2.0	1.5	2.4	2.9	3.3	3.3	3.4	2.1	0.9
exch K (cmol kg^{-1})	0.4	0.2	0.3	0.3	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.1
exch Na (cmol kg^{-1})	0.7	0.7	0.5	0.6	1.0	0.7	0.6	0.7	0.8	0.6	0.5	0.7	0.5	0.7	0.1
exch Ca (cmol kg^{-1})	15.3	11.8	5.4	12.0	12.4	13.9	14.9	7.6	7.1	9.3	7.2	9.4	7.4	10.3	3.2
exch Mg (cmol kg^{-1})	4.7	3.3	1.4	3.9	3.9	4.2	5.7	2.4	2.5	3.2	2.5	3.2	2.4	3.3	1.2
sum of bases (cmol kg^{-1})	21.4	16.5	7.8	16.8	17.6	19.0	21.5	10.9	10.6	13.3	10.4	13.5	10.6	14.6	4.5
CEC (cmol kg^{-1})	20.5	15.5	6.1	18.0	14.9	15.9	20.9	8.6	9.0	10.0	9.5	12.5	9.6	13.2	4.8
base saturation (%)	104	106	128	93	118	120	103	121	118	133	109	108	110	113	11

(Landon 1984:124) and the very high levels of Ca in most of Rora's soils may mean that P is less available for plant uptake in certain areas.

Most of Rora's surface soils were clay loams, loams or sandy loams with clay contents ranging from 9% to 48%. Cation exchange capacity ranges from 6.1 to 30.5 cmol kg^{-1} with a mean of 17.0 cmol kg^{-1}, which is considered medium for most soils (Landon 1984:120). The sum of bases ranged from 7.8 to 45.0 cmol kg^{-1} with a mean of 17.8 cmol kg^{-1}, indicative of nearly 100 percent base-saturated soils (Table 4.2). Exchangeable Ca amounted to between 70% and 90% or more of the sum of all bases, with values ranging from 5.4 to 33.9 cmol kg^{-1}, and a mean of 13.4 cmol kg^{-1}.

Exchangeable K ranged from 0.2 to 3.1 cmol kg^{-1} with a mean of 0.6 cmol kg^{-1}, although since our soils were air dried, measured values of exchangeable K are likely to have been altered somewhat from field conditions (Landon 1984:125). Exchangeable K is regarded as deficient with respect to plant uptake in soils where it constitutes less than 2% of the sum of all bases (Boyer 1972, Jones and Wild 1975; cited in Landon 1984:126). This was the case in 17 of the 39 surface soils we examined from Rora Habab. Exchangeable K amounted to less than 2.0% of the sum of bases in two profiles from Bacla, five profiles from Berige and ten from Laba.

Exchangeable Mg ranged from 0.9 to 7.8 cmol kg^{-1} with a mean of 3.3 cmol kg^{-1}, which is medium to high for tropical soils (Landon 1984:125). The ratio of Ca to Mg ranged from 3 to 12 with a mean of 4.5 (Table 4.2). In soils where the Ca:Mg ratio is more than 5, Mg may become increasingly less available to plants (Landon 1984:124). In soils where the ratio of exchangeable K to Mg is more than 2, Mg uptake by plants may be inhibited (MAFF 1967; cited in Landon 1984:127). The range of K:Mg ratios in Rora's surface soils was 0.05 to 0.8. This fact, together with the low levels of exchangeable K in much of Rora, indicates that a response to K fertiliser is likely and that reasonable applications of K fertiliser would not further jeopardise uptake of Mg, which may already be reduced in some places by relatively high exchangeable Ca levels.

Exchangeable Na ranged from 0.0 to 1.0 cmol kg^{-1} with a mean of 0.3 cmol kg^{-1}. The relatively high values of exchangeable Na which were found in the south are discussed further below.

Given the fact that many of the soils in the survey were sampled from cultivated fields, I sampled one profile, central zone no. 10, by 10 cm depth increments, as well as by horizon, in order to determine the possible influence of ploughing on soil development. Seven chemical properties were analysed on the 10 cm samples from this profile (a Typic Ustropept) and the results illustrate three major processes common to many soils on the plateau. Firstly, the interacting effects on soil development of mineral weathering from below and organic additions from above are shown by the generally increasing concentrations of exchangeable K, exchangeable Mg, and pH, and decreasing concentrations of C, N and P, and Ca from the top to the bottom of the profile (Table 4.4).

Secondly, the slight increase in pH in the lower depths may be due to eluviation of exchangeable Ca and Mg from the 51 to 70 cm depth, or to the greater influence of parent material weathering in supplying these nutrients from below. These depths correspond to the Bw (cambic) and BC horizons identified in the field on the basis of increased redness and greater structural development (Table 4.4, Appendix 4, plot Berige no.10). These between-depth differences illustrate the incipient soil development typical of Inceptisols, which were found at 11 of the 39 sites on the plateau.

Finally, the profile shows higher C, N, P, Ca, and Mg in the 10 to 30 cm depth than in either the surface 0-10 cm or at depths below 31 cm (Table 4.4). This is probably a consequence of ploughing which on Rora usually reaches depths of between 8 cm and 30 cm, increasing water infiltration and transport

Table 4.4 Values for seven soil properties from samples taken at 10 cm intervals at Berige plot no. 10, Rora Habab, Eritrea.

Depth (cm)	organic C (g kg-1)	total N (g kg-1)	total P (g kg-1)	exch. K cmol kg-1	exch. Ca cmol kg-1	exch. Mg cmol kg-1	pH
0-10	14	2.2	0.8	0.9	10.8	2.3	7.0
11-20	20	4.3	1.5	1.6	17.2	4.8	7.1
21-30	7	2.7	1.8	1.6	14.8	4.2	6.7
31-40	6	1.5	1.2	1.8	11.2	3.0	6.9
41-50	3	1.2	1.3	2.1	10.7	3.4	7.1
51-60	4	0.9	1.3	2.2	10.1	3.0	7.2
61-70	3	0.9	1.1	2.4	10.0	3.8	7.5
71-80	2	0.8	1.0	2.3	10.4	4.2	7.7

of mobile surface soil constituents into lower horizons . Such ploughed horizons occurred in 15 of the 39 profiles sampled.

Surface Horizon Properties by Site

There are several important differences among the soils of the three sites, the most significant of which relate to organic carbon and particle size distribution. By chance, most of central zone plot 5 was used by villagers for threshing grain. Because this profile has high, outlying values for organic C, total N, total P, available P, and exchangeable cations, it was omitted from the by-site means and standard deviations used for between-site comparisons.

Moving from north to south, mean organic carbon in surface horizons decreased from 16 g kg^{-1} to 10 g kg^{-1} to 8 g kg^{-1}, and mean total nitrogen decreased from 3.2 g kg^{-1} to 1.8 g kg^{-1} to 1.2 g kg^{-1} (Fig. 4.1 and Table 4.3). Mean clay content in surface horizons was more than twice as high in north and central soils (36% and 35%) than in southern soils (16%), while sand content in north and central soils (27% and 28%) was just over half of that in the south (51%) (Fig. 4.2 and Table 4.3). Cation exchange capacity (CEC) decreased from 19.9 cmol kg^{-1} (north) to 16.8 cmol kg^{-1} (central) to 13.2 cmol kg^{-1} (south) (Fig. 4.5 and Table 4.3). Thus, by comparison to the north, central zone soils had 38 percent less organic carbon, the same clay content, and 16 percent less CEC, and soils in the south had 50 percent less organic carbon, 55 percent less clay content, and 33 percent less CEC. It is likely that the differences in CEC among the sites reflect an average of the differences in clay and organic matter because CEC is determined by the relative amounts of different soil colloids (clay and humus) in the soil (Brady 1990:177-83, 203).

At all three sites, the sum of bases approximately equalled or exceeded the CEC, i.e. surface soils were close to or more than 100% base-saturated, and soils were approximately neutral in pH (Fig. 4.5, Table 4.3). In soils of similar

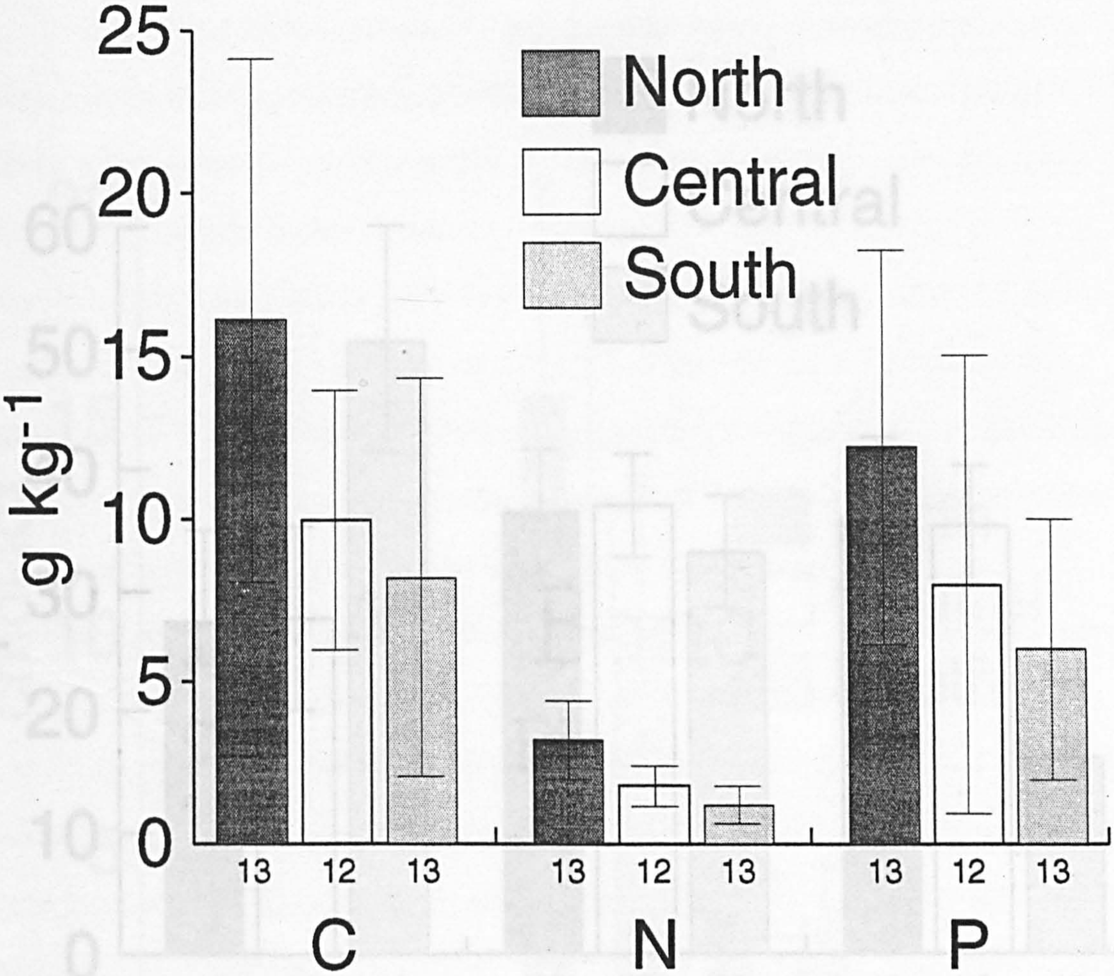

Fig. 4.1. Organic carbon, total nitrogen, and available phosphorus in surface soil horizons along north, central and south transects on the Rora Habab plateau, Eritrea. Vertical bars are ± SD from means of thirteen samples (north and south) and twelve samples (central).

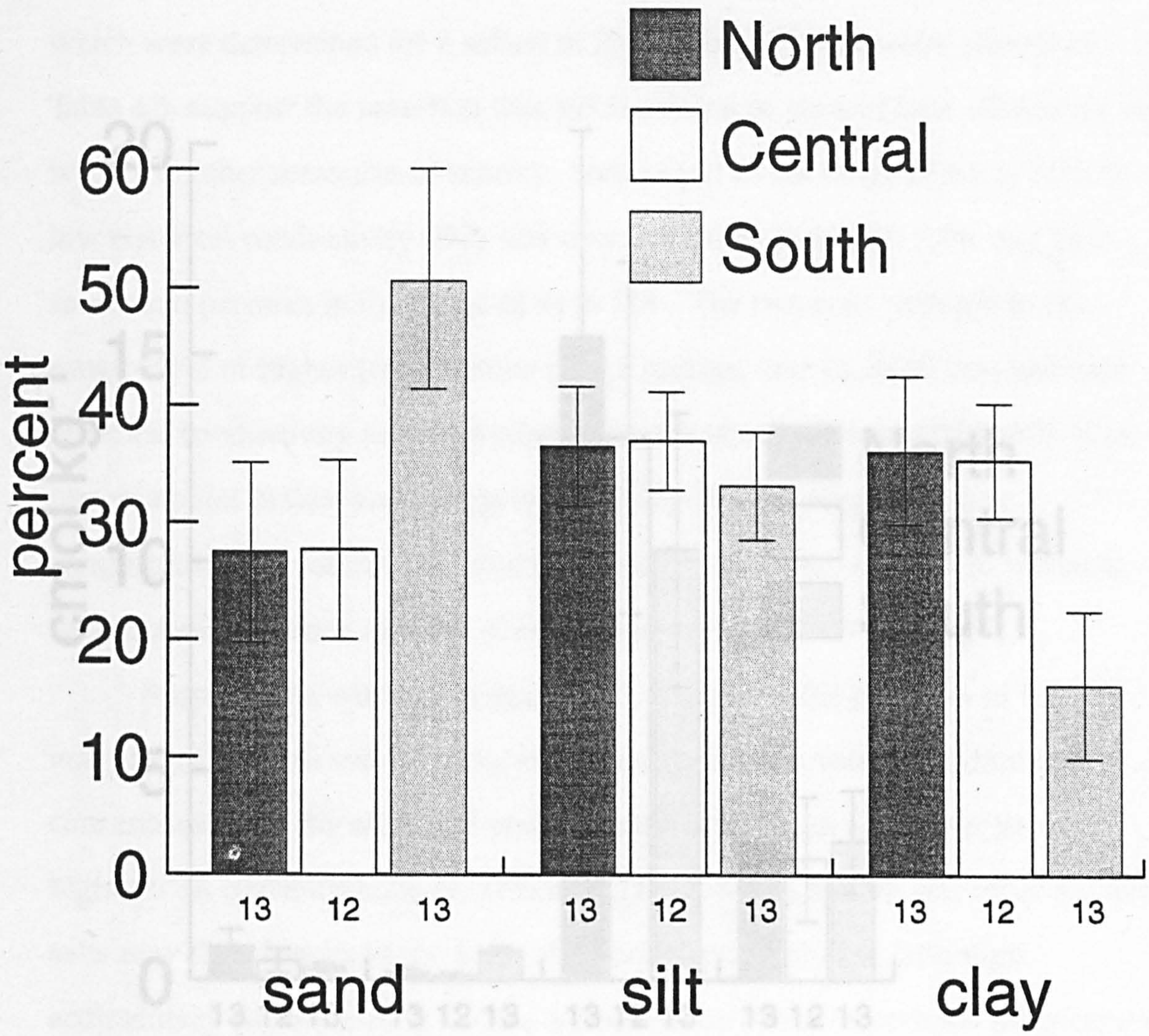

Fig. 4.2. Particle size distribution in surface soil horizons along north, central and south transects on the Rora Habab plateau, Eritrea. Vertical bars are ± 1 SD from means of thirteen samples (north and south) and twelve samples (central).

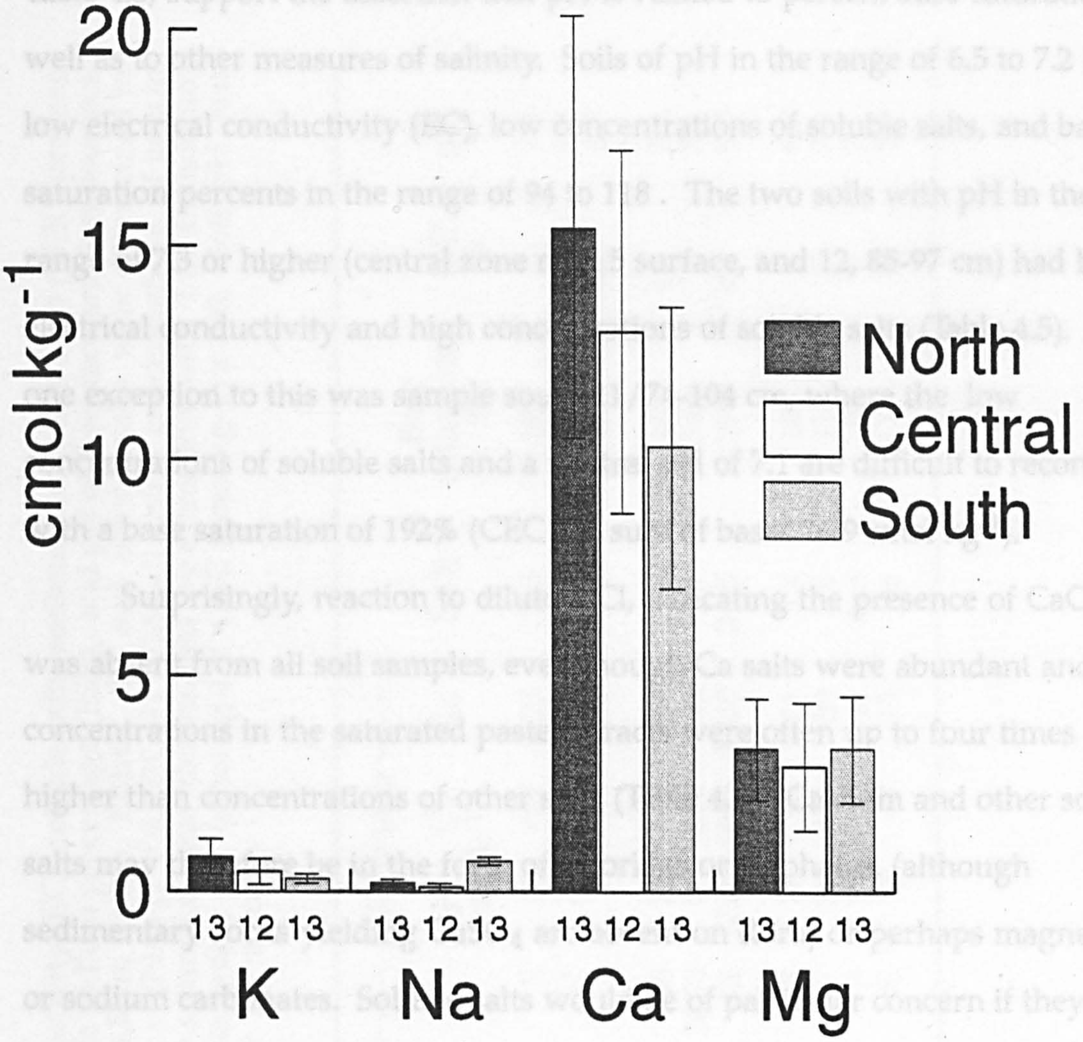

Fig. 4.3. Exchangeable cations in surface soil horizons along north, central, and south transects on the Rora Habab plateau, Eritrea. Vertical bars are ± 1 SD from means of thirteen samples (north and south) and twelve samples (central).

origin, organic matter content, and texture, pH is correlated with base saturation, and a base saturation greater than 80% implies neutral pH in most soils (Brady 1990:220-221).

Base saturation in excess of 100% implies the presence of soluble salts, which were determined for a subset of 10 samples. These results, shown in Table 4.5, support the assertion that pH is related to percent base saturation, as well as to other measures of salinity. Soils of pH in the range of 6.5 to 7.2 had low electrical conductivity (EC), low concentrations of soluble salts, and base saturation percents in the range of 94 to 118 . The two soils with pH in the range of 7.3 or higher (central zone no's. 5 surface, and 12, 85-97 cm) had high electrical conductivity and high concentrations of soluble salts (Table 4.5). The one exception to this was sample south 11/74-104 cm, where the low concentrations of soluble salts and a neutral pH of 7.1 are difficult to reconcile with a base saturation of 192% (CEC 8.8, sum of bases 16.9 cmol kg^{-1}).

Surprisingly, reaction to dilute HCl, indicating the presence of $CaCO_3$, was absent from all soil samples, even though Ca salts were abundant and concentrations in the saturated paste extracts were often up to four times higher than concentrations of other salts (Table 4.5). Calcium and other soluble salts may therefore be in the form of chlorides or sulphates, (although sedimentary rocks yielding $CaSO_4$ are absent on Rora) or perhaps magnesium or sodium carbonates. Soluble salts would be of particular concern if they indicated a high sodium content of soils. In semi-arid areas, Na^+ can have adverse effects on crops, to which it is toxic, and on the structure and erodibilty of soil, since high levels of Na^+ in the exchange complex tend to de-flocculate clays (Brady 1990:211; Jenny 1980:148-51).

According to Brady (1990:244) there are two ways of assessing the sodium status of soils. These are the exchangeable sodium percentage (ESP) and the sodium adsorption ratio (SAR). An ESP (determined as exchangeable Na / CEC x 100) or SAR (determined as $[Na^+] / \sqrt{(0.5\ [Ca^{2+}] + [Mg^{2+}])}$ of 15 or

Table 4.5. Electrical conductivity (EC), soluble salts, sodium adsorption ratio (SAR), percent base saturation, exchangeable sodium percentage (ESP), and pH of 8 surface and 2 subsurface soils from three transects on Rora Habab, Eritrea. EC and soluble salts were determined in saturated paste extract. SAR = [NA+] / √ 0.5 ([Ca+] + [Mg+]) using concentrations of ions in saturated paste extract. Base saturation was determined by extraction with 1 M ammonium acetate, pH 7.0. ESP = exchangeable Na (cmol kg-1) / CEC (cmol kg-1) x 100. Soil pH was determined in 1:1 soil:water by volume.

profile	depth	EC	------ Soluble salts ------				SAR	Base saturation	ESP	pH
			K	Na	Ca	Mg				
	cm	dS m^{-1}		mg L^{-1}				%	%	
north 2	0-6	0.8	9	20	107	21	2.5	106	1	7.2
north 5	0-5	0.8	63	11	86	24	1.5	94	1	6.5
north 13	0-22	0.7	11	7	91	21	0.9	103	<1	6.8
central 1	0-35	1.4	49	23	149	49	2.3	102	<1	7.2
central 5	0-10	5.8	3050	98	3600	843	2.1	148	1	7.3
central 12	85-97	10.5	12	1270	1050	1020	39.5	358	<1	8.0
south 1	0-14	0.7	5	18	87	21	2.4	104	3	6.8
south 5	0-15	1.4	7	30	179	50	2.8	118	7	7.2
south 11	74-104	0.4	3	12	25	11	2.8	192	9	7.1
south 13	0-15	0.5	8	9	47	15	1.6	110	5	7.0

more and a pH of greater than 8.5 indicates a sodic soil in which Na^+ levels may be problematic. On the other hand, an EC greater than 4 with a pH less than 8.5 and an SAR or ESP of less than 15 indicates a saline soil, with a concentration of soluble salts sufficiently high to impair plant growth processes. Although the ESP and SAR are closely related in most soils, they were not closely related in the soils we examined.

For selected soils in Table 4.5, only central zone profile no's. 5 (surface) and 12 (subsurface) samples met the criteria for a saline soil using the SAR as a measure, although the concentrations of soluble salts at central profile no. 5 were elevated because this area was used for threshing grain. Taking ESP as the indicator produces different results (Table 4.5). The ESP of surface soils ranged between 0.01 and 8.9 with a mean of 2.5, indicating that no surface soils are saline. However, when analysed by site, ESP values were 0.01 to 2.0 (mean 2.0) in north and central soils but 3.1 to 8.9 (mean 5.7) in the south (Table 4.5). The correlation of ESP with sand content was 0.85 and with clay, -0.87, and the southern soils at Laba were significantly more sandy than soils further north.

This means that none of Rora's surface soils were saline or sodic. Using ESP or percent base saturation as a proxy for soluble salt content of soils I did not analyse, the clay-loam surface soils in north and central zones (mean ESP 2, mean base saturation 98% and 99%) probably have few or no soluble salts whilst those at Laba village in the south (mean ESP 5.7, mean base saturation 113%) probably have slightly higher levels of soluble salts (Table 4.5). This suggests that if irrigation were attempted at Laba, for example in tree nurseries, salinity problems may be encountered.

Many soils in the tropics, particularly the humid tropics, have variable charge, meaning that the CEC varies depending upon the pH of the soil. However, in these soils, pH in KCl never exceeded pH in water, indicating that there is a net negative charge (cation rather than anion exchange capacity) in all of these soils (Sanchez 1976:142, Uehara and Gillman 1981:58-9). The measure $pH_{KCl} - pH_{H_2O}$, called the Δ pH, is always negative in layer silicate systems, but ranges between negative and positive values when measured over a range of pH values for soils whose exchange complex is dominated by variable charge materials such as iron and aluminium oxides or allophane (Sanchez 1976:141-143).

Although having a net negative charge does not guarantee that there is no variable charge (Uehara and Gillman 1981:31), it seems likely that none of the soils of Rora Habab is dominated by variable charge materials . The cation exchange complex probably is dominated instead by 1:1 or 2:1 layer silicate clays (Brady 1990:186-90). This is further implied by the lack of any significant reddening (suggestive of iron oxides) or extremely sticky consistency (suggestive of allophane) in any profile, the neutral pH (at which no Al will be soluble) (Birkeland 1984:69), and by the parent material, which consists of intermediate to acid igneous rocks unlikely to weather to form amorphous materials under the relatively dry conditions found on Rora (Birkeland 1984:72-3, Brady 1990:162,181,197-8).

Exchangeable Ca also differed between sites according to differences in organic C and clay content. Exchangeable Ca averaged 15.4 cmol kg^{-1} in the north, 13.0 cmol kg^{-1} in the central zone, and 10.3 cmol kg^{-1} in the south. In the soils of Rora Habab, as in many soils of semi-arid lands, exchangeable Ca dominates exchange sites (Brady 1990:182), and at Rora the between site differences in exchangeable Ca mirror those of CEC (Fig. 4.3 and 4.5, Table 4.3).

The available and exchangeable soil constituents I measured (P, K, Na, Ca and Mg) can be derived from weathering of primary minerals as well as from organic matter decomposition. Any differences in the concentration of these ions is therefore some function of the interaction between mineral and organic matter releases of the ions.

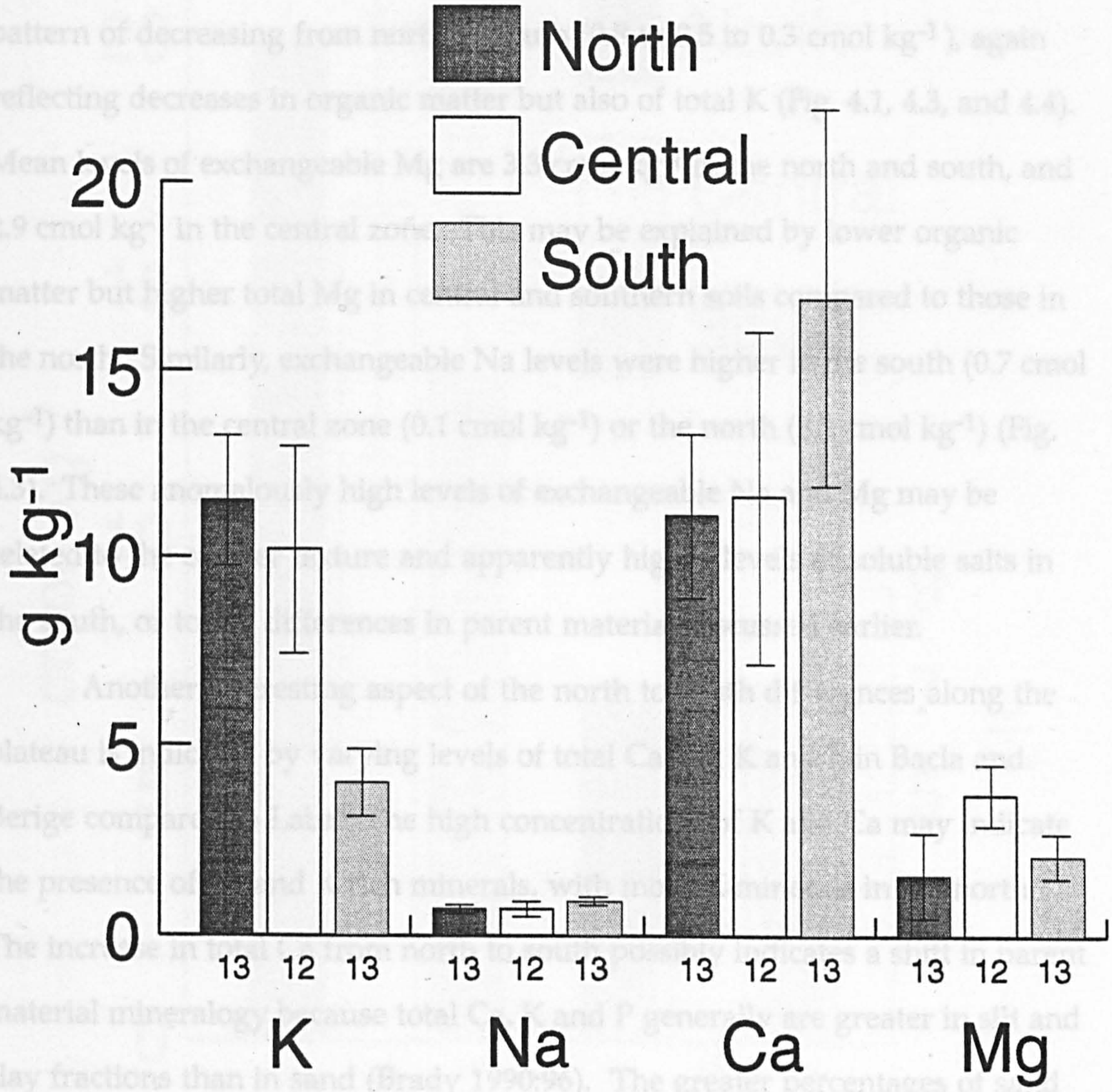

Fig. 4.4. Total cations in surface soil horizons along north, central and south transects on the Rora Habab plateau, Eritrea. Vertical bars are ± 1 SD from means of thirteen samples (north and south) and twelve samples (central).

The average available P at all sites (excluding central profile no. 5) from north to south along the plateau decreased from 12 to 8 to 6 mg kg^{-1} at Bacla, Berige and Laba. This coincided with decreases in organic matter but constant levels of total P (Fig. 4.1 and Table 4.3). Exchangeable K followed the same pattern of decreasing from north to south (0.8 to 0.5 to 0.3 cmol kg^{-1}), again reflecting decreases in organic matter but also of total K (Fig. 4.1, 4.3, and 4.4). Mean levels of exchangeable Mg are 3.3 cmol kg^{-1} in the north and south, and 2.9 cmol kg^{-1} in the central zone. This may be explained by lower organic matter but higher total Mg in central and southern soils compared to those in the north. Similarly, exchangeable Na levels were higher in the south (0.7 cmol kg^{-1}) than in the central zone (0.1 cmol kg^{-1}) or the north (0.2 cmol kg^{-1}) (Fig. 4.3). These anomalously high levels of exchangeable Na and Mg may be related to the coarser texture and apparently higher levels of soluble salts in the south, or to the differences in parent material discussed earlier.

Another interesting aspect of the north to south differences along the plateau is indicated by varying levels of total Ca and K and P in Bacla and Berige compared to Laba. The high concentrations of K and Ca may indicate the presence of Ca and K rich minerals, with more K-minerals in the north. The increase in total Ca from north to south possibly indicates a shift in parent material mineralogy because total Ca, K and P generally are greater in silt and clay fractions than in sand (Brady 1990:96). The greater percentages of sand would be associated with a decrease in total Ca at Laba if parent materials were similar across the plateau. A comparison of levels of these ions and of particle size (Fig's. 4.2 and 4.4) therefore suggest similar parent materials in Bacla and Berige with a transition to a more quartz-rich and Ca-rich parent material at Laba.

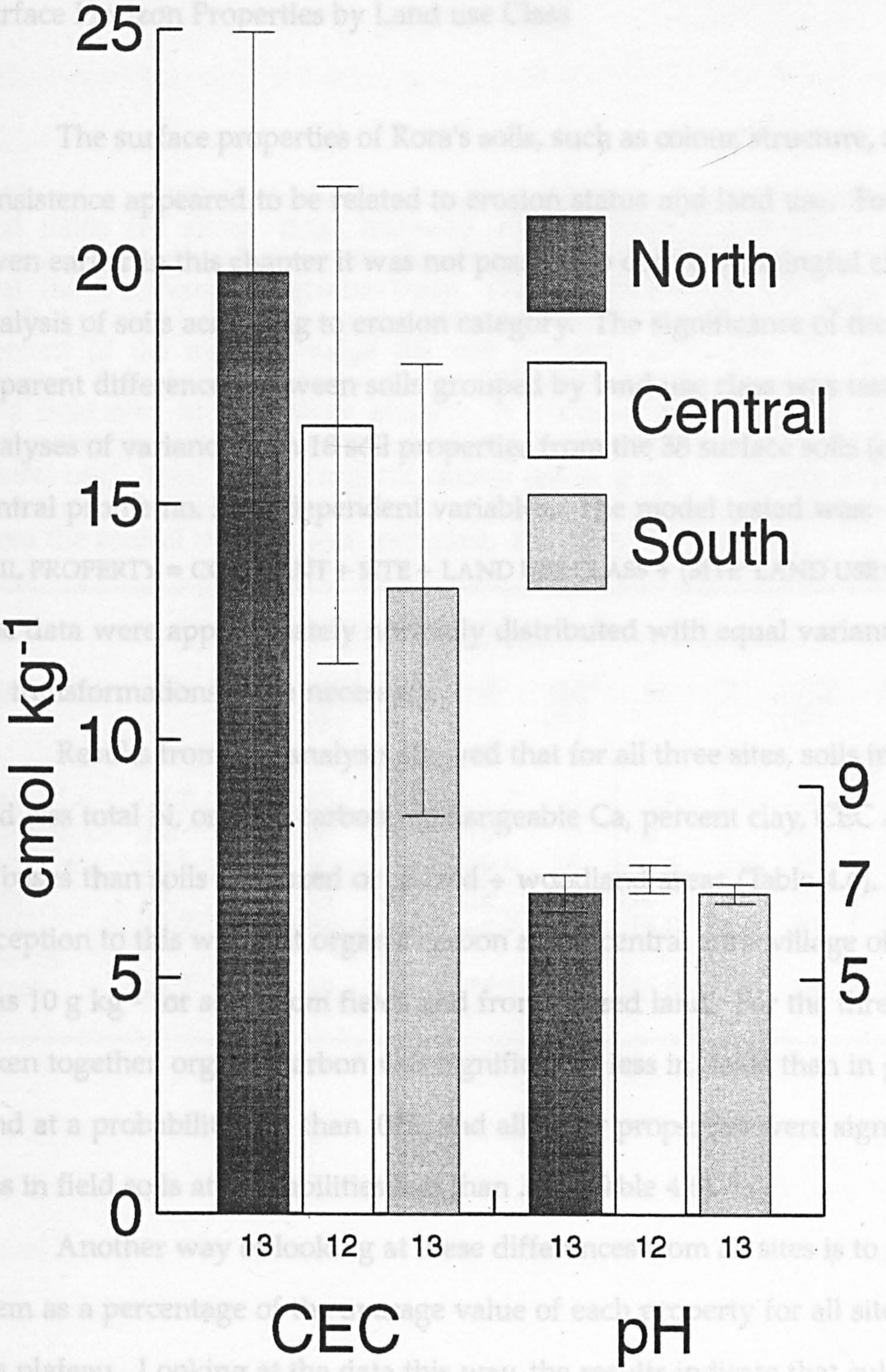

Fig. 4.5. Cation exchange capacity and pH in surface soil horizons along north, central, and south transects on the Rora Habab plateau, Eritrea. Vertical bars are ± 1 SD from means of thirteen samples (north and south) and twelve samples (central).

Surface Horizon Properties by Land use Class

The surface properties of Rora's soils, such as colour, structure, and consistence appeared to be related to erosion status and land use. For reasons given earlier in this chapter it was not possible to derive meaningful classes for analysis of soils according to erosion category. The significance of the apparent differences between soils grouped by land use class was tested using analyses of variance with 18 soil properties from the 38 surface soils (excluding central profile no. 5) as dependent variables. The model tested was:

SOIL PROPERTY = CONSTANT + SITE + LAND USE CLASS + (SITE*LAND USE CLASS).

The data were approximately normally distributed with equal variances and no transformations were necessary.

Results from this analysis showed that for all three sites, soils in fields had less total N, organic carbon, exchangeable Ca, percent clay, CEC and sum of bases than soils of grazed or grazed + woodland areas (Table 4.6). The only exception to this was that organic carbon at the central zone village of Berige was 10 g kg^{-1} for soils from fields and from grazed land. For the three sites taken together, organic carbon was significantly less in fields than in grazed land at a probability less than .013, and all other properties were significantly less in field soils at probabilities less than .005 (Table 4.6).

Another way of looking at these differences from all sites is to estimate them as a percentage of the average value of each property for all sites across the plateau. Looking at the data this way, the results indicate that cultivated soils have, on average, between 22% and 31% less total N, organic carbon, exchangeable Ca, CEC and sum of bases than grazed sites, and about 16% less clay than grazed sites (Table 4.6).

All grazed sites were classified as moderately or severely eroded, and all cultivated fields were classified as slightly or moderately eroded. Therefore, this analysis produced the unexpected result that moderately and

Table 4.6 Differences between surface soil properties from grazed land (**G**) and fields (**F**) along three transects on the Rora Habab plateau, Eritrea. Numbers are means of values for 5 to 8 plots classified as grazed or field, and the % differences between them. The column labelled **diff** (grazed minus field) / grazed) is the average difference between grazed and field sites as a percent of the average value for that property on all sites. The last column, labelled **P** is the significance of the difference between samples from grazed and field sites in a twoway analysis of variance with site and land use as independent variables, i.e. soil property = constant + site + land use +(site x land use). Total N and organic carbon are in g kg^{-1}; exchangeable Ca, CEC, and sum of bases are in cmol kg^{-1}; and clay is in percent. N=38; profile no. 5 from the central transect was excluded, see text.

	------ North ------			---- Central ----			----- South -----			All sites	
property	G	F	diff (%)	G	F	diff (%)	G	F	diff (%)	diff	P
n	8	5		6	6		5	8		38	
total N	3.7	2.4	35	1.8	1.7	6	1.6	0.9	44	28	.005
organic C	20	9	55	10	10	0	10	7	30	28	.013
exch Ca	18.1	11.1	39	15.2	10.9	28	11.4	9.6	25	31	.001
clay	38	33	13	39	32	18	18	15	17	16	.005
CEC	22.7	15.5	32	18.9	14.7	22	15.0	12.0	20	25	.003
sum of bases	22.7	14.7	26	19.0	14.1	26	15.8	13.7	13	22	.002

severely eroded sites have more fertile, not less fertile, surface soils than slightly eroded sites.

These results provide ambivalent support for predictions from my 1985 survey in which I found eroded soils to have more organic C and available P but higher pH, exchangeable Ca, Mg, and Na than less eroded soils. The different outcomes of these studies can be explained by two factors. Firstly, soils in the 1987-9 survey were not sampled according to erosion class and land use. Erosion class and land use designations described the condition of the 20 m plot, and may not have applied to the point where the soil was sampled. They also produced unequal sample sizes for comparison of grazed compared with cultivated, and severely compared with moderately or slightly eroded groups. In the smaller 1985 survey, only two pairs of soil profiles from eroded and less eroded sites, about 5 m apart from one another were deliberately sampled to facilitate comparison by erosion class.

Secondly, there is an interaction between erosion, land use and topography, with steeper soils tending to be grazed and not cultivated today (though they may once have been) (Table 3.1). Steep, grazed soils in the north of the plateau often have greater densities of woody perennials (Tables 3.1, 3.4 and 3.6) and may be much less disturbed, in patches, than cultivated soils, even though they appear to be more severely eroded than valley or footslope soils at the 20 m plot scale. Therefore, an expected loss of organic matter and associated soil properties from eroded or grazed plots apparently was compensated for by the sampling of relatively undisturbed profiles in these areas.

Thus, the larger 1987-9 survey, in contrast to the 1985 survey, would suggest that eroded, grazed plots had no less, or even slightly more organic matter and related soil constituents. A more intense survey with random sampling, stratified by erosion class or land use class, may well show greater variability, and perhaps lower levels of organic carbon and associated properties on eroded, grazed soils. Given the high levels of soil erosion encountered on the plateau, such a survey, conducted alongside soil conservation measures and repeated over time, is a logical next step.

Soil Classification and Mapping

Soils were classified to the Family level according to the USDA Soil Taxonomy (Soil Survey Staff 1975). The following features of this classification system, as they relate to the soils of Rora Habab, are summarised from Soil Survey Staff (1975 and 1990), Brady (1990) and Buol et al (1980).

Four soil Orders were found on Rora: Entisols, Inceptisols, Alfisols and one Mollisol. Entisols are weakly developed soils with absent or minimal horizon development and which typically have an ochric epipedon. An ochric epipedon is a surface horizon which is light in colour, has low organic matter content and may be hard and massive when dry. Inceptisols are embryonic soils with some horizon development and a cambic sub-surface horizon. A cambic sub-surface horizon is one which has been altered by physical or chemical activity. Alfisols have a grey to brown surface horizon (often ochric) with either an argillic horizon (a horizon of clay accumulation) or a natric horizon (an argillic horizon high in sodium content) and a base saturation of 35% or more at 125 cm. Mollisols are characterised by a mollic epipedon, a relatively thick, dark surface horizon which is dominated by base-forming cations (base saturation 50% or more).

These four Orders were further classified into five Suborders: Orthents, Fluvents, Tropepts, Ustalfs and Ustolls. Orthents are Entisols found primarily on recent deposits, or on surfaces which have been recently eroded, for example by geological processes or cultivation, so that any former soil has either been removed, mixed, or truncated to the point where horizons which are diagnostic of other orders are absent. Fluvents are Entisols formed by water deposited sediments, for example on flood plains or alluvial fans. In semi-arid regions such as Rora Habab, the age of the sediments can be more than several hundred years. Tropepts are freely drained Inceptisols found mostly in inter-tropical areas and characterised by very little active amorphous clay or pyroclastic materials, often having an ochric epipedon and a cambic horizon. Ustalfs are Alfisols of warm sub-humid to semi-arid regions with an ustic moisture regime. An ustic moisture regime is one with a warm rainy season where in most years, soils are dry for more than 90 consecutive days but less than 180 days. Ustolls are Mollisols of mid to low latitudes and sub-humid to semi-arid climates where rain falls mainly during the growing season, usually as erratic, heavy storms, and where drought is often severe.

The five Suborders found on Rora have one of two classifications at the Great Group level, "Ust-" or "Hapl-", each of which was further classified into one of two Subgroups, "Lithic" or "Typic". The prefix "Ust-", as in Ustorthent, is derived from the Latin *ustus*, or burnt, and implies dry climates. The prefix "Hapl-", as in Haplustalf, is derived from the Greek *haplous*, meaning simple, and implies minimum horizon development. The Subgroup modifier "Lithic", as in Lithic Ustorthent, is applied where a coherent matrix such as rock (a lithic contact) or saprolite (a paralithic contact) is found within 50 cm of the soil surface. The Subgroup modifier "Typic", as in Typic Haplustalf, represents the central or defining concept of the Great Group.

The final element in the classification of Rora's soils is at the family level and consists of three modifiers describing an average textural class for the whole profile, a mineralogy class for the dominant mineralogy, and a soil temperature class based on mean annual soil temperature at 50 cm. The temperature class for all Rora's soils was estimated to be isomesic, meaning that the mean annual soil temperature is at least 8°C but less than 15°C, and that it fluctuates less than 5°C during the year.

The mineralogy class for all soils on the plateau was estimated to be mixed. For very fine and fine soils, this meant that the less than 0.002 mm fraction did not have more than 50%, by weight, of any one clay mineral. For loamy soils this meant that the 0.02 to 2.0 mm fraction had less than 40% of any one mineral other than quartz or feldspars. Four textural classes were found on Rora; very-fine (one profile in the north), fine (eleven profiles in north, all profiles in the central zone), fine-loamy (one profile in the north, seven in the south), and coarse-loamy (six profiles in the south). A very fine texture is one which has 60% or more clay in the less than 2.0 mm fraction and a fine texture is one which has 35 to 59% clay. Coarse-loamy and fine-loamy textural classes both have 15% or more by weight of sand in the less than 2.0 mm fraction but coarse-loamy soils have less than 18% clay and fine-loamy soils have 18 to 34% clay.

Detailed descriptions of all profiles are given in Appendix 4. In this appendix, it may be helpful to consider five profiles as broadly representative of their Great Groups. They are:

1) Bacla 2: Typic Ustropept, representative of Ustropepts (11 plots)

2) Berige 12: Typic Haplustalf, representative of Haplustalfs (12 plots)

3) Laba 10: Typic Ustorthent, representative of Ustorthents (14 plots)

4) Berige 5: Lithic Haplustoll

5) Laba 6: Typic Ustifluvent

In summary, the soils I examined on Rora Habab were classified into one of eight Subgroups in four Orders. At the family level, all soils were estimated to have mixed mineralogy and an isomesic moisture regime, but the textural classes differed with the southern soils at Laba being loamy, and all but one profile further north in Bacla and Berige (north profile 3) being clayey.

Although this survey was not undertaken in order to generate a map of Rora's soils, to what extent does the classification of these soils according to the

US Soil Taxonomy assist us in defining map units? The four kinds of map units outlined in the USDA Soil Survey Manual (Soil Survey Staff 1980; Ch 5:8-9) are: consociations, complexes, associations, and undifferentiated groups, the last two of which were appropriate to describe the soils of Rora. When arrayed according to topography, the classifications of the soils sampled in the south varied from plot to plot and show some regularly repeating pattern (Fig. 4.6). Soils in the south could therefore be described as a "Lithic Ustorthent-Typic Haplustalf association", meaning that these two dissimilar taxa occur in a regularly repeating pattern whose elements could be mapped separately at 1:24 000, that less than 25% of the area consists of dissimilar inclusions (in this case, Typic Ustorthents, Typic Ustifluvents, Lithic Ustropepts and Typic Ustropepts), and that there is no single area of dissimilar soil that occupies 10% or more of the total (Soil Survey Staff 1980; Ch. 5:8-9). Lithic Ustorthents occurred on the grazed, uncultivated summits and steep upper and middle slopes, while Typic Haplustalfs occurred on the gentle, cultivated lower slopes and valleys (Fig. 4.6).

Soils in the north and central zones (Bacla and Berige), which showed no repeating geographical pattern, could be mapped using two "undifferentiated groups" of soils that have similar management. The first group, "Typic Ustropepts and Typic Haplustalfs" are deep, cultivated soils which occupy lower slopes and valleys at both sites. The second group, "Lithic Ustorthents, Lithic Ustropepts, and Typic Ustropepts" are shallow, uncultivated soils that are grazed or have woodland cover and occupy mid slopes, upper slopes, or summits (Fig. 4.6).

The foregoing soil classification and potential mapping units derived from it are helpful in characterising Rora's soils with respect to other soils in Eritrea and elsewhere, using one internationally recognised classification scheme. At the local level, however, such an approach may be less useful and it is appropriate to consider the soil and land classification approaches of Rora's

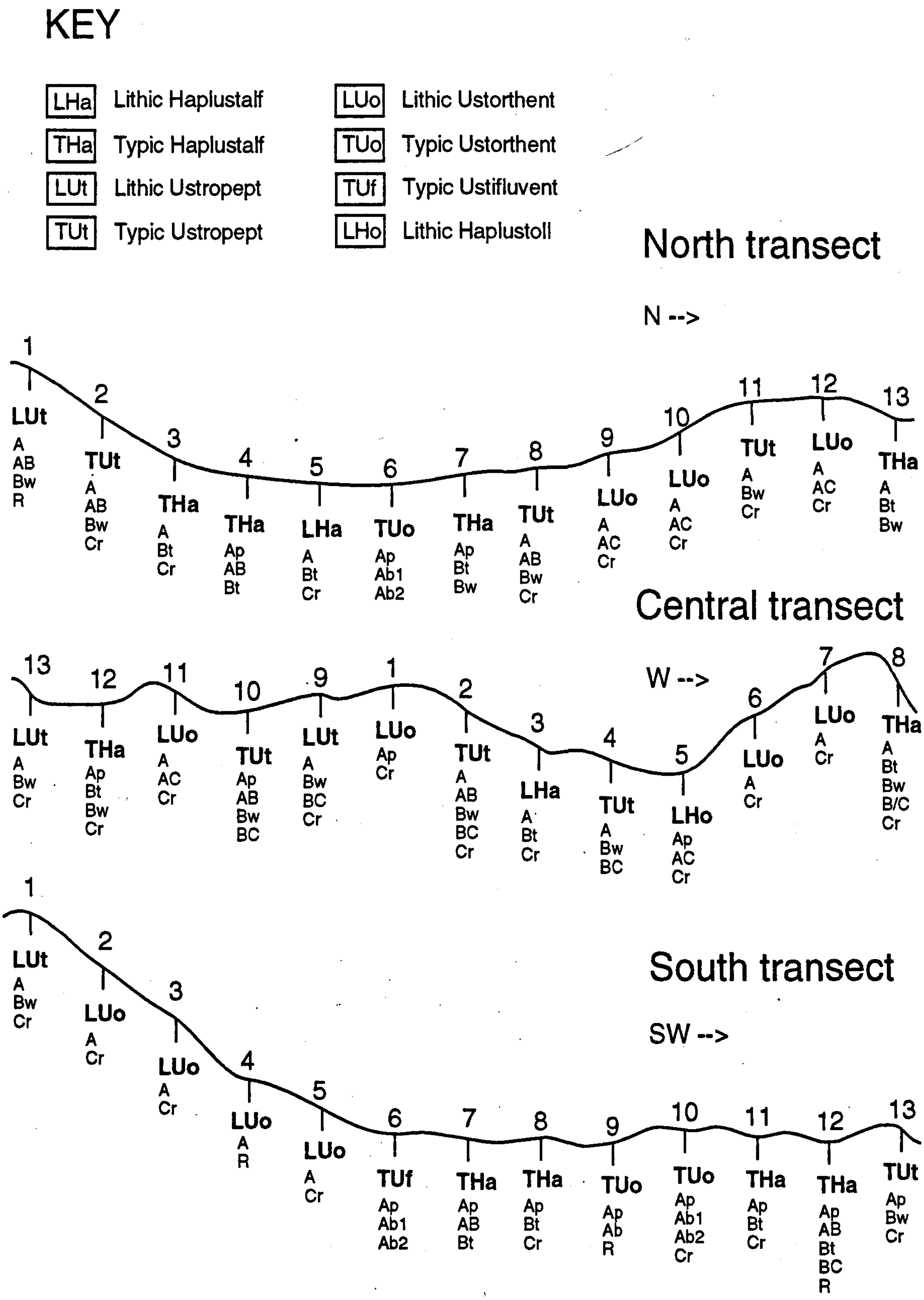

Fig. 4.6. Locations of soil profiles, subgroup level classification of soils, and major soil horizons along north, central and south transects on the Rora Habab plateau, Eritrea. Profiles are numbered in the order in which they were sampled.

farmers who make land use decisions according to criteria that may not correspond with outside classifications.

Soil Management Practices

Local Soil Classification and Land use Considerations

Decisions about land use reflect some assessment of soils by the land user (Hecht 1989) and the soil classification schemes of subsistence farmers usually are based on soil properties which are in some way related to crop productivity (Gladwin 1980, Johnson 1980, Sherman 1980). Soil colour is often used as a surrogate for fertility with simple colour distinctions proving effective in distinguishing land-use potential (Richards 1975:106). This is the case on Rora Habab where farmers distinguish between "good soil" which is black or brown and "bad soil" which is white or red.

In order to test whether a soil classification scheme based on soil colour differences is a reliable indicator of soil fertility, it would be necessary to sample soils according to those locally identified differences and compare them with other measures of fertility such as CEC, or with a measure such as crop productivity which integrates several aspects of soil fertility. Such a survey has not yet been undertaken on Rora but in order to determine whether Munsell-colour differences at a coarse level were related to other differences in soil properties, the three darkest and three lightest surface soils from each transect were grouped into two categories (Table 4.7 a). One-way analyses of variance were undertaken with colour (dark and light) as the independent variable and 15 soil properties as dependent variables: percent clay, pH, organic C, sum of bases, CEC, total N and P, and K, Na, Ca, and Mg (total and exchangeable). The data for each colour class were normally

Table 4.7 a Moist and dry colour of surface horizons from selected soil profiles from Rora Habab, Eritrea, used for comparison with other soil properties.

------- soils designated dark -------			------- soils designated light -------		
Soil profile	Moist colour	Dry colour	Soil profile	Moist colour	Dry colour
North 1	10YR 3/4	10YR 6/4	North 4	10YR 5/6	10YR 7/4
North 12	7.5YR 3/4	10YR 5/4	North 7	10YR 5/6	10YR 7/4
North 13	10YR 3/4	10YR 5/4	North 8	10YR 5/6	10YR 7/4
Central 1	10YR 3/3	10YR 5/4	Central 7	10YR 6/8	10YR 7/7
Central 2	10YR 3/3	10YR 5/4	Central 10	10YR 5/6	10YR 6/6
Central 4	10YR 3/3	10YR 5/4	Central 11	10YR 4/6	10YR 5/4
South 2	10YR 3/2	10YR 3/3	South 3	10YR 4/4	10YR 7/4
South 6	10YR 2/1	10YR 4/4	South 8	10YR 4/4	10YR 6/4
South 13	2.5 Y 3/2	2.5 Y 5/4	South 10	10YR 4/4	2.5 Y 5/4

Table 4.7 b Significant results from one-way analyses of variance of 15 surface soil properties with soil colour as the independent variable. Numbers are means (± 1 SD) of 9 samples per group.

Soil property	dark soil	light soil	F	significant @ P ≤
total N (g kg^{-1})	2.7 (1.5)	1.6 (0.9)	3.4	.08
exch. Ca (cmol kg^{-1})	15.4 (6.0)	10.7 (4.6)	3.6	.08
total P (g kg^{-1})	0.9 (0.4)	0.6 (0.2)	3.7	.07
sum of bases (cmol kg^{-1})	20.3 (6.6)	13.7 (4.8)	6.0	.026
CEC (cmol kg^{-1})	20.0 (6.6)	13.1 (5.2)	6.1	.025
depth of A horizon (cm)	22.4 (10.7)	11.6 (4.4)	7.9	.012
organic carbon (g kg^{-1})	17.6 (7.9)	7.2 (4.9)	11.1	.004
exch. Mg (cmol kg^{-1})	4.0 (1.0)	2.2 (0.6)	20.1	.0004

distributed with approximately equal variances and no transformations were necessary.

Organic C and exchangeable Mg were significantly higher ($p < 0.01$) in the darker soils. Total N and P, exchangeable Ca, sum of bases and CEC also were higher ($p < 0.05$ or < 0.10) in the darker soils, and darker soils were deeper ($p < 0.05$), (Table 4.7 b). Given the inter-correlations that exist between many soil properties and organic matter (Duxbury et al 1989, Brady 1990:279) it is not surprising that high levels of organic carbon often indicate fertile soils. In Rora Habab, where rainfall is low, organic matter content is reflected by darker coloured soils. Since commercial fertilisers have never been used on the plateau, nutrient levels have not been artificially increased in areas where soil organic matter is low and the correlation between darker soils, higher levels of organic carbon, and higher nutrient status remains unperturbed.

Given the foregoing results, it is perhaps surprising that there was no difference in available P between colour classes. In fact, available P was un-correlated with any soil properties for which colour differences were significant, including organic carbon and total P (Table 4.1). Nevertheless, it seems that even this cursory examination of local farmers' classification of soil fertility based on colour is meaningful with respect to many other measures of fertility.

When discussing soil properties with Rora's farmers, it became clear that "soil" was not the frame of reference for agricultural decisions but that the broader word "land" was used instead. In fact, my specific questions about local criteria for soil classification and soil fertility assessment were always answered with the word "land" being substituted for "soil". When I pointed this out, farmers often asked why I separated the two words when soil was a part of land. Their point was that land use and management decisions are not based solely, or even primarily on soil characteristics , but on a number of environmental factors including aspect, hillslope position, slope, and extent of grass cover. West-facing slopes are regarded as better than slopes facing east because "late-season easterly winds hurt the crops". Lower slopes which "have deeper soils" are preferred to upper slopes, and flatter land is preferred to sloping land because on flat land "the soil holds more water". Local farmers also correlate greater productivity with greater grass cover.

Another feature of Rora's cultivated land that farmers frequently commented on was the large number of rocks and stones which were ubiquitous but of particular concern to farmers in certain areas. Large rocks were most common on shallow soils on middle and upper slopes, and on deeper valley soils which were situated close to steep, unstable, bare slopes. In one of these areas, a recently ploughed field on an upper slope near Abhaklu in Bacla village (Fig. 3.1), I estimated the weight of the rocks resting on the soil surface by randomly placing four 1 m^2 grids at different points in the field and weighing all rocks > 1 kg. A total of 58 rocks were collected ranging between 1.02 kg and 7.55 kg with an average total weight of rocks in the four grids of 21.0 kg m^{-2}. In such areas, farmers told me that they needed to have their plough shares refashioned up to four times a year because of damage caused by rocks.

Until the early part of this century the Habab relied almost exclusively on animal husbandry so that the land classification schemes and farming systems described above and in Chapter 2 have been developed within just three generations. Today there are several elderly farmers on Rora who as children were directly involved in the transition from a pastoral society to one in which crops became increasingly important. These men, now more than seventy five years old, all have many stories about declining crop yields, reduced forest cover, and the disappearance of wild animals and birds.

Many farmers have taken me to fields which they used to plough and which are now bare rock or have soils too thin for a plough, and to parts of the plateau which are either devoid of woody perennials or have many tree stumps today but which " .. were covered with trees when I was a young man". In Berige and Laba, I have spoken with several farmers who say that crop yields used to be almost twice present-day yields. When asked how they accounted for these changes farmers often responded by saying that there was no water, or that the soil has gone.

Soil and Water Conservation

The two most serious impediments to farming on Rora Habab are soil erosion and unreliable, often low rainfall. Both of these factors result in soil moisture levels that frequently are low and which fluctuate over the growing season.

On eroded soils, it may be possible for some plants, especially woody perennials, to develop root systems which can penetrate weathered rock or cracks within the bedrock matrix and extract water under fairly high tensions (Zhengqi Wang 1991) although this has not been examined on Rora. In general, though, available moisture holding capacity will be lower in shallow, eroded soils. Also, where horizons exposed by surface erosion are higher in clay content than less eroded soils, which is often the case in central and northern areas of Rora (Appendix 4), water infiltration will be slower and surface runoff higher (Brady 1990:148). A further problem caused by soil erosion is the loss of nutrients and organic matter.

Rainfall problems relate not only to the total rainfall in any year but to its temporal and spatial distribution. Ordinarily crops are planted at the beginning of the rainy season when soils have been sufficiently wetted by the first storms. On several occasions in recent years, one or two heavy storms falling in April or May have been followed by several weeks without rain (Fig. 2.2). The rooting systems of established plants may be extensive and responsive enough to withstand a prolonged dry period between storms but annual grasses, including cultivated cereals, usually die.

In order to combat the problems of erosion and unreliable soil moisture, villagers and the EPLF Agriculture Commission have studied several alternatives including irrigation, protecting natural vegetation, mulching, structures for harvesting and storage of water such as small canals and reservoirs, and water retention structures such as bunds and terraces.

It has not been possible to use supplemental irrigation in Rora because of the expense involved in managing and distributing water which is mostly lost in high energy overland flows. In fact, much of Rora's rain is lost as waterfalls over the escarpments of the plateau, reaching the Anseba and Inkema drainages where slower water flows across gentler gradients make irrigation a cheaper, more manageable option at lower elevations (Eritrean Relief Association 1985).

Protecting natural vegetation has met with limited success because while cutting of trees has been fairly well controlled, grazing remains virtually un-managed, even on steep, eroding surfaces.

In many tropical areas mulching has been found to decrease soil erosion by reducing the energy of rain drops and improving soil hydrological properties via its effects on soil structure, soil moisture and surface temperature, and water transmissivity through the soil body (Lal 1984). Mulch rates of 6 to 8 t ha^{-1} have proven effective in controlling soil erosion in the tropics on slopes of 2% to 20% (Lal 1984). However, on Rora it is difficult to imagine how farmers could use mulches in a mixed farming system where crops and animals play equally important roles in the economy. The most readily available mulch on Rora Habab is the cereal stalks and leaves which are left uncut after harvest. There is an opportunity cost involved in using crop residues as mulch on Rora since animals are grazed on them at the end of the year, and in doing so, they manure the fields prior to ploughing. For the present, mulching with crop residues is not an option for Rora's farmers and no other species on the plateau could be used without threatening their survival, unless they were deliberately grown and protected. Other options, such as plastic sheeting or importing straw are not economically feasible.

Three small dams and five earthen embankments have been built on the plateau since 1984 in order to harvest and store rain water. Most of these structures have check dams upslope to reduce sedimentation problems in the main reservoir. The reservoirs receive their water mostly from surface runoff over adjacent slopes and seasonal water courses and are mainly used to supply water for people and animals. Small quantities of water are taken from two reservoirs in Bacla and Endlal to supply small tree nurseries adjacent to them. For the present, none of these structures is large enough to accommodate the water required to irrigate small fields close to them.

In other parts of Eritrea, the EPLF has built canals which snake around hills and capture water which was previously lost down escarpments to ephemeral desert streams. A system of sluice gates at the terminus of these canals directs the harvested water onto fields in a regulated fashion which aims to increase soil moisture storage and ensure equitable distribution of water. Such structures have not been built on Rora Habab and a feasibility study of their potential value on the plateau has not yet been undertaken.

The most widespread and effective method of erosion control and water harvesting has been the building of terraces described in Chapter 2. No studies of soil erosion or of crop yields before and after terracing have been undertaken on Rora but local informants say that the terraces have improved their land. However, the large inter-annual variation in crop yields since the terraces were built makes it impossible to judge how effective the terraces have been in improving yields. Terracing and other conservation measures are now underway across most of Eritrea. Since the war has now ended, these activities can perhaps be linked with a research programme to study the efficacy of several erosion control and water conservation practices.

DISCUSSION

From the historical evidence reviewed in Chapters 1 and 2, it seems that in the early part of this century, the Rora plateau was covered with forests, with olives dominant in the south and junipers increasingly dominant as one travelled north from Berige. From the evidence discussed in Chapter 3, the vegetation is now very different. There are almost no trees in the south and very few in the central zone, where they are virtually restricted to seasonal streams and cemeteries. Even the most intact woodlands, which are in the northern zone villages of Shamotet and Bacla, have a patchy distribution.

Results from the soil survey presented this chapter indicate that several soil properties differ across the plateau. Organic C, total N, available P, and exchangeable Ca decline from north to south, and the southern village of Laba has coarser soils, with decreased total K and exchangeable K, and increased total Ca and exchangeable Na. An obvious question therefore, is are these observations related in any way?

Deforestation has been frequently associated with soil erosion (e.g. Stocking 1988) and nutrient impoverishment (e.g. Binkley 1986). It is tempting to attribute soil erosion and low nutrient levels on Rora, where they occur, solely to deforestation, although this is difficult to prove without prior data on vegetation cover or soils. Moreover, I did not stratify my soil sampling according to differences in vegetation. Contemporary land use, and as yet unknown differences in climate further complicate the interpretation of the patterns in vegetation and soils across the plateau.

Some of the observed differences in soils could be attributed to the loss of forests on Rora. For example, the lower levels of organic carbon and associated soil properties at Laba could result from forest clearance leading to decreased litter inputs, increased surface erosion, and possibly increased decomposition resulting from ploughing. Other differences between sites, however, probably are more related to geology than to vegetation. For example, the soils in the southern village of Laba have a coarser texture and higher total Ca (which could have contributed to the increased exchangeable sodium percentage) than soils in the central and northern villages of Berige or Bacla.

There are some differences in geology at Laba compared to further north, but my impressions are based on a limited collection of samples. Bacla and Berige seem to be dominated by andesite, rhyolite, trachyite (including phonolite) and tuff in various stages of weathering. The four samples I collected at Laba were identified as phonolite, diorite, granodiorite, and quartzite (A. Grunder, Department of Geosciences, Oregon State University, personal communication). As previously mentioned, granodiorite probably is the dominant parent material for Laba soils because its coarser grain size results in more rapid weathering than the other rock types. This might explain why the texture of the soils at Laba is coarser than soils further north. A coarse-textured soil is likely to have lower nutrient levels than a fine-textured soil (Brady 1990:95-96) although P-fixation tends to be higher in clayey soils than in sandy soils (Brady 1990:363). Moreover, the coarser soil texture at Laba would produce droughtier soils, and this, combined with the drought-tolerance of olive (G. Martin, Department of Pomology, University of California at Davis, personal communication)) could account for the predominance of olives over juniper at Laba noted in the early 1900s (Naldini 1916). It is also interesting to note that olive is more tolerant of saline conditions than many other tree species (Hartmann et al 1980:15) and that while soils at Laba are not saline, they do have higher levels of Na than sites further north.

A more complete survey and experimental work need to be undertaken to determine the effects on vegetation and soils that these different parent materials (Laba vs. further north) may have. For the moment, geological differences across the plateau seem to be a major explanatory factor which accounts for soil, and possibly vegetation differences

Because these soils were sampled at intervals of up to 400 metres between pits (Appendix 3) my data cannot provide any insight into the degree of soil spatial variability over short distances. However, my observations indicate that the high degree of variability in soils over short distances (i.e. 10^0 to 10^1 metres) is going to be a crucial factor to consider, and experimentally control for, when outplanting trees in a restoration programme and when choosing sites for tree nurseries.

CHAPTER 5

PROPAGATION OF OLIVE AND JUNIPER

INTRODUCTION

The restoration of the vegetation of Rora Habab is certain to involve the deliberate propagation of plants, whether by direct seeding, or through nursery production of seedlings or vegetatively grown propagules. In Rora's remaining woodlands, there are sufficient disturbances and enough gaps producing well lit and shady areas under the canopy for regeneration to occur naturally where a seed source exists. A few areas along the plateau appear capable of natural regeneration, and seedlings of J. excelsa and O. europaea subsp. africana were growing in several plots we surveyed (Chapter 3). However, it was not clear how many of these seedlings will survive the grazing and cutting pressures currently facing Rora's woodlands.

In many areas of the plateau, particularly in the central and southern zones, no local seed source for trees exists, and seeds would have to be brought to the site by birds or animals. Young plants are particularly threatened in the climate of Rora because a pronounced dry season imposes severe drought stress, and torrential storms can be destructive to vegetation. Given these facts it is important to consider restoration not just as a passive process, principally reliant on conservation and exclosures, but as an active one where reforestation plays a key role. Developing appropriate means of propagating species of interest is an essential first step in this process.

The propagation of J. excelsa and O. europaea subsp. africana within Eritrea has met with poor success. Germination of 5% or less, high mortality of young seedlings, and slow initial growth rates has led to the EPLF's principle focus on exotic plants for reforestation. Since it is important to use native species to restore Rora's woodlands, I conducted several experiments on the germination and vegetative propagation of J. excelsa and O. europaea subsp. africana. These are the initial steps toward a much broader programme which will eventually include many native species, not just trees, whose populations and natural regeneration rates are low.

The success of nursery production of seedlings and of any future tree breeding programme depends on the ability to successfully propagate plants of interest from seed. Although field survival of seed is usually less than laboratory germination tests indicate (Hartmann et al 1990:108), laboratory determinations of viability could provide a measure of the germination potential of seeds from plants used in a reforestation programme. However, no experimental work has been conducted on J. excelsa and O. europaea subsp. africana in Eritrea. Previous published work on juniper and olive germination has been mainly undertaken outside Africa on other juniper species and on commercial olive cultivars. Therefore, germination trials of these two species were undertaken in the glasshouse using seeds gathered from trees in the northern and central zones of Rora Habab, in order to establish whether germination percentage could be increased by treating seeds in different ways.

Vegetative propagation methods have become increasingly relevant to afforestation and tree improvement programmes over the past decade. Of the many different types of vegetative propagation (Hartmann et al 1990), the use of stem cuttings in particular has proven very successful in forestry in temperate and in tropical areas (Leakey, Last and Longman 1982, Leakey 1983, Zobel and Talbert 1984:310, Zobel et al 1987:206 et seq). Many factors influence the rooting ability of stem cuttings. Leakey (1985:119-127) describes twelve variables: the role of auxins, co-factors and leaves; carbohydrate and nitrogen metabolism; water relations; light; temperature; season of collection; gravity; mycorrhizal fungi; and stock plant factors. He notes that the requirements for root initiation are mainly influenced by the plant's physiological state while root elongation is more sensitive to environmental factors.

Propagation using stem cuttings is useful from a research as well as an operational perspective, permitting genotype x environment studies and reducing between-plant experimental error in non-genetic studies (Zobel and Talbert 1984:311). By-passing the seed stage -- "speeding up the reproductive cycle" as Zobel and Talbert (1984:311) put it -- allows a more rapid production of test plants or of propagules for afforestation. In the Eritrean context, research and afforestation must go hand in hand so that evaluating the use of stem cuttings to enhance research capability in the field, and for use directly as a means for afforestation, is of great importance.

There are several references in the literature which discuss the propagation of olive and juniper species by stem cuttings. This is particularly the case for Olea europaea varieties which are propagated vegetatively in the Californian, Spanish and Italian olive industries. However, I am aware of no studies which consider the rooting ability of J. excelsa or O. europaea subsp. africana in Africa. Four experiments using cuttings from these two species were established in high humidity propagators in the village of Bacla in August 1987. However, they were destroyed by flooding following an unusually heavy storm a few weeks later. Therefore, a series of experiments was undertaken on each species using one or two year old stock plants grown in the greenhouse from seed collected from Rora Habab. The experiments will be discussed for O. europaea subsp. africana and J. excelsa in turn.

FACTORS AFFECTING THE GERMINATION OF OLEA EUROPAEA SUBSP. AFRICANA

Introduction

Olea europaea ssp. africana is the commonest tree along the Rora plateau (Chapter 3). It is used extensively by villagers, providing fuelwood, construction timber and fodder (Chapter 2). Local attempts to re-forest Rora using this species have been unsuccessful due to seed germination ranging from 0% to 5% (Semere Amlesom, Department of Agriculture, Nacfa, personal communication). Germination from commercial O. europaea cultivars also has been reported as low, varying with cultivar, seed maturity and storage time (Lagarda, Martin and Polito 1983).

The olive fruit is a drupe potentially having two carpels and four ovules (King 1938:452). The growth and development of flowers and fruits in O. europaea ssp. africana are similar to those described for cv. Manzanillo (Hartmann 1949:86), with fruits typically ripening in September, toward the end of the rainy season. Usually, only one ovule is fertilised (King 1938:452) although about 2% of the fruits collected from Rora contained two seeds. The fleshy, oil-bearing mesocarp used in commercial olive growing is absent in the much smaller fruits of O. europaea ssp. africana.

Studies on O. europaea cultivars show that increases in germination can be obtained by removing or clipping the stony endocarp, stratifying seed at certain temperatures (according to cultivar), scarifying with H_2SO_4 or NaOH, storing seed for about a year, and by excising the embryo (Lagarda Martin and Polito 1983, Crisosto and Sutter 1985a, 1985b, Ellis et al 1985). Villagers and nursery staff in the southern Eritrean highlands told me that germination could be increased by rolling a heavy stone over Olea seeds to crack or break the endocarp. They were unable, however, to quantify by how much this increased germination.

The purpose of this experiment was to examine the effect on germination of parent plant, stratification temperature, duration of stratification, and removing or cracking the endocarp.

Methods

Seeds

Seeds were collected in November 1988 from the ground underneath three plants, one from a cemetery in Bacla village (plant A), one from a cemetery in Endlal village (plant B), and the third from an isolated individual 600 m north of B (plant C). Seeds were also collected in November 1987 from plant A. Maternal plants A and B were apparently healthy and produced a good crop of fruit, since tree cutting and the grazing of animals is forbidden in cemeteries. Plant C had been cut only a little, appeared to be healthy, but was much smaller than the others and produced far less fruit. These were the only three trees I have found on Rora which produced moderate amounts of fruit.

After collection, seeds were stored for three months at 23°C in sealed brown paper bags. They were then transferred to sealed, dark plastic vials at 20°C until the beginning of the experiment in April 1989. Therefore, seed collected in 1987 had been stored for 18 months while seed collected in 1988 had been stored for 6 months. Before the experiments, the thin non-fleshy exocarp was removed by vigorous brushing of seed lots in bowls of water. Seeds were then surface sterilised with 1% sodium hypochlorite for 15 min and washed through a sieve five times with distilled water. To cull empty seeds, the seed lots were immersed in distilled water and those which floated were discarded. Seeds from each plant then were divided into groups for the experiments.

Experimental design and treatments

Prior to the experiment, fifty seeds from each of the four parent plant groups (A 1987, A 1988, B, C) were measured and weighed with the endocarp intact, and then weighed with the endocarp removed. Endocarps were removed using a hand vice similar to a 'G' clamp.

A total of 5,900 seeds were used in this study: 2,600 from plant A(1987 and 1988), 1,900 from B and 1,400 from C. It was not possible to design a balanced experiment because there were not enough seeds. Therefore, a fractional factorial design (Table 5.1, discussed further below) was used, with seeds randomly allocated to treatment groups, in order to test the following six hypotheses:

H1: removing the endocarp has no effect on germination.

H2: cracking the endocarp has no effect on germination.

H3: seed age has no effect on germination.

H4: stratifying seed at 7°C or 15°C, for 7, 14 or 28 days does not increase germination over control seeds stratified at 23°C.

H5: alternating stratification temperature from 23°C to 7°C does not increase germination over seeds stratified at a constant temperature.

H6: seeds from different parents do not have different germination rates.

Imbibition was carried out prior to stratification by wrapping the seeds in moist paper towels and keeping them at 23°C. The experiment was started 84 h after imbibition was begun, this being the time taken for seeds with the endocarp removed to reach a constant weight. Stratification was undertaken in the dark with seeds placed 5 mm apart on two layers of moist Whatman No. 1 filter paper in 10 cm diameter petri dishes, 25 seeds per petri dish. Each

Table 5.1 Maternal plant group, endocarp, and stratification treatments on Olea europaea subsp. africana seeds from Eritrea. Numbers in cells refer to the hypotheses tested by each treatment, (see text).

		Stratification temperature and duration										
		7°C			15°C			23°C			23°C / 7°C	
maternal plant	endocarp treatment	7d	14d	28d	7d	14d	28d	7d	14d	28d	7d	14d
A 1987	intact					3	3					
A 1987	removed					3	3					
A 1988	intact	1 4 6	1 4 6	1 4 6	1 4 6	1 2 3 4 6	1 2 3 4 6	1 4 6	1 4 6	1 4 6		
	removed	1 4 6	1 4 6	1 4 6	1 4 5 6	1 2 3 4 5 6	1 2 3 4 5 6	1 4 5 6	1 4 5 6	1 4 5 6	5	5
A 1988	cracked					2	2					
B	intact		1 4 6	1 4 6	1 4 6	1 2 4 6	1 2 4 6		1 4 6	1 4 6		
B	removed	1 4 6	1 4 6	1 4 6	1 4 5 6	1 2 4 5 6	1 2 4 5 6	1 4 5 6	1 4 5 6	1 4 5 6	5	5
B	cracked						2					
C	intact		1 4 6	1 4 6	1 4 6	1 4 6	1 4 6		1 4 6	1 4 6		
C	removed		1 4 6	1 4 6	1 4 6	1 4 6	1 4 6		1 4 6	1 4 6		

treatment had four replicates of 25 seeds. Seeds were examined every two days and were watered with distilled water as necessary.

The 7°C temperature was obtained using a refrigerator, 15°C using a growth chamber, and 23°C by placing seeds in a laboratory cabinet. Max/Min thermometers placed in each environment and read every two days indicated that temperature variation was 6.6 to 8.5°C in the refrigerator, 14.8 to 15.3°C in the growth chamber and 22.2 to 23.5°C in the cabinet.

The following treatments were applied to test hypotheses 1 through 6 using subsets of experimental treatments shown in Table 5.1. Seeds were randomly allocated to treatment groups.

H1: removing the endocarp has no effect on germination.

A total of 1,800 seeds from plant A 1988, 1600 from plant B and 1,400 from C were used. The endocarp was removed from half of the seeds in each group.

H2: cracking the endocarp has no effect on germination.

A total of 400 seeds from plant A 1988 and 300 from plant B were used. The endocarp was cracked in half of the seeds in each group, except that the 14 d, endocarp cracked treatment for plant B was omitted due to insufficient seed.

H3: seed age has no effect on germination.

A total of 400 seeds from plant A 1987 and 400 from plant A 1988 were used. The endocarps were removed from half of the seeds in each group.

H4: stratifying seed at 7°C or 15°C, for 7, 14 or 28 days does not increase germination over control seeds stratified at 23°C.

a) endocarp removed. A total of 900 seeds from plant A 1988, 900 from plant B, and 700 from plant C were used.

b) endocarp intact. A total of 900 seeds from plant A 1988, 700 from plant B, and 700 from plant C were used.

H5: alternating stratification temperature from 23°C to 7°C does not increase germination over seeds stratified at a constant temperature.

A total of 800 seeds from plant A 1988 and 800 from plant B were used. The alternating temperature regime consisted of stratifying the seeds at 23°C for either 7d or 14 d, followed by stratification at 7°C for either 7d or 14d, and then returning them to 23°C. Those germinated at a constant temperature were the (endocarp removed) seeds used to test hypothesis H1, but with the 7°C stratification treatment excluded.

H6: seeds from different parents do not have different germination rates.

a) endocarp removed. A total of 900 seeds from plant A 1988, 900 from plant B, and 700 from plant C were used.

b) endocarp intact. A total of 900 seeds from plant A 1988, 700 from plant B, and 700 from plant C were used.

After stratification seeds were placed in the 23°C cabinet. The experiment was terminated after 42 days, this being 14 days beyond the longest stratification period. In all cases, the criterion for germination was positive geotropism and elongation of the radicle to 5 mm. Germinated seedlings were removed from the petri dish and planted when the radicle had reached 10 mm and the cotyledons had emerged.

Statistical Analysis

Data were assessed for normality by plotting sorted data against quantiles of a standard normal distribution, and with stem and leaf plots (Wilkinson 1989). The equality of variances between treatment groups and presence of outlying data points were examined visually using box plots and stem and leaf plots.

The mean and standard deviation only were obtained for seed lengths, and for seed weights with and without the endocarp (n = 50 in each case) using untransformed data. Germination data were converted to percentages and arc-sine transformed following Snedecor and Cochrane (1967) prior to analysis of variance (ANOVA). Because there were only 25 seeds per cell (n=25), zero proportions were counted as 1/4n (i.e. 0.01) prior to transformation to angles (Snedecor and Cochrane 1967).

In testing H1, the full model could not be estimated due to missing cells in the fractional factorial design (Table 5.1) (Wilkinson 1989:216). The SSE therefore was re-calculated using treatment means as a single variable. In this way, the factorial design was re-expressed as a one-way ANOVA with one treatment having 48 levels. This resulted in a MSE of 0.008, a discrepancy of minus 0.001 over the multiple ANOVA. Because this discrepancy was so small and because higher order effects were of no theoretical importance (Wilkinson 1989:218), the multiple ANOVA was considered appropriate.

Tests for significant differences between selected treatment means were undertaken using contrast statements (Wilkinson 1989:191 et seq., Petersen 1985:85 et seq.). Although all contrasts were undertaken on a computer, contrast statements can be described, using the notation of Petersen (1985), in the following way:

$$L = k_1 \bar{y}_1 + k_2 \bar{y}_2 + \ldots + k_p \bar{y}_p$$

is a contrast if $\quad k_1 + k_2 + \ldots + k_p = 0,$

where $\bar{y}_1 \ldots \bar{y}_p$ are means of p treatments, and $k_1 \ldots k_p$ are contrast coefficients.

Student's **t** test (SYSTAT™ uses the F test) may be used to test

$$L = k_1\mu_1 + k_2\mu_2 + \ldots + k_p\mu_p = 0,$$

as $t = L / \text{S.E.}\{L\}$, where

$\text{S.E.}\{L\} = \sqrt{\text{MSE}\,[\,(k_1^2/r_1) + (k_2^2/r_2) + \ldots + (k_p^2/r_p)\,]}$,

$r_1 \ldots r_p$ = the number of replicates associated with treatments 1 to p,

MSE = the mean square error from the ANOVA, and

the t test degrees of freedom (d.f.) are the d.f. for error from the ANOVA.

Because multiple hypotheses were tested following several ANOVA's which used subsets of the same data set, probabilities were conservatively adjusted using the Bonferroni procedure (Neter et al 1985, Wilkinson 1989). Thus, for **k** comparisons and a level of significance of α, each of the **k** comparisons was undertaken using α /**k**. In this study, each factorial ANOVA was treated as a multiple comparison (Wilkinson 1989:215) and each contrast as an additional comparison. Therefore the denominator **k** = 47 was used.

Results

Seed Length and Weight

The length of seeds from plant A1987 was significantly less than all other seed lots (Table 5.2). The same plant produced seed one year later (A1988) which was significantly longer than the other seed lots. There was no difference in length between seeds from plants B and C.

The weight of seeds from A1987, with or without endocarp, also was significantly less than the other seed lots. Seeds from A1988 with endocarp left intact were heavier than the other seed lots although when the endocarp was removed there was no difference in seed weight between A 1988 and B. All seeds lots were significantly different from each other in weight in the order A1988 heavier than B > C > A1987. Most noticeable is the two to three fold difference in weight between the lightest seed, A1987 (mean = 60 mg) and the other seed lots.

Taking the arithmetic mean weights of seeds with endocarp intact, the number of seeds per kilogram would be roughly estimated at 5,600 for the heaviest seed (A1988) and 16 700 for the lightest seed (A1987). The increase in seed weight following imbibition for 84 h (Table 5.3) was between 6% and 43% for seeds with endocarp left intact, 15% and 23% for seeds with the endocarp cracked and 65% and 80% for seeds with endocarp removed.

Hypotheses 1 to 6.

Table 5.4 shows the percentage of seeds which germinated for all treatments. Tables 5.5 to 5.10 show the percentage of seeds which germinated for treatment groups testing hypotheses H1 through H6. Table 5.11 shows

Table 5.2 Length of seeds with endocarp, and weight of seeds with and without endocarp from four maternal plant groups of <u>Olea europaea</u> subsp. <u>africana</u>. Numbers are means (± 1 SD) with n = 50 from each maternal plant. Numbers followed by the same letter are not significantly different from each other at $P < .00001$. Numbers followed by † are not significantly different at $P < .005$.

Maternal Plant	Endocarp Length (mm)	Weight seed only (mg)	Weight seed + endocarp (mg)	Number of seeds per kg
A 1987	5.6 ± 0.6 [a]	13 ± 2 [a]	60 ± 9 [a]	16 700
A 1988	8.3 ± 0.8 [b]	25 ± 5 [b]	177 ± 38 [b †]	5 600
B	7.3 ± 0.5 [c]	24 ± 4 [b]	158 ± 32 [a †]	6 300
C	7.4 ± 0.5 [c]	20 ± 4 [c]	130 ± 23 [a]	7 700

Table 5.3 Increase in weight after imbibition of Olea europaea subsp. africana seeds from three maternal plants from Eritrea. Numbers are mean weights of 10 seeds.

Maternal plant	endocarp treatment	Weight: initial (mg)	Weight: after 84h (mg)	Increase (%)
A 1987	intact	88	125	43
A 1987	removed	14	25	80
A 1988	intact	187	223	19
A 1988	removed	24	40	65
A 1988	cracked	168	206	23
B	intact	157	167	6
B	removed	23	39	68
B	cracked	168	193	15
C	intact	109	141	29
C	removed	18	32	79

Table 5.4 Percent germination of Olea europaea subsp. africana seeds from Eritrea by length of stratification at different temperatures, with endocarp intact, removed, or cracked. Numbers are means of four replicates of 25 seeds.

		Stratification temperature and duration										
		7°C			15°C			23°C			23°C/ 7°C	
maternal plant	endocarp treatment	7d	14d	28d	7d	14d	28d	7d	14d	28d	7d	14d
A 1987	intact					16	28					
A 1987	removed					36	42					
A 1988	intact	0	1	0	0	0	0	0	0	0		
A 1988	removed	48	51	53	83	66	65	61	69	66	78	76
A 1988	cracked					16	20					
B	intact		1	0	3	6	9		6	36		
B	removed	39	52	33	52	52	53	55	51	60	60	41
B	cracked						15					
C	intact		19	5	16	27	36		28	20		
C	removed		44	34	58	58	56		57	71		

Table 5.5 Percent germination of Olea europaea subsp. africana seeds from Eritrea by length of stratification at different temperatures, with endocarp intact or removed. Numbers are means of four replicates of 25 seeds.

		Stratification temperature and duration								
		7°C			15°C			23°C		
maternal plant	endocarp treatment	7d	14d	28d	7d	14d	28d	7d	14d	28d
A 1988	intact	0	1	0	0	0	0	0	0	0
A 1988	removed	48	51	53	83	66	65	61	69	66
B	intact	--	1	0	3	6	9	--	6	36
B	removed	39	52	33	52	52	53	55	51	60
C	intact	--	19	5	16	27	36	--	28	20
C	removed	--	44	34	58	58	56	--	57	71

Table 5.6 Percent germination of Olea europaea subsp. africana seeds from Eritrea stratified for 14 or 28 days at 15°C, with endocarp removed or cracked. Numbers are means of four replicates of 25 seeds.

maternal plant	endocarp treatment	14d	28d
A 1988	intact	0	0
A 1988	removed	66	65
A 1988	cracked	16	20
B	intact	6	9
B	removed	52	53
B	cracked	--	15

Table 5.7 Percent germination of Olea europaea subsp. africana seeds from Eritrea collected in 1987 and 1988, stratified at 15°C for 14 or 28 days, with endocarp removed or intact. Numbers are means of four replicates of 25 seeds.

maternal plant	endocarp treatment	14d	28d
A 1987 †	intact	16	28
A 1987 †	removed	36	42
A 1988 †	intact	0	0
A 1988 †	removed	66	65
A 1988 §	intact	0	--
A 1988 §	removed	92	--

† germinated in 1989
§ germinated in 1990

Table 5.8 Percent germination of Olea europaea subsp. africana seeds from Eritrea by length of stratification at different temperatures, with endocarp removed. Numbers are means of four replicates of 25 seeds.

	Stratification temperature and duration								
	7°C			15°C			23°C		
maternal plant	7d	14d	28d	7d	14d	28d	7d	14d	28d
A 1988	48	51	53	83	66	65	61	69	66
B	39	52	33	52	52	53	55	51	60
C	--	44	34	58	58	56	--	57	71

Table 5.9 Percent germination of Olea europaea subsp. africana seeds from Eritrea by length of stratification at different temperatures, with endocarp removed. Numbers are means of four replicates of 25 seeds.

	Stratification temperature and duration							
	15°C			23°C			23 / 7°C	
maternal plant	7d	14d	28d	7d	14d	28d	7d	14d
A 1988	83	66	65	61	69	66	78	76
B	52	52	53	55	51	60	60	41

Table 5.10 Percent germination of Olea europaea subsp. africana seeds from Eritrea by length of stratification at different temperatures, with endocarp intact. Numbers are means of four replicates of 25 seeds.

	Stratification temperature and duration								
	7°C			15°C			23°C		
maternal plant	7d	14d	28d	7d	14d	28d	7d	14d	28d
A 1988	0	1	0	0	0	0	0	0	0
B	--	1	0	3	6	9	--	6	36
C	--	19	5	16	27	36	--	28	20

Table 5.11 Results of ANOVAs for each hypothesis concerning germination of Olea europaea subsp. africana seeds from Eritrea. P values are Bonferroni adjusted with denominator k = 47. strat. = stratification temperature.

Hypothesis	N	Source	degrees of freedom	F	P<
1	192	endocarp	1	803.0	.0001
		strat. temp.	2	32.5	.0001
		parent * endocarp	2	35.3	.0001
2	28	endocarp	1	98.1	.0001
3	32	endocarp	1	216.3	.0001
		parent * endocarp	1	85.1	.0001
4 and 6 endocarp intact	100	parent	2	13.2	.005
		strat. temp.	2	25.0	.0001
4 and 6 endocarp removed	92	parent	2	26.3	.0001
		strat. temp.	2	12.3	.005
		parent * strat. temp.	4	9.3	.001
5	64	parent	1	51.0	.0001
		strat. temp.	1	114.0	.0001

Table 5.12 Results of contrasts for hypotheses 4 and 6, concerning germination of Olea europaea subsp. africana seeds from Eritrea. P values are Bonferroni adjusted with the denominator k = 47.

Hypothesis	N	contrast hypothesis	degrees of freedom	F	P<
4 and **6** endocarp intact	100	7°C ≠ {15,23°C} **b**	1	50.0	.0001
		15°C ≠ 23°C **b**	1	0.0	NS
		parent B ≠ C	1	0.1	NS
		parent A ≠ C	1	11.0	.05
4 and **6** endocarp removed	92	7°C ≠ {15,23°C} **b**	1	23.7	.0001
		15°C ≠ 23°C **b**	1	0.8	NS
		parent B ≠ C	1	15.1	.01

b = stratification temperature

ANOVA results for each treatment group and Table 5.12 shows the results of contrasts conducted on treatment groups 4 and 6.

H1: removing the endocarp has no effect on germination.

The percentage germination of seeds with endocarp intact ranged from 0 to 36 while for seeds where the endocarp was removed between 34% and 83% germinated (Table 5.5). There also are clear differences between parents with A1988 seeds (endocarp intact) producing almost no germination and seeds from B and C (endocarp intact) having up to 36% germination. ANOVA confirms these observations with significant differences also in the effect of stratification temperature on germination (Table 5.11).

H2: cracking the endocarp has no effect on germination.

The percentage germination of seeds with endocarp cracked ranged from 15 to 36 while for seeds where the endocarp was removed between 52% and 65% germinated (Table 5.6). The germination rate of the cracked seeds is significantly lower (Table 5.11). Seeds where the endocarp was left intact had zero or significantly less germination (Table 5.6).

H3: seed age has no effect on germination.

a) seed collected in 1987 and 1988 and germinated in 1989.

The difference in percentage germination between 1987 and 1988 seeds (Table 5.7) was obscured in the ANOVA (Table 5.11) by the non-additivity effect with endocarp (intact or removed). Seeds collected in 1988 had significantly more germination than seeds collected in 1987 where both had the endocarp removed . However, with the endocarp left intact, 1988 seeds did not germinate, whereas 1987 seeds produced between 16% and 28% germination.

b) seed collected in 1988 and germinated in 1989 and 1990.

In order to clarify whether seed storage or year of collection was a factor in determining the above result, seed collected in 1988 was stored for 18 months. The endocarp was removed from 100 seeds randomly chosen and allocated to four replicates of 25 seeds as previously done with 1987 seed. A second group of 100 seeds with endocarp intact were similarly treated. Both groups were stratified at 15°C for 14 d. In this trial, there was no germination of seeds with endocarp intact, but an increase in germination to 92% for those where the endocarp had been removed (Table 5.7).

H4: stratifying seed at 7°C or 15°C, for 7, 14 or 28 days does not increase germination over control seeds stratified at 23°C.

The percentage of seeds with endocarp removed which germinated following stratification at 7°C ranged between 33% and 53%, at 15°C between 52% and 86%, and at 23°C between 51% and 71% (Table 5.8). Germination percentages for seed where the endocarp was left intact were: 7°C ,0% to 19%; 15°C, 0% to 36%; and 23°C, 0% to 36%. Contrasts following ANOVA (Table 5.12) confirm that the percentage germination with a 7°C stratification is significantly less than at either 15°C or 23°C, which are not significantly different from one another.

H5: alternating stratification temperature from 23°C to 7°C does not increase germination over seeds stratified at a constant temperature.

Significantly more seeds germinated with the 23/7°C fluctuating stratification temperature than for either 15°C or 23°C constant temperature (Table 5.9). However, while this result is statistically significant (Table 5.12) it is not practically significant since the differences between treatments are small and mostly accountable to increased germination in seeds from only one parent , A1988 (Table 5.9).

H6: seeds from different parents do not have different germination rates. Contrasts performed on data from treatment groups 4 and 6 (Tables 5.8 and 5.10) confirm that there are significant differences in percent germination between seed from different parent plants (Table 5.12). Moreover, while percent germination from seed lot A was significantly greater than for B or C with endocarp removed, almost no seed from plant A germinated if the endocarp was left intact. The percent germination of seeds from plant C was significantly greater than for seeds from plant B with endocarp intact (Tables 5.10 and 5.12).

Discussion

The most important result of this study is the large increase in germination obtained by removing the endocarp. This result also has been reported for commercial olive cultivars (Crisosto and Sutter 1985a, 1985b, Ellis et al 1985). Crisosto and Sutter (1985a) found that Olea cv. Manzanillo seeds germinated only if the endocarp had been removed or clipped. However, Krugman (1974:559) states that removing or cracking the endocarp does not hasten seed germination in all olive cultivars. In our study seeds collected from plant A in 1988 did not germinate after six months or eighteen months in storage unless the endocarp was removed or cracked, but had high germination if the endocarp was removed (Tables 5.4 and 5.7). In contrast, seeds from plants A1987, B, and C all had some germination even if the endocarp was left intact. It seems, therefore, that there is not only a difference between parents but also between years for the same parent. The fact that cracking the endocarp increased germination over un-cracked controls suggests that the endocarp imposes a mechanical constraint to germination not a chemical one. This conclusion was reached also by Crisosto and Sutter

(1985a) whose test seeds attained 76% germination when the radicle end of the endocarp was clipped off.

One explanation for differing germination rates may be inter-annual and inter-plant variation in seed viability. A second possibility relates to dormancy, control over which appears to reside in either the endosperm or seed coat, possibly both (Lagarda, Martin and Kester 1983). These authors found that while excised embryos, with endosperm and testa removed, did not require stratification, whole seed did. They also suggest that seed maturity is influential in dormancy with germination decreasing after one year of storage, and that cv. Manzanillo seed was viable for three years at best. In a related study, Lagarda, Martin and Polito (1983) found that dormancy occurred in whole seeds after October but not in excised embryos.

However, in our experiment we did not remove the endosperm or testa, only the endocarp. Therefore, if seed maturity and duration of storage were the explanation for the absence of germination in plant A1988 seeds with endocarp intact, they do not explain the high germination rates of these seeds when the endocarp was removed. Moreover, seeds from plant A collected in 1987 and stored for 18 months germinated irrespective of endocarp treatment, albeit to a lesser extent if the endocarp was intact (Table 5.7). Seeds from plant A collected in 1988 and stored for 18 months had the highest germination rate (92%) in our experiment. Therefore, older seed and increasing storage time had either a small negative or else a large positive effect on germination. These observations mean that we must again consider the influence of the endocarp on germination.

The endocarp needs to be broken before radical emergence can occur. This typically is achieved by the endocarp splitting down a suture line which bisects it. Cracking with a hand vice or by rolling a stone over seeds can cause the endocarp to break along or across the suture line. While I am not aware of studies which document germination of <u>O. europaea</u> ssp. <u>africana</u> in the wild, I am familiar with two mechanisms which permit the endocarp to crack or be be removed.

In Rora, I saw parrots, possibly Poicephalus spp. (Williams and Arlott 1980:99-100), feeding on olive seeds in 1984. In order to get access to the seed, a bird would remove a fruit and then crack the endocarp using one foot and its beak to explore the seed with its tongue. Sometimes the birds ate the seed, sometimes they discarded it, and sometimes the seed simply fell as the endocarp was cracked open. Thus, seed minus endocarp would fall beneath the canopy of the tree. I have not seen any bird ingest whole fruits or any parrots fly with whole fruits in their beaks from tree to tree, though this probably happens. The parrots have not been seen on the plateau since 1984, possibly because of drought and possibly because of a decline in their food source.

A second mechanism that will crack the endocarp requires that the seed lay on or in the ground for several months. Krugman (1974:559) states that olive seeds planted in autumn may not germinate until the second year. In the wild, seeds from olives in Eritrea would fall to the ground any time from late September, depending on the timing and duration of the rains. At maturation, the endocarp is very slightly elastic because of the water it contains. During the dry season, from October to May, the endocarp loses moisture, becoming inelastic and harder. The seed also loses moisture, though by a smaller percentage of original weight. In the process, depending on their original status and the intensity of the drying out, a proportion of seeds probably die or lose viability.

Since the endocarp is permeable to water, it swells and increases in weight when wetted, for example during the following rainy season. In this way, sufficient forces exist along the suture line to crack the endocarp, permitting imbibition and releasing the mechanical constraint to radicle emergence. This is the mechanism that occurred in our experiment after seeds had been stored (Table 5.4). The reason why the endocarp did not split in seeds collected from plant A in 1988 and stored for either six or eighteen months is unclear. It is possible that these fruits needed to dry out more thoroughly than our storage method (dark plastic vials at 20°C) permitted. Microscopic examination of the endocarp from different parents, after different drying periods and storage regimes would be a desirable next step.

Stratification temperature and duration are important factors in the germinability of cv. Manzanillo and other cultivars. Ellis et al (1985:516) state that intact dormant olive seeds will not germinate above 25°C whereas excised embryos will germinate at 25°C. Lagarda, Martin and Polito (1983) found that whole seed germination rate was greater at 15°C than at 25°C but that excised embryo germination rate was greater at the higher temperature. Crisosto and Sutter (1985a) found that germination did not occur at 7°C, 20°C or 25°C but that 85 to 95% germination occurred in cv. Manzanillo at a stratification temperature of 15°C.

In our study, there was no difference in germination with stratification temperatures of 15°C and 23°C but stratifying at 7°C reduced germination. There was no difference in percent germination between stratification periods of 7, 14 or 28 d duration. It seems then that while there may be a requirement for a cold period for germination in O. europaea cultivars (Lagarda, Martin and Kester 1983), no such requirement exists for seed germination for O. europaea ssp. africana.

Conclusion

Growing O. europaea ssp. africana plants from seed is important in Eritrea both as part of a reforestation effort and to maintain germplasm for use in breeding programmes. Germination is greatly enhanced by removing the endocarp from seeds, reaching up to 92% in seed stored for 18 months. Low-temperature stratification does not appear to be necessary. Further increases in germination may be obtainable by more detailed study of the effects of seed maturity and storage regime and of inter-annual and parent plant differences in germination.

A moderate percentage of seed germinates even with no treatment so that mortality of this species in the wild probably relates to adverse environmental conditions or predation by livestock after the seed has germinated. There appears to be no germination constraint to the nursery production of olive trees in Eritrea, using locally obtained seed with endocarps removed. Given the declining state of the woodlands in which O. europaea ssp. africana is a dominant plant, such production should begin as soon as possible.

VEGETATIVE PROPAGATION OF OLEA EUROPAEA SUBSP. AFRICANA

Introduction

Olive trees have been cultivated for oil extraction and for edible fruit for at least 5000 years. The deliberate propagation of O. europaea cultivars has long been practised in Mediterranean countries as well as in southern Africa, Australia and the New World where olive trees were introduced by Italian and Spanish travellers (Fernandez-Diez 1971). Many hundreds of O. europaea cultivars now are grown for various characteristics (Fernandez-Diez 1971) but because the cultivar is not produced from seed (Hartmann et al 1980), plants typically are propagated vegetatively.

Hartmann et al (1980) describe the four commonest methods of vegetative propagation for O. europaea: hardwood cuttings, semi-hardwood cuttings, detached suckers and grafting. In addition, olive may be propagated by branch segments, or "truncheons", up to 20 cm long and 15 cm diameter, which are planted directly 8 to 15 cm under the soil surface. In California, several O. europaea cultivars now grown as hedgerows are being experimentally propagated by truncheons (Isern and Osgood 1990). Recently embryogenesis and micro-propagation techniques also have been investigated for *in vitro* propagation of O. europaea (Rugini 1984, Cañas et al 1987, Rama and Pontikis 1990).

While I am not aware of any work on subsp. africana, most O. europaea cultivars are propagated from hardwood or semi-hardwood cuttings. Experiments on many O. europaea cultivars have demonstrated the influence on rooting of misting, shading, rooting hormone, applying heat to propagation beds, the concentration and type of rooting hormone, rooting medium, wood age, the position on the tree from which cuttings are taken, and time of year when cuttings are taken (Hartmann 1946, Loretti and Hartmann

1964, Hartmann and Loretti 1965, Opitz and Hartmann 1975, Hartmann et al 1980, Lee et al 1983). The results of these studies also suggest that propagation by cuttings is influenced by the physiological state of the parent plant, something recognised as a general principle in vegetative propagation (Leakey 1985:110, Moe and Andersen 1988). Also noted in studies of other species is that the rooting ability of tree cuttings is strongly influenced by genotype, although little is known of the mechanisms controlling genetic effects on vegetative regeneration (Leakey 1985, Haissig and Riemenschneider 1988:51-3).

O. europaea subsp. africana is not deliberately propagated vegetatively in Eritrea or, to my knowledge, elsewhere. However, suckers may be found in ungrazed areas and new growth emerges readily from the stumps of felled trees and from the cut surfaces of trees which have been pollarded to provide dry-season animal fodder. Olive propagation by cuttings is attractive in Eritrea because of the relatively rapid growth rates reported for olive cuttings elsewhere (Tom Dungan, nurseryman, Visalia California, personal communication) and the shortage of olive seed locally. However, olive woodlands in Eritrea apparently have declined rapidly in recent years and the remaining trees almost certainly have been stressed over the past decade by repeated droughts and soil nutrient impoverishment associated with severe erosion. I examined several hundred olive trees in Eritrea between 1986-9 and found that all but a few were heavily coppiced and had little foliage.

Initially, field experiments were established in Bacla village in 1987 to investigate whether the age of the material and its position on the parent plant affected rooting and growth of cuttings. However these were lost in a flood. For repeat experiments in the glasshouse only one-year old stock plants were available; these had been grown from seed collected from three parents along Rora Habab and grown in pots in the glasshouse. Two experiments were carried out. Experiment (1) examined the effects of rooting hormone, parent plant and type of cutting (heel vs. obliquely cut base). Experiment (2) examined the effects of parent plant, the type of cutting, and various fertiliser and watering regimes to which parent plants had been subjected prior to taking cuttings.

Methods

Experimental Design

In both experiments, semi-hardwood cuttings between 10 and 12 cm long (3 to 5 nodes) were taken between 7 and 11 a.m. in July 1990 from the basal portions of lateral branches of one year old parent plants. All plants were watered to field capacity two days before cuttings were taken. Leaf area for each cutting was reduced to between 10 and 15 cm^2 by removing lower leaves and trimming the remaining two to three leaves. Thus, confounding effects between parents were minimised by having all parent plants of the same age and from a known seed source, and with parents and cuttings treated identically except where specific environmental conditions (described below) were experimentally introduced (Haissig and Riemenschneider (1988:53).

Experiment 1

A total of 200 cuttings were taken on 5 July 1990, 100 from each of two parents. All parents had been fertilised with 2.0 g l^{-1} water-soluble Complete fertiliser with B, Cu, Fe, Mn and Zn micronutrients. Half of the cuttings from each parent were dipped in commercial rooting hormone powder with fungicide ("Rootone", containing 0.20% 1-Napthalene acetamide (NAA), 0.10% Indole-3-butyric acid (IBA) and 4.04% 'Thiram' fungicide in a talc base), and half were untreated controls. From each parent, sixty cuttings were taken with a clean, obliquely-cut base, and forty cuttings were taken with a heel left at the base. The cuttings were inserted into 3 mm grain size washed silica, in two 50 by 30 by 15 cm planting trays, 10 cuttings per row, one planting tray for each parent. One half of each tray was used for cuttings with hormone and the other half for untreated controls.

The planting trays were placed in a shaded greenhouse where daylight was attenuated by 60% (maximum was 900 uE m^2 sec^{-1}), under a misting regime of 3 seconds of fine mist every 4 minutes. No supplementary lighting was used and photoperiod was between 15 h and 12 h of light. The position of the planting trays was changed weekly. Air temperatures varied between 23°C and 27°C during the day and 15 to 18°C at night. For three two-hour periods temperatures reached 30 to 33°C when the greenhouse air conditioning failed. Relative humidity, which never fell below 70%, typically was between 75% and 80% during the day and 95% to 100% at night. Temperatures in the rooting media varied between 22°C and 24°C. Bottom heat was not applied to the planting trays.

Cuttings were examined weekly from 2 weeks after planting. After 90 d the presence or absence of roots (RPA) was recorded as a categorical variable with 1 = rooting negative, 2 = callus formed, and 3 = rooting positive. Where rooting occurred the total root length (RL), including branchlets ≥1 mm, was measured. The presence or absence of new leaves (LPA) was recorded with 1 = no new leaves, and 2 = new leaves. For cuttings which grew leaves, the number of new leaves ≥5 mm long (LN) was counted.

Experiment 2

A total of 240 cuttings were taken on 13 July 1990, 80 from each of three parent groups. The plants from which cuttings were taken had been subjected to 3 months of various fertiliser and watering regimes (Table 5.13, methods fully described in chapter 7). The fertilised parents had been watered to field

Table 5.13 Number of cuttings taken by watering and fertiliser regimen (10 cuttings per combination) from each of three O. europaea subsp. africana parent groups for experiment (2), (see text).

	parent group watered every (d)				
	7	14	21	28	x 3 parents =
fertilised	10	10	10	10	120
un-fertilised	10	10	10	10	120
x 3 parents =	60	60	60	60	240

Table 5.14 Numbers of O. europaea subsp. africana cuttings which rooted or formed callus after 90 d, according to parent plant, application of rooting hormone, and type of cutting. Numbers are counts with X^2 residuals in parenthesis ($[o-e]^2/e$, where **o** = observed frequency and **e** = expected frequency. Signs indicate the direction of departure from homogeneity). Chi square significance adjusted to ensure a family comparison error rate not larger than $\alpha = .01$ for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968.

	no root	callus	rooted	total	Chi square
parent A	13 (0.1) +	11 (7.3) -	76 (2.6) +	100	
parent B	11 (0.1) -	38 (7.3) +	51 (2.6) -	100	20.0, p< .01
with hormone	6 (2.9) -	12 (6.3) -	82 (5.3) +	100	
no hormone	18 (2.9) +	37 (6.3) +	45 (5.3) -	100	29.5, p< .01
heel cutting	14	24	42	80	
oblique cut	10	25	85	120	7.5, NS

capacity weekly with 2.0 g l^{-1} water-soluble complete fertiliser with Cu, Fe, Mn and Zn micronutrients. Twenty-eight days after the last application of fertiliser, each of these plants, together with unfertilised controls, were subjected to varying lengths of drought. This was achieved by watering different groups to field capacity every 7, 14, 21, or 28 d with distilled water. Ten cuttings were taken from each combination of fertiliser and watering regime 42 days after this watering regime was started (Table 5.13).

The combinations of watering and fertiliser regime resulted in parent plants which were dissimilar in physiological status and appearance at the time cuttings were taken. All unfertilised parents showed signs of nutrient deficiency, having leaves which were yellow or very pale green with purple mottles and brown tips. Many of the older leaves had been abscised by the time cuttings were taken, though wilting was never observed in these leaves prior to abscission. Between two and ten new leaves grew on 63% of the cuttings from unfertilised parents during the 42 d of the watering regime. In contrast, all fertilised parents had uniformly dark green leaves with no yellow or brown patches and no mottles. No leaves were abscised in the 7d or 14 d watering treatment and all parents produced abundant new leaves especially at growing tips, where up to 8 cm of new shoot growth occurred on some plants.

The parents which had been fertilised and watered every 21 d were wilting heavily by the 37th day of the watering regime with many newly grown leaves brown and shrivelled. After they were watered to field capacity at 42 d, all but two plants recovered although newly formed leaves and the growing tips of many plants had died. The parents which had been fertilised and watered every 28 d had lost most of their leaves and were wilting heavily by the 24th day of the watering regime. After they were watered at 28 d all of the plants in this group appeared dead. However, while none of these plants had leaves at the time cuttings were taken, the stem and branches remained moist, with a film of sap visible under a hand lens at the cut end of branches. Because the cuttings in this group were the only ones which were leafless, it was important to assess whether the absence of leaves in itself would prevent rooting or the growth of new leaves. Therefore, leaves were removed from a further ten cuttings taken from healthy parents watered at 14 d or 21 d intervals, five each from fertilised and unfertilised plants.

The base of all cuttings was dipped in "Rootone" rooting hormone. The cuttings were inserted into 3 mm grain size washed silica, in tapered tubular pots measuring 2.5 cm at the top by 16 cm long, 10 cuttings per row, in two planting trays. The planting trays were placed in a shaded greenhouse where their position was changed weekly and where environmental conditions and misting were the same as for experiment (1).

Cuttings were examined weekly from 2 weeks after planting. After 45 d and 90 d RPA, RL, LPA and LN were recorded as in experiment (1), except that LPA and LN were examined only after 90 d. Additionally, where rooting occurred the number of roots emerging from the cutting (RN) was counted.

Statistical Analyses

Experiment 1

Differences in RPA and LPA between parents, rooting hormone treatment, and type of cutting were examined via contingency tables using the X^2 test of homogeneity (Daniel 1978:160-188, Wilkinson 1989:470-505). Because the same data were used for several tests, the tests were not independent. Therefore, the multiple tests were conducted simultaneously using Bonferroni X^2 statistics to ensure a family comparison error rate not larger than α = .01, following Jensen et al (1968:46-56).

Comparisons of differences in RL between parents, hormone treatment and type of cutting were undertaken using distribution-free methods. This was because of the 127 cuttings which rooted, the roots of 46% were 10 mm long and a further 23% were 20 mm long. With so many data at the lower end of the distribution, transformations to permit conventional Analysis of Variance (Anova) were not possible. Therefore, analyses employed the Mann-Whitney U-test on a data set reduced to the 127 cases which rooted, following Daniel (1978:82-6) and Wilkinson (1989:365-7).

Data for LN were assessed for normality, equality of variances between groups, and presence of outlying data points. Following these measures and appropriate analysis of residuals (Wilkinson 1989, Neter et al 1989), logarithmic transformations were undertaken prior to an Anova.

Correlations between RPA and LPA were examined via contingency tables using the X^2 test of homogeneity and Bonferroni X^2 statistics as above.

Experiment 2

Differences in RPA and LPA between treatment groups were examined using X^2 analysis as in experiment (1). After appropriate assessment as in experiment (1), logarithmic transformations were undertaken on LN and RL prior to Anova. Correlations between RPA and LPA were examined via contingency tables using X^2 analysis as in experiment (1).

Transformations of RN to permit Anova were not possible. Therefore differences in RN between parents, fertiliser treatment, watering regime and type of cutting were examined via contingency tables and analysed using the the Mann-Whitney U test for 2 x 2 tables and the Kruskal-Wallis test for > 2 x 2 tables, on a data set reduced to the 91 cases which rooted, following Daniel (1978:201-5) and Wilkinson (1989:365-7).

Results

In the following tables which present results based on X^2 analysis, squared residuals (counts of numbers of observed minus expected { $[o-e]^2/e$ }) from the analysis are given in parentheses. Significant departures from homogeneity are indicated as such in the tables but referred to in the text simply as "significant differences". The largest squared residuals indicate the largest departures from homogeneity and their sign indicates the direction. Where the sum of the squared residuals does not equal the X^2 value, this is due to rounding error.

Experiment 1

There were significant differences in the number of cuttings which rooted or formed callus between parents and between hormone treatments (Table 5.14). More cuttings from parent A rooted (76%) than for parent B (51%). The differences in the number of cuttings which formed callus were in the opposite direction and accounted for three quarters of the significant X^2 statistic with more callused cuttings from parent B (38%) than from parent A (11%). Nearly twice as many cuttings rooted with hormone applied (82%) than untreated controls (45%) but more callus formed on the controls (37%) than on hormone-treated cuttings (12%). There were no significant differences in the number of rooted cuttings between those taken with a heel or those which were obliquely cut.

There was a weakly significant difference in RL between cuttings which had been dipped in rooting hormone (median 30 mm) and those which had not (median 20 mm) (X^2 5.2, $p < 0.09$). There were no significant differences in RL between parents or type of cutting.

Significantly more cuttings which were treated with hormone grew new leaves than did untreated controls (68% vs. 40%) (Table 5.15). There were no

Table 5.15 Numbers of O. europaea subsp. africana cuttings which produced new leaves after 90 d, according to parent plant, application of rooting hormone, and type of cutting. Numbers are counts with X^2 residuals in parenthesis ($[\mathbf{o}-\mathbf{e}]^2/\mathbf{e}$, where **o** = observed frequency and **e** = expected frequency. Signs indicate the direction of departure from homogeneity). Chi square significance adjusted to ensure a family comparison error rate not larger than $\alpha = .01$ for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968.

	no new leaves	new leaves	total	Chi square
parent A	36	64	100	
parent B	56	44	100	8.1, NS
with hormone	32 (4.4) -	68 (3.6) +	100	
no hormone	60 (4.4) +	40 (3.6) -	100	15.8, p< .01
heel cutting	43	37	80	
oblique cut	49	71	120	3.2, NS

Table 5.16 Numbers of O. europaea subsp. africana cuttings which rooted and formed new leaves after 90 d. Numbers are counts with X^2 residuals in parenthesis ($[\mathbf{o}-\mathbf{e}]^2/\mathbf{e}$, where **o** = observed frequency and **e** = expected frequency. Signs indicate the direction of departure from homogeneity). Chi square significance adjusted to ensure a family comparison error rate not larger than $\alpha = .01$ for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968.

	no root	callus	rooted	total	Chi square
no new leaves	18 (4.4) +	39 (12.3) +	35 (9.6) -	92	
new leaves	6 (3.6) -	10 (10.2) -	92 (7.8) +	108	
total	24	49	127	200	47.8, p< .01

significant differences in the number of cuttings which grew new leaves between parents, or between type of cutting (Table 5.15). There were no significant differences in the LN between parents or treatment groups.

There was a strong association between rooting and the growth of new leaves (Table 5.16). New leaves grew on only 28% of the cuttings which formed callus or did not root, whereas 72% of rooted cuttings also grew new leaves.

Experiment 2

In order to facilitate comparison between groups of unequal sizes, data are presented as percentages in the text. However, tables present data as frequency counts. After 45 d, there were significant differences in the number of cuttings which rooted or formed callus between parents, between prior fertiliser regimes, and between prior watering regime treatments (Table 5.17). More cuttings from parent A rooted (45%) than from parent B (16%) or parent C (18%). However, more cuttings from parents B and C formed callus (24% and 25%) than did cuttings from parent A (4%). For cuttings taken from fertilised parents 38% rooted and 32% formed callus whereas 83% of cuttings taken from unfertilised parents failed to root or form callus. Rooting occurred in between 25% and 37% of cuttings taken from parents watered at intervals of 7 d, 14 d or 21 d but in only 8% of cuttings from parents watered at 28 d intervals. When the data were reanalysed with the 28 d category removed, the Bonferroni-adjusted X^2 of 2.9 was not significant, indicating no differences between the numbers of rooted cuttings between 7 d, 14 d or 21 d watering regimes. There were no significant differences in the number of rooted cuttings between those taken with a heel or those which were obliquely cut.

After 90 d, there were also significant differences in rooting between parents, fertiliser and watering regime, but no differences by type of cutting (Table 5.18). As at 45 d, when the data for watering regime were reanalysed

Table 5.17 Numbers of O. europaea subsp. africana cuttings which rooted or formed callus after 45 d, according to parent plant, whether parent plants were fertilised, the intervals between watering of parent plants, and type of cutting. Numbers are counts with X^2 residuals in parenthesis ($[\mathbf{o}-\mathbf{e}]^2/\ \mathbf{e}$, where **o** = observed frequency and **e** = expected frequency. Signs indicate the direction of departure from homogeneity). Chi square significance adjusted to ensure a family comparison error rate not larger than α = .01 for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968.

	no root	callus	rooted	total	Chi square
parent A	41 (0.4) -	3 (8.6) -	36 (10.7) +	80	
parent B	48 (0.2) +	19 (1.8) +	13 (3.1) -	80	
parent C	46 (0.0) +	20 (2.6) +	14 (2.3) -	80	29.7, p < .01
fertilised	36 (14.7) -	38 (13.8) +	46 (6.7) +	120	
un-fertilised	99 (14.7) +	4 (13.8) -	17 (6.7) -	120	70.3, p < .01
watered every 7d	32 (0.1) -	13 (0.6) +	15 (0.0) -	60	
watered every 14d	24 (2.8) -	14 (1.2) +	22 (2.5) +	60	
watered every 21d	25 (2.3) -	14 (1.2) +	21 (1.7) +	60	
watered every 28d	54 (12.2) +	1 (8.6) -	5 (7.3) -	60	40.5, p < .01
heel cutting	36	11	19	66	
oblique cut	99	31	44	174	0.3, NS

Table 5.18 Numbers of O. europaea subsp. africana cuttings which rooted or formed callus after 90 d, according to parent plant, whether parent plants were fertilised, the intervals between watering of parent plants, and type of cutting. Numbers are counts with X^2 residuals in parenthesis ($[\mathbf{o}-\mathbf{e}]^2/\ \mathbf{e}$, where **o** = observed frequency and **e** = expected frequency. Signs indicate the direction of departure from homogeneity). Chi square significance adjusted to ensure a family comparison error rate not larger than $\alpha = .01$ for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968.

	no root	callus	rooted	total	Chi square
parent A	29 (1.1) -	7 (3.8) -	44 (6.2) +	80	
parent B	43 (1.7) +	19 (1.5) +	18 (5.0) -	80	
parent C	34 (0.0) -	17 (0.5) +	29 (0.1) -	80	19.8, $p < .01$
fertilised	34 (6.8) -	35 (8.5) +	51 (0.7) +	120	
un-fertilised	72 (6.8) +	8 (8.5) -	40 (0.7) -	120	31.9, $p < .01$
watered every 7d	24 (0.2) -	15 (1.7) +	21 (0.1) -	60	
watered every 14d	17 (3.4) -	14 (0.1) +	29 (1.7) +	60	
watered every 21d	16 (4.2) -	12 (0.1) +	32 (3.8) +	60	
watered every 28d	49 (19.1) +	2 (7.1) -	9 (8.3) -	60	50.8, $p < .01$
heel cutting	27	15	24	66	
oblique cut	79	28	67	174	1.5, NS

Table 5.19 Percent of Olea europaea subsp. africana cuttings which rooted after 45d and 90d in experiment (2), according to parent plant, whether parent plants were fertilised, the intervals between watering of parent plants, and type of cutting.

	percent of cuttings rooted after	
	45 days	90 days
parent A	45	55
parent B	16	23
parent C	18	36
fertilised	38	43
unfertilised	14	33
watered every 7d	25	35
watered every 14d	37	48
watered every 21d	35	53
watered every 28d	8	15
heel cutting	29	36
oblique cut	25	39

Table 5.20 Percentages of O. europaea subsp. africana cuttings which rooted according to fertiliser and watering regime treatments applied to parent plants.

Watered every	Fertilised (%)	Unfertilised (%)	Total (%)
7 days	43	27	35
14 days	63	33	48
21 days	63	43	53
28 days	0	30	15
Total (%)	43	33	38

Table 5.21 Numbers of O. europaea subsp. africana cuttings which produced new leaves after 90 d, according to parent plant, whether parent plants were fertilised, the intervals between watering of parent plants, and type of cutting. Numbers are counts with X^2 residuals in parenthesis ($[o-e]^2 / e$, where **o** = observed frequency and **e** = expected frequency. Signs indicate the direction of departure from homogeneity). Chi square significance adjusted to ensure a family comparison error rate not larger than α = .01 for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968.

	no new leaves	new leaves	total	Chi square
parent A	52	28	80	
parent B	54	26	80	
parent C	55	25	80	0.3, NS
fertilised	52 (10.1) -	68 (20.5) +	120	
un-fertilised	109 (10.1) +	11 (20.5) -	120	61.3, p < .01
watered every 7d	36 (0.4) -	24 (0.9) +	60	
watered every 14d	36 (0.4) -	24 (0.9) +	60	
watered every 21d	29 (3.1) -	31 (6.4) +	60	
watered every 28d	60 (9.7) +	0 (19.7) -	60	41.7, p < .01
heel cutting	44	22	66	
oblique cut	117	57	174	0.01, NS

with the 28 d category removed, the Bonferroni-adjusted X^2 (4.7) was not significant. Two differences in rooting between 45 d and 90 d are noteworthy (Table 5.19). Whereas rooting from parents B and C was almost identical at 45d, 15 more cuttings from parent C but only 5 more from parent B had rooted after 90 d. Secondly, a further 23 cuttings taken from unfertilised parents rooted in contrast to only 5 more from fertilised parents.

None of the (leafless) cuttings from the fertilised, 28 d watering regime rooted or formed new leaves, in contrast to cuttings from the unfertilised 28 d watering regime, nine of which rooted (Table 5.20). Of the ten cuttings which had been deliberately stripped of their leaves, two rooted and six grew new leaves.

There were significant differences in RN by parent, fertiliser and watering regime, but no differences by type of cutting. Cuttings from parent B grew more roots ($\bar{x}$ 5.6) than parents A or C ($\bar{x}$ 4.4, 4.2) (K-W 17.0, $p < 0.002$). Cuttings from fertilised parents grew more roots ($\bar{x}$ 5.9) than those from unfertilised parents ($\bar{x}$ 2.9) (X^2 4.9, $p < 0.05$). Cuttings from parents with the 28d watering regime grew significantly fewer roots ($\bar{x}$ 1.8) than those from 7 d, 14d, 21 d regimes ($\bar{x}$ 5.3, 4.1, and 5.3) (K-W 24.6, $p < 0.002$). When the data were reanalysed with the 28 d category removed, the Bonferroni-adjusted K-W of 3.7 was not significant.

There was a significant difference in RL between cuttings from fertilised (median RL 230 mm) and unfertilised plants (median RL 50 mm) (F 14.0, $p < 0.004$). There were no significant differences in RL between parents, watering regime or type of cutting.

There were significant differences in the number of cuttings which grew new leaves according to fertiliser and watering regime treatments, but not by parent or type of cutting (Table 5.21). Only 11 (9%) cuttings taken from unfertilised parents grew new leaves in contrast to 68 (57%) cuttings from fertilised parents. No cuttings from parents watered every 28 d grew new leaves. When the data for watering regime were reanalysed with the 28 d category removed, the Bonferroni-adjusted X^2 (2.2) was not significant. There were no significant differences in the LN between parents or treatment groups.

There was a strong association between rooting and the growth of new leaves (Table 5.22). New leaves grew on only 9% of the cuttings which did not root but 40% of callused cuttings and 57% of rooted cuttings grew new leaves.

The average rooting for experiment (1) was 63.5% while that for experiment (2) was 26.3%, largely because of the influence of unfertilised parents, the 28d watering regime, and the low rooting of parent B in experiment (2) compared with experiment (1).

Discussion

The percentage of cuttings which rooted was significantly influenced by parent plant, hormone treatment, and prior fertiliser treatment, but not by prior watering regime or type of cutting (Table 5.23). Parent plant influenced rooting and root number but not root length, the growth of new leaves, or the number of new leaves. Applying rooting hormone to cuttings increased rooting, root length, the growth of new leaves, and the number of new leaves. Prior fertilisation of parent plants increased rooting, root number, root length and the growth of new leaves in cuttings, compared to unfertilised parents. The formation of roots or callus was likely to be associated with the growth of new leaves.

The absence of leaves on the cuttings from the fertilised, 28 d watering regime group was not in itself responsible for the absence of rooting in that group, since rooting occurred in two of the ten cuttings from the 14 d or 21 d watering regime which had been deliberately stripped of their leaves. This indicates that photosynthesis is not a requirement for root formation (Hartmann et al 1990:241) and suggests that the cuttings from the fertilised 28 d

Table 5.22 Numbers of O. europaea subsp. africana cuttings which rooted and formed new leaves after 90 d. Numbers are counts and percentages, with X^2 residuals in parenthesis ($[o-e]^2/ e$, where **o** = observed frequency and **e** = expected frequency. Signs indicate t he direction of departure from homogeneity). Chi square significance adjusted to ensure a family comparison error rate not larger than $\alpha = .01$ for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968. Chi square significance adjusted to ensure a family comparison error rate not larger than $\alpha = .01$ for **t** simultaneous tests, with **u** degrees of freedom for each, following Jensen et al 1968.

		no root	callus	rooted	total	Chi-square
new leaves	frequency *percent*	10 (17.7) - *9*	17 (0.6) + *40*	52 (16.2)+ *57*	79	
no new leaves	frequency *percent*	96 (8.7) + *91*	26 (0.3) - *60*	39 (8.0) - *43*	161	
total		106	43	91	240	51.5, $p < .01$

Table 5.23 Summary of the effects of parent plant, hormone, cutting type, and prior fertiliser and watering regimes on rooting (RPA), root number (RN), root length (RL), new leaf production (LPA), and leaf number (LN) in O. europaea subsp. africana cuttings from two experiments. "Y" indicates a significant effect, "N" a non-significant effect, "--" indicates not tested.

	Response										
	---- Experiment 1 ----				------------ Experiment 2 ------------						
					-- RPA --			--- RL ---			
Factor	RPA	RL	LPA	LN	45d	90d	RN	45d	90d	LPA	LN
parent plant	Y[1]	N	N	N	Y	Y[2]	Y	N	N	N	N
hormone	Y[3]	Y	Y[4]	Y	--	--	--	--	--	--	--
cutting type	N	N	N	N	N	N	N	N	N	N	N
prior watering[5]	--	--	--	--	Y	Y	Y	N	N	Y	Y
prior fertilization	--	--	--	--	Y	Y	Y	Y	Y	Y	N

[1] Parent A had greater rooting but parent B had greater callus formation.
[2] At 45 d, parent A had greater rooting than parents B and C but parents B and C had greater callus formation; at 90d rooting in parent A > parent C > parent B.
[3] Cuttings treated with hormone had greater rooting but cuttings without hormone treatment had greater callus formation.
[4] Because rooting was greater in cuttings treated with hormone, and LPA was greater in rooted cuttings.
[5] For all "Y" outcomes, cuttings from the 28d prior watering regime did significantly less well than cuttings from the 7d, 14d, and 21d regimes, which were not significantly different from each other.

watering regime were dead, not simply drought stressed, at the time cuttings were taken. Assuming this, and given the rooting percentages from all other fertiliser/watering regime combinations (Table 5.20), it appears that rooting was not influenced by the different water regimes applied to parent plants, including the severe drought stress reached by the parents watered every 21d. Indeed, if there is a trend, it is toward increased rooting as drought length increased from 7d to 21d (Table 5.20). Moreover, when the 28 d watering treatment is omitted then the rooting percentage of cuttings is 57% for fertilised parents and 34% for unfertilised parents, compared with 43% and 33% with the 28d watering treatment included (Table 5.20).

Rooting percentages reported for O. europaea range from zero to 99% but are highly variable according to cultivar, propagation and environmental conditions. Most O. europaea cultivars apparently root without difficulty but some, such as cv. Sevillano, apparently are difficult to root and require the application of bottom heat to the rooting medium and rooting hormone to the base of the cutting (Hartmann 1946, Hartmann et al 1980). Opitz and Hartmann (1975) found that IBA in a talc carrier was as effective in rooting olive cuttings as a five second dip in 4 000 ppm solution of IBA. For O. europaea cv. Swan Hill in Australia, Lee et al (1983) found that while the number of roots was greatest on cuttings to which 3 000 ppm IBA had been applied, 50% to 60% rooting occurred throughout the range 3 000 to 10 000 ppm IBA. Rooting percentages in our study ranged from 8% to 76%, with cuttings from fertilised plants with hormone applied having the greatest rooting.

Since O. europaea is an evergreen species, cuttings could be taken at any time of year but rooting typically is greater if cuttings are taken in spring or summer and rooting hormone is applied (Hartmann and Loretti 1965, Tom Dungan, nurseryman, Visalia California, personal communication). While this study did not address seasonal effects on rooting results suggest that rooting from O. europaea subsp. africana cuttings taken in mid-summer is improved by the application of NAA/IBA hormone. Bottom heat was not required although its use may possibly have increased rooting.

Our experiments ended at 90 d. Differences between parents and treatments might have become less pronounced if the cuttings had been harvested at a later date, although olive cuttings generally root by 84 d (Hartmann et al 1980:25). This trend is suggested by the fact that unfertilised plants and some parents, which had lower rooting in the first 45 d, had greater rooting between 45 d and 90 d. Also, our results suggest that cuttings which formed callus later grew roots. However, the data do not reveal whether callus formation is independent of or a precursor to root initiation. Hartmann et al (1990:204) suggest that callus formation might be a necessary precursor to root initiation for some, but not all species.

Fertilising parent plants increased their leaf area and growth of woody tissues (Chapter 6). An analysis of the carbohydrates present in parent plants or cuttings was not undertaken in this study although there is presumably a trade-off between storage of carbohydrate reserves and depletion of carbohydrates for new root and shoot growth in cuttings (Kramer and Koslowski 1979). Hartmann et al (1990:239) state that while root initiation is temperature driven, subsequent root growth is strongly dependent on available carbohydrates and that shoot growth can divert carbohydrates from developing root initials. The fact that unfertilised parents produced cuttings which had fewer roots (RN), much less total root length (RL) and were associated with much less new leaf growth (LPA) than fertilised plants, suggests that fertilisation had not only increased the growth of parents (Chapter 6) but increased the amount of carbohydrate in the tissues used for cuttings. Further work is required to explore this hypothesis.

It is clear that cuttings from fertilised parents grew more rapidly than those from unfertilised parents and needed transplanting to bigger pots at

90 d. Thus, the vigour of the parent plant was an important controlling factor in the vigour of explants, increasing the speed and reliability with which they may be grown. Future work involving fertilisation of cuttings following root initiation will be important in assessing nursery practices and growth rates prior to outplanting.

Conclusion

Under the experimental conditions of this study, cuttings from O. europaea subsp. africana root fairly easily. Rooting and the growth of new leaves are strongly influenced by the nutrient status of parent plants and the application of rooting hormone to the base of cuttings. Significantly greater rooting and growth of new leaves occurred in cuttings from fertilised parents and cuttings to which rooting hormone had been applied, than in cuttings from unfertilised parents, or with no hormone applied. In both instances, root initiation and the growth of new leaves were strongly correlated.

There were clear differences between parents with respect to rooting, though not with new leaf growth, indicating the importance of considering parental effects experimentally in order to identify appropriate stock plants.

Future research in Eritrea will focus on the interactions between the physiological status of parent plants, the type and concentration of rooting hormone applied to cuttings, the effects on root formation and other variables of parent plant over successive years, season at which cuttings are taken, and cutting age, size and position on parent plant.

FACTORS AFFECTING THE GERMINATION OF JUNIPERUS EXCELSA

Introduction

Juniperus excelsa is the second commonest tree along the Rora plateau, providing fuelwood, construction timber and fencing material (Chapter 2). Efforts to propagate this species in Eritrea have met with poor success due to low germination rates and growth rates of only a few cm per year. (Semere Amlesom, Department of Agriculture, Nacfa, personal communication). In nurseries I have visited in southern Eritrea, attempts to propagate J. excelsa for reforestation purposes no longer are made. Germination from other juniper species has been reported as highly variable and various treatments are needed to break the embryo dormancy which inhibits germination in most species (Johnsen and Alexander 1974:465). One study with J. excelsa, however, reported germination of 50% to 70% with immersion of seeds in hot water and acid scarification as pre-treatments (Laurent and Chamshama 1987).

The juniper fruit is a berry typically having one to four seeds which have a hard resinous testa approximately 1 mm thick. In Eritrea, berries ripen in September or October, toward the end of the rainy season. Birds are primarily responsible for seed dispersal although animals possibly eat fallen ripe berries (Johnsen and Alexander 1974). If passage through an animal or bird digestive tract is not necessary for germination to occur, berries presumably may germinate where they fall from the tree. I have not observed birds or animals eating juniper berries in Eritrea and many trees have copious quantities of berries from at least two seasons on the soil underneath their canopies.

Studies on many juniper species have shown that increases in germination can be obtained by stratifying seeds for different periods at various temperature, and by scarifying seeds mechanically or with acid (Johnsen and Alexander 1974). The purpose of this experiment was to examine the influence of stratification, scarification, hot water and maternal plant on the germination of J. excelsa seeds. What follows is taken mainly from a paper I published in the International Tree Crops Journal (Jones 1989).

Methods

Seeds

Seeds used in this study were taken from trees located in the village of Bacla (Fig. 2.1). Seeds were collected in August 1987 from six plants which were at least 800 m apart from one another. The plants were between 4 and 12 m high, apparently healthy, and had a good crop of fruit. Seeds were collected from different parts of the tree in order to randomise positional effects of seed development and sample a wide age-range of berries. The sampled trees were selected to be of different form and branching habit. On the date of collection, intact, mature (purple) berries were placed in clean water and those which floated were discarded. The pericarp was removed by hand and the seeds (1 to 4 per berry) were again separated by flotation in water.

Several seeds contained grubs from a parasitic wasp in the family Torymidae (J.T. Longino, Organisation of Tropical Studies, Costa Rica, personal communication). To permit metamorphosis of any further grubs, all 4 000 seeds were stored in paper bags at 21°C for eight weeks after air-drying. After this period, three dead adult wasps were found. Seeds were surface-sterilised with 1% sodium hypochlorite for 15 minutes and washed through a sieve five times with distilled water.

One hundred seeds from each of the six maternal plants (A to F) were weighed and measured. Thirty seeds from each maternal plant were subjected to the tetrazolium test (Hartmann et al 1990:142) to estimate percent viability before the experiment.

Experimental Design and Treatments

The six maternal plants had differing proportions of seeds which floated: 5%, 9%, 10%, 17%, 23%, and 70% of the seeds were discarded. The plants with 23% and 70% discarded seeds were omitted from the experiment. A total of 1 300 seeds were subjected to thirteen treatments, summarised in Table 5.24, with each treatment having 25 seeds from each of the four maternal plants.

Imbibition was conducted after scarification and hot water treatments but before all other treatments. Seeds were wrapped in moist paper towels at 21°C for 72 h which was the length of time required for them to imbibe moisture to reach a constant weight.

Stratification was undertaken in the dark with seeds placed 5 mm apart on 1 cm thick, moist cotton in 20 x 15 x 10 cm plastic storage boxes. Seeds were scarified in concentrated H_2SO_4 followed by five rinses with distilled water. For the hot water treatment seeds were immersed in 1 l of water at 80°C which was then allowed to cool. Seeds were removed one hour later.

Germination Conditions

Seeds were planted radicle down in 3.8 x 3.8 x 6.0 cm cells, in 72-cell planting trays. Two seeds per cell were placed at 1 to 2 mm depth in a soil mix containing equal parts washed sand, perlite, and humus. Those seeds which germinated during stratification were removed from the refrigerator and planted as above. Seeds were checked every two days and watered with distilled water when necessary.

Seeds for treatments 2 and 6 (Table 5.24) were incubated in a growth chamber at 22°C for 13 h of light (50 μE^{-2} sec^{-1}) and 7°C for 11 h of darkness.

Table 5.24 Stratification, scarification and hot water treatments on Juniperus excelsa seeds from Eritrea.

Treatment number	Scarification (min)	Stratification temp. (°C)	Stratification time (d)	Hot Water	GH or C*
1	--	--	--	--	GH
2	--	--	--	--	C
3	--	5	60	--	GH
4	--	5	90	--	GH
5	--	5	120	--	GH
6	--	5	90	--	C
7	60	5	120	--	GH
8	60	10	120	--	GH
9	15	5	60	--	GH
10	30	5	60	--	GH
11	15	5	90	--	GH
12	30	5	90	--	GH
13	--	--	--	YES	GH

*GH = greenhouse, C = growth chamber

Although not as bright as daylight, this photoperiod and temperature range closely approximated those of Rora Habab in winter.

Seeds for all treatments except 2 and 6 were germinated in the greenhouse. Greenhouse temperatures were mostly between 25°C and 30°C with a night minimum of 13°C and a daytime maximum of 36°C. Relative humidity was between 50% and 65% but occasionally reached a low of 20% or a high of 90%. These conditions were very different from those along Rora Habab where temperatures >30°C or humidities >25% rarely occur.

The criterion for germination was emergence and elongation of the radicle to 4 mm. The experiment was terminated after 240 days (d), after which time thirty ungerminated seeds from each maternal plant were subjected to the tetrazolium test.

Statistical Analysis

Data were analyzed on a VAX 750 computer using the S statistical software package (Becker and Chambers 1984). Weight, length, and width data for seeds (n=100 for each of the six maternal plants) were assessed for normality using stem-and-leaf plots and by plotting sorted data against quantiles of a standard normal distribution. Seed weight data were subjected to an analysis of variance (ANOVA) and differences in treatment means were compared for statistical significance using Duncan's Multiple Range Test (Alder and Roessler 1977). Germination data were summarised monthly for the 240 d period, producing eight matrics with four columns (seed) and 13 rows (treatment). Data were converted to percentages and arcsin transformed following Snedecor and Cochrane (1967) prior to two-way ANOVA. Because there were only 25 seeds per cell zero proportions were counted as 1/4n (i.e. 0.01) prior to transformation to angles (Snedecor and Cochrane 1967).

Treatment means from the 240 d data were compared with each other using Duncan's Multiple Range Rest (Alder and Roessler 1977).

Results

Table 5.25 shows a comparison of seed width, length, and weight between the six maternal plants. Seeds from maternal plants B, D, and E were significantly heavier, longer and wider than the seeds from plants 1, 3, and 6 ($p < 0.01$). Plant E produced the heaviest seed, which with a mean weight of .037 g was twice the weight of seeds from plant F. From these data 1 kg of air-dried seed would contain between 27 000 and 53 000 seeds (the mean for 6 plants was 35 000 seeds kg^{-1}), making them heavier on average than those of von Breitenbach (1963) who reported 42 750 seeds kg-1. The mean width and lengths of seeds from all six maternal plants were 3.8 and 5.3 mm respectively, with plant 4 producing significantly longer seeds (5.9 mm) than the other plants ($p<0.01$).

The viability of seeds from maternal plants A to D, as determined by the tetrazolium test, was 57%, 90%, 87% and 40% respectively before the experiment and 0% for all four seed lots at 240 d (Table 5.26). The mean increase in weight for seeds from plants 1 through 4, following imbibition for 72 hr, was 19.7% (Table 5.26).

Germination did not appear to be related to seed dimensions and weight. The biggest and heaviest seed lots (D and B) had the lowest percentage germination (18%) and the second highest (46%) respectively (Table 5.27). From plants A through D, the highest germinating seed lots (C and B) (Table 5.27) had significantly different weight, length and width at $p<0.01$ (Table 5.26).

Germination at 240 d was significantly higher ($p < 0.01$) in seeds from plants B and C than those from plants A and D (Table 5.27). These differences

Table 5.25 Differences between mean width, length and weight of seeds (± 1 SD, n=100) from six Juniperus excelsa plants from Eritrea.

Plant	Width (mm)	Length (mm)	Weight (mg)
A	3.7 ± 0.4 [b]	5.0 ± 0.2 [a]	24 ± 1 [b]
B	4.2 ± 0.5 [c]	5.4 ± 0.5 [b]	34 ± 9 [a]
C	3.4 ± 0.4 [a]	5.1 ± 0.3 [a]	23 ± 4 [b]
D	4.1 ± 0.6 [c]	5.9 ± 0.3 [c]	34 ± 7 [a]
E	4.2 ± 0.4 [c]	5.5 ± 0.2 [b]	37 ± 6 [a]
F	3.4 ± 0.5 [a]	5.1 ± 0.4 [a]	19 ± 9 [c]

NB. Treatments in the same column with the same letter are not significantly different ($p<0.01$) by Duncan's Multiple Range Test.

Table 5.26 Weight increase before and after imbibition for 72 h, and percentage viability at 0 and 240 days, of Juniperus excelsa seeds from 4 mother plants from Eritrea.

Plant	Weight @			Viability ¶	
	Before Imbibition (g)	After Imbibition (g)	Increase (%)	0 days (%)	240 days (%)
A	0.611	0.740	21.2	57	0
B	0.838	1.008	20.3	90	0
C	0.608	0.706	16.1	87	0
D	0.874	1.055	20.7	40	0
$\bar{x}$	0.733	0.877	19.7	68.5	0
$S_{\bar{x}}$	0.143	0.180	--	24.1	--

@ Mean of two replicates of 25 seeds from each mother plant.
¶ Tetrazolium test on 30 seeds from each mother plant.

Table 5.27 Per cent germination of _Juniperus excelsa_ seeds from Rora Habab by maternal plant and by treatment.

Maternal Plant	Germination @ ¶	Rank
A	26 c	3
B	46 b	2
C	60 a	1
D	18 c	4
Treatment		
1	53 ab	4
2	47 ab	6
3	63 a	1
4	53 ab	5
5	53 ab	3
6	40 ab	8
7	8 c	11
8	7 c	12
9	57 ab	2
10	35 b	9
11	43 ab	7
12	33 b	10
13	0 c	13

@ Treatments with same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test (DMR).

¶ ANOVA and DMR conducted after arcsin transformation. Data reported as original germination percentage.

were clear after 90 d. The germination of seed lot C (60%) was also significantly higher at $p < 0.05$ than lot B (46%), lot A (26%), or lot D (18%) (Table 5.27). Very few seeds germinated after 180 d. Maximum germination rates were obtained at 120 d for seeds from all four maternal plants.

Seed from treatment 3 (60 d stratification) had the highest germination (63%) after 240 d (Table 5.27). Germination following this treatment was 10% greater than for a 90 d stratification, a 120 d stratification, or untreated controls, although these differences are not significant. Treatment 9 had higher germination than untreated controls but again this was not sigfnificant. No seeds germinated after immersion in hot water, and subjecting them to 5°C for 60 d at the end of the experiment also did not result in germination. Seeds in the greenhouse had higher germination than those in the growth chamber in paired treatments (4, 6) and (1, 2) although the differences were not significant. Treatments 7, 8 and 13 produced significantly lower germination than all other treatments (Table 5.27).

Treatment 3 had significantly greater percentage germination ($p<0.05$) than treatments 7,8,10,11 and 13 (Table 5.27). While the differences are not significant, the results suggest that percentage germination at 5°C stratification for 60 d is greater than that for 90 d and 120 d, and that percentage germination after scarification for 15 min is greater than that after 30 min which in turn exceeds the value for 60 min scarification. These trends held irrespective of subsequent stratification periods.

Discussion

Experimental Observations

Ordinarily, germination of J. excelsa is epigeal, with the radicle emerging first, and the hypocotyl emerging three to four days later (Khalique 1977). The megagametophyte and seed coat remain around the cotyledons as the hypocotyl extends, falling off as the cotyledons develop 10 to 15 d after emergence. The hypocotyl is green so that heterotrophic growth (*sensu* Khalique 1977) is presumably augmented somewhat by photosynthate, even while the cotyledons remain enclosed by the testa. In this study several seeds germinated abnormally, whether or not they had been soaked in H_2SO_4.

1. In 32 of the 492 seeds which germinated, the hypocotyl and cotyledons emerged but the radicle did not. Sometimes the radicle appeared to develop while still within the megagametophyte and testa, resembling the hypogeous germination described for J. virginiana by Djavanshir and Fechner (1976). More commonly, however, the seed coat failed to split, the radicle remained enclosed, and the seedling died. Gently splitting the seed coat with pointed pliers sometimes permitted elongation of the radicle and seedling growth, suggesting mechanical, rather than chemical inhibition of radicle development.
2. A second, rather similar phenomenon, affecting 18 seeds, was the emergence of cotyledons alone; the hypocotyl did not elongate outside the testa, but the cotyledons simply detached from the embryo and were shed.
3. Scarification caused a noticeable thinning of the seed coat: a 60 min scarification often created a hole in the seed which presumably allowed acid to enter and kill the embryo. This probably accounts for the very low germination of seeds in treatments 7 and 8.
4. Although radicle emergence to 4 mm was the criterion for germination, this was not a good predictor of seedling survival. While most of those seeds whose radicles emerged to 4 mm matured into seedlings, many stopped growing following the abrupt change in temperature from the refrigerator. A better criterion for germination would have been extension of the radicle to 10 mm, plus the emergence and negative geotropism of the hypocotyl.

5. The megagametophyte also appeared to impose a mechanical impediment to cotyledon growth in 46 seedlings. Although extension to greater than 10 mm of both hypocotl and radicle was attained, the megagemetophyte remained tightly constricted around the cotyledon and epicotyl, and was white, leathery, and up to 0.8 mm thick. Careful removal of the megagametophyte did not result in cotyledon growth, and there appeared to be no true leaves developing between the cotyledons.

6. Almost 70% of seedlings from maternal plant 1 had three cotyledons, as compared to the normal number of two. There appeared to be no difference in early growth or branching habit between three-cotyledon and two-cotyledon progeny.

Comparison with other Studies

Results from this study do not agree with those of Laurent and Chamshama (1987), where hot water, acid scarification, and fire-scorching were the pre-treatments for J. excelsa seeds collected from Tanzania. Laurent and Chamshama (1987) who referred to J. procera rather than J. excelsa, obtained between 50% and 70% germination in the 14 d following pre-treatment. In our study, however, germination over the first 30 d was negligible.

Immersion in hot water, acid scarification and untreated controls had different outcomes in this study compared to that of Laurent and Chamshama (1987). They found that immersion in 100°C water for 1 min followed by soaking in cool water for 6 h resulted in 70% germination after 14 d, whereas in the present study no seeds germinated after immersion in 80°C water followed by soaking in cooling water for 1 h. Differences in immersion temperature and duration may be sufficient to explain these different outcomes. Laurent and Chamshama also reported 75% germination after soaking seeds in H_2SO_4 for 30 min, while in the present study only 35% of the seeds germinated within 240 d with a 30 min acid treatment, and significantly lower germination was obtained for a 60 min acid scarification. Laurent and Chamshama (1987) reported that no seeds germinated after 14 d if left untreated but in our study nearly 50% germinated within 150 d if left untreated. Laurent and Chamshama recommended the use of hot water in rural areas as the preferred treatment for J. excelsa seeds, whereas results from this study would strongly argue against this treatment in Eritrea.

Two possible reason for the differences in results are: (1) the provenance of maternal plants was different; and (2) seeds for each study were stored for different lengths of time. Provenance may greatly affect germination and growth characteristics (Hartmann et al 1990:86). Laurent and Chamshama used seed collected at Lushoto, Tanzania (4°40'S, 38°10'E), 2,400 km south of the seed source for this study. Moreover, in our study seed was stored for eight weeks only whereas in the Tanzanian experiment seed had been stored for nearly two years. Hall (1981) stated that J. excelsa (J. procera) seed has a viability of only 6 to 12 months, and the data of Khalique (1977) showed that J. excelsa does not necessarily require a period of after-ripening. However, it could be that storage facilitated greater and faster germination for the seeds used by Laurent and Chamshama. Seeds of J. scopulorum are reported to require up to 2 years of after-ripening (Afanasiev and Cress 1942), and seeds of J. deppeana, J. communis, and J. pinchotii may take two of even three years to mature (Johnsen and Alexander 1974). It would have been interesting to know whether an experimental period longer than 14 d would have permitted Laurent and Chamshama's control seeds to germinate. In any event, with a high premium on nursery space and foresters' time, it is attractive to achieve 70% germination in two weeks. I plan therefore to repeat part of Laurent and Chamshama's (1987) experiment with seed from Eritrea.

Conclusion

Based on results from this study, stratification at 5°C for 30 to 60 d following imbibition is recommended for unstored seeds of J. excelsa in Eritrea. It is important to resolve questions of provenance differences and after-ripening requirements for J .excelsa through multiple location experiments with seed from different provenances following varying lengths of storage.

Results also showed that seeds from different maternal plants had significantly different germination rates. However, fruit may be found on some J. excelsa trees throughout the year on Rora. Any selection process therefore should determine whether percentage seed germination is season specific.

VEGETATIVE PROPAGATION OF JUNIPERUS EXCELSA

Introduction

The vegetative propagation of juniper by cuttings has met with varying degrees of success, with some species and cultivars rooting readily and others proving difficult to root (Banko 1981:658, 1983:9; Pounders and Gilliam 1983:23). Commercial growers have propagated J. scopulorum by grafting because of the difficulty of rooting cuttings (Duer 1981:141). For some species and cultivars the application of rooting hormones has been necessary for root initiation or elongation while for others rooting hormones have had negligible or negative results (Banko 1981, Duer 1981, Evans and Martell 1983, Lanphear and Meahl 1961). Crude water extracts derived from leafless twigs of Salix alba or Populus nigra have proved as successful in some treatments as Indolebutyric acid (IBA) in increasing rooting of J. sabina cuttings over untreated controls (Richer-Leclerc et al 1984). Pounders and Gilliam (1983:23) found liquid dips of IBA or Naphthaleneacetic acid (NAA) to be significantly more effective than talc dips of these hormones in rooting J. virginiana, J. chinensis and J. scopulorum cuttings.

Other factors which have been examined in rooting juniper cuttings include the role of bottom-heating propagation beds (Wetherington 1983), the time of year at which cuttings are taken (Banko 1981, Major and Grossnickle 1990), photoperiod (Evans and Martell 1983, Richer-Leclerc et al 1984, Lanphear and Meahl 1961), and rooting environment (Whitcomb 1973). A common feature of these studies is that results are species-specific or cultivar-specific. This, together with the interactive effects of multiple factors, makes it difficult to generalise beyond specific experimental situations.

J excelsa rarely propagates vegetatively naturally. Unlike O. europaea subsp. africana, it does not form suckers or new growth from wounded woody tissue. However, J. excelsa is capable of vegetative propagation under certain unusual conditions in nature. Pontecorvo and Bokhari (1975) report that where strong winds blow uphill through narrow passes in the Zagros mountains, heavy layers of snow bend J. excelsa branches, pressing them to the ground. If the soil is loose enough and the presence of large boulders prevents wind destroying new growth, then roots grow from the layered branches. In this fashion, J. excelsa plants "move" uphill as new growth is established vegetatively on the leeward side and old growth is killed by strong, cold winds on the windward side.

Hartmann et al (1990:264) suggest that hardwood cuttings of J. excelsa taken from older growth from the sides and lower portion of stock plants root better than succulent tips. This was the type of material taken for my experiments in Eritrea which were destroyed by flooding so that the only material then available was from 2 year old stock plants grown from seed and raised in the greenhouse. These small stock plants did not provide sufficient cuttings to test many of the factors which have been noted as influential in rooting juniper cuttings. The purpose of this study was to assess the capacity of softwood stem cuttings of J. excelsa to form roots.

Methods

Experimental Design

Two experiments were conducted. In both, cuttings between 4.0 cm and 9.0 cm were taken from the current year's growth from lateral branches, with juvenile foliage, of two-year old stock plants between 7 and 11 a.m. The stock plants had been grown from seed collected from several parents in Bacla village, Rora Habab and grown in pots in the greenhouse. Cuttings were taken using a sharp scalpel to make a clean, oblique cut. Experiment (1) examined the effects of rooting hormone, misting and parent plant. Experiment (2) examined the effects of rooting hormone and of fertilising stock plants in different ways.

Experiment (1)

A total of 320 cuttings were taken on August 16, 1989 from five parent plants, 64 cuttings per parent. The basal surface of 32 cuttings from each parent was dipped in rooting hormone powder with fungicide ("Rootone", containing Naphthaleneacetic acid (NAA) 0.20%, Indolebutyric acid (IBA) 0.10% and 'Thiram' fungicide 4.04% in a talc base). A second group of 32 cuttings received no hormone treatment. Sixteen cuttings from each treatment were then placed under intermittent mist with two seconds of fine spray every three minutes (high mist), and sixteen were placed in a watering system which provided fifteen seconds of fine mist three times a day (low mist).

The lower leaves were removed from all cuttings which were inserted for a third of their length into a mixture of 75% sand (1 mm grain size) and 25% perlite, one cutting per 2.5 x 2.5 x 4.0 cm cell, in 180-cell planting trays. Cuttings were randomly allocated to cells taking care not to contaminate cells with rooting hormone powder. The planting trays were placed in a shaded greenhouse where daylight was attenuated by 60% (maximum was 900 uE m^2 sec^{-1}), with no supplementary lighting, on adjacent gravel beds which were bottom heated to maintain a temperature of 25°C. The position of the planting trays was changed weekly. Air temperatures varied between 20°C and 24°C during the day and 18°C and 21°C at night.

Cuttings were harvested after 120 days (d) and transplanted to 5 x 5 x 8 cm pots in a 4:2:2:1 by volume mixture of sand, perlite, loam and peat, one cutting per pot. Potted cuttings were replaced on the (now unheated) gravel bed under the low-mist watering regime. The potted cuttings were harvested 240 d after transplanting. It proved impossible to remove the roots from the soil mix without a number of roots breaking. Therefore roots could not accurately be harvested and the dry weight of shoots only was obtained. Stems were cut at the root/stem junction and oven dried at 65°C for 72 h prior to weighing.

The following measurements were made: Prior to planting, the length of the cuttings was measured. At 120 d, when the cuttings were harvested prior to transplanting, four root parameters were recorded. The presence or absence of roots was recorded. Where rooting occurred the total root length, including branchlets ≥1 mm, was measured, and the number of roots emerging from the cutting was counted. At 360 d, (240 d after transplanting), the dry weight of the shoots was obtained.

Experiment (2)

A total of 256 cuttings was taken on June 25, 1990 from parent plants which had been fertilised in four different ways, 64 cuttings from each fertiliser treatment. The basal surface of 32 cuttings from each fertiliser treatment was were dipped in "Rootone" rooting hormone. A second group of 32 cuttings received no hormone treatment. Cuttings were placed under intermittent mist with two seconds of fine spray every twenty minutes.

Cuttings were inserted into gravel of 4 mm grain size, randomly allocated to cells in planting trays as for experiment (1). The planting trays were placed in the greenhouse. Temperature in the cells was 24 ±1°C. Air temperatures varied between 21°C and 29°C during the day and 18°C and 23°C at night. Cuttings were harvested after 120 d.

Statistical Analysis

The major objective of the statistical analyses was to investigate differences in rooting between cuttings dipped in rooting hormone and untreated controls, and between the five parent plants. This was achieved by means of analysis of variance (ANOVA) for initial cutting length (CL), total root length (RL), number of roots (RN), and shoot dry weight (DW). For rooting positive or negative (RPN), analysis was based on the χ^2 distribution. Five regression analyses were undertaken. Three logistic regressions were undertaken on RPN with CL (no hormone), CL (with hormone), and CL (both hormone treatments) as the independent variables. Two linear regression models were applied separately to CL and RL, with DW as the independent variable.

Prior to analyses using linear models, the data for CL, RL and RN were assessed for normality, equality of variances between groups, and presence of outlying data points. Following these measures and appropriate analysis of residuals (Wilkinson 1989, Neter et al 1989), logarithmic transformations were undertaken on RL and DW variables. Tests for significant differences between selected means were undertaken using contrasts (Wilkinson 1989:191 et seq., Petersen 1985:85 et seq., see olive propagation section, this chapter)

For RPN, 2x2 contingency tables were constructed for each of the five parents, and for the summed data from all five parents, with hormone treatment as the rows and RPN the columns. Data were examined using the χ^2 procedure and Fisher's Exact Test following Alder and Roessler (1977:252-66) and Cox and Snell (1989:3, 47-8).

The logistic regression models were estimated using Maximum Likelihood methods following Freeman (1987), Neter et al (1989:589-95) and Wilkinson (1989:339-41). For these analyses, the CL data, initially measured to the nearest 0.5 cm, were rounded up to produce 1.0 cm intervals. Similarly, the RL data, initially measured in 0.1 cm intervals, were rounded up to make 2.0 cm intervals.

Results

None of the cuttings in experiment (2), or in the experiment (1) high-mist environment rooted or formed callus. Almost 50% of these cuttings had rotted tissues below the gravel and almost 10% had rotted tissue above the gravel at 120 d. By contrast, 125 (78%) of the cuttings in the experiment (1) low-mist environment rooted (Table 5.28) and no cuttings had rotted tissues. The following results therefore apply only to low-mist experiment (1) cuttings.

Cuttings to which rooting hormone had been applied had significantly higher rooting than the no-hormone controls (χ^2= 4.43, P<.04). However, when the χ^2 procedure and Fisher's Exact Test were applied to each of the five parents separately, only parent C showed a significant difference (χ^2= 6.79, P<.005) between hormone treatments. Anova and contrasts showed that cuttings from parent C, whose average length was 4.5 cm, were significantly smaller than cuttings from parents A, B, D and E, whose average length was between 5.3 and 6.3cm (F=12.2, P<0.000001) (Table 5.29).

In order to determine whether it was cutting size or some other attribute of parent C which resulted in significant differences between hormone treatment on rooting, logistic regression was performed on RPN for parents A, B, D and E with CL as the independent variable. Regressions were undertaken with all CL data (N=128), and then by hormone treatment (CL with hormone and CL without hormone, N=64 in each case). For all three regressions, the 95% confidence intervals for the odds ratios included zero indicating that there was no significant relationship between the length of the cutting and the probability of rooting.

Root length at 120 d ranged between 0.1 cm and 33.7 cm. Dry weight at 360 d was between 30 mg and 810 mg. Anova and contrasts showed that parents {A and D} had significantly greater RL (F 10.2, P<0.002) and DW (F 47.4, P<0.000001) than parents {B, C and E}. Parents' {A,D} average RL was

Table 5.28 Numbers (out of 16 per treatment) of rooted Juniperus excelsa cuttings from five parent plants from Eritrea, according to rooting hormone treatment.

parent	with rooting hormone	without rooting hormone	TOTAL
A	14	11	25
B	10	13	23
C	14	7	21
D	16	15	31
E	14	11	25
TOTAL	68	57	125

Table 5.29 Initial length of cutting, total root length at 120d, and dry weight of shoot at 360d of softwood cuttings taken from five 2 yr-old Juniperus excelsa plants and either treated with hormone rooting hormone or untreated.

	cutting length (cm)		root length(cm)		dry weight (mg)	
parent	hormone	no hormone	hormone	no hormone	hormone	no hormone
A	5.4	5.3	14.9 [b]	12.0	318 [c]	265
B	6.0	5.9	6.1	9.4	119	144
C	4.7 [a]	4.3	6.3	7.7	203	133
D	6.3	6.4	13.0 [b]	9.3	335 [c]	278
E	6.0	5.2	6.6	7.9	189	141

a parent C cuttings significantly shorter ($p < 0.000001$)
b parent A and D root length significantly greater ($p < 0.002$)
c parent A and D dry weight significantly greater ($p < 0.000001$)

12.3 cm and DW 301 mg, while parents' {B,C,E} average RL was 7.3 cm and DW 156 mg (Table 5.29). There was no difference in RN between parents. There were no significant differences in CL, RL, RN, or DW between hormone treatments.

Simple Linear Regression showed there to be a positive relationship between CL and RL ($Y=5.21+0.23X$; F 5.6, $P<.02$), between RL and DW ($Y=2.86+0.60X$; F 11.7, $P<.001$), and between CL and DW ($Y=7.45+1.04X$; F 47.7, $P<.000001$).

Discussion

With one exception, that of plant C, the application of rooting hormone did not influence rooting, the numbers of roots which formed, root length, or shoot dry weight. In the case of plant C the application of rooting hormone did not influence RN, RL or DW but was associated with an increase in rooting over untreated controls. It is not possible with these data to account for this except to note that parent C produced the smallest number of rooted cuttings in the absence of hormone but that with hormone, rooting was similar to the other four parents.

The root lengths of cuttings from parents A and D were twice that of cuttings from parents B, C and E. The dry weight of shoots at 360 d similarly was greater for parents A and D. These results confirm that future experiments should continue to include parental effects in order to identify stock plants which produce faster growing cuttings with more robust root systems.

It is noteworthy that in the moister environments no cuttings rooted whereas a high percentage of cuttings rooted in the low-mist environment, with or without hormone. While there were minor differences between experiments (1) and (2) in the month cuttings were taken, in misting regimes and in air temperature, the high number of cuttings which had rotted by 120 d suggests that the environment was too warm and moist for these plants. Noting the failure of the high-mist cuttings to root in experiment (1), the second experiment was conducted using a larger grain sized rooting medium and a reduced level of mist. These measures did not reduce the level or speed of fungal infection. In a previous experiment, J. excelsa seedlings also had high mortality immediately following germination due to damping-off organisms (previous section, this Chapter). Several workers note the need for good sanitation in propagating juniper cuttings and dipped the base of cuttings in fungicide prior to applying rooting hormone or planting (Reinsvold and Reeves 1986:109; Wight 1975:477-8; Duer 1981:143). In contrast, growers in Alabama saturate heavy clay soils until it is a "muddy slurry" and mechanically compress soil around roots to exclude air in open-field propagation of 20 cm long, current-season's growth cuttings from J. horizontalis, J. chinensis, J. virginiana, J. conferta and J. communis (Byers 1977). Nevertheless it seems that J. excelsa softwood cuttings propagated in high-humidity, high temperature conditions are highly susceptible to fungal attack.

Many aspects of vegetative propagation of J. excelsa require further study in order to reach a point where clones of a reasonable size can be established in field trials within a year or two of taking cuttings. An important next step is to increase the reliability of rooting J. excelsa cuttings and to conduct experiments which take account of factors other than rooting hormone and which use hardwood cuttings taken from older stock plants. Additionally, given the positive relationship between CL and RL, RL and DW, and CL and DW in this experiment where CL ranged between 4.0 cm and 9.0 cm, it will be important to evaluate the effects of CL on RL and DW for hardwood cuttings over a greater size range.

CHAPTER 6

INFLUENCE OF FERTILISER AND WATERING INTERVAL ON *OLEA EUROPAEA* SUBSP. *AFRICANA* SEEDLINGS

INTRODUCTION

The farmers on the Rora Habab plateau cannot afford fertilisers and do not irrigate their crops (Chapter 2). Rainfall on Rora is low and variable and there is a long dry season (Chapter 2). Many areas of Rora suitable for tree planting, especially hillslopes which are not used for food production, have shallow, well drained soils which often are low in organic matter and plant nutrients (Chapter 4). While the highest density of olive and juniper seedlings were found in these areas, they appear to be growing very slowly (Chapter 3). Thus to successfully reforest Rora Habab, it is necessary in many areas not only to germinate seeds or vegetatively propagate cuttings from olive and juniper (Chapter 5), but also to carefully monitor them during early growth and subsequent outplanting.

A key question that arises in developing appropriate methods for the successful propagation and outplanting of tree seedlings is how fertilisation and watering regime may influence seedling growth and survival. Small amounts of fertiliser and carefully managed watering may speed the growth of seedlings in the nursery and produce physiologically robust plants with a higher chance of survival following outplanting.

The objective of the factorial experiment described in this chapter was to investigate the effects of fertilisation and four watering regimes on five plant parameters and on soil moisture, using one-year old olive seedlings from three parent plants. The experiment was carried out in the artificial setting of the glasshouse using pots. While this gave adequate experimental control the experiment will be modified and repeated in more representative field situations in Eritrea using other species as well as olive.

Many environmental factors and nursery practices in tree nursery culture influence growth and quality of nursery stock (Duryea and Landis 1984, Rose et al 1990). Fertiliser and irrigation are used in many tree nurseries to avoid nutrient and moisture stress, and to ensure optimal survival and growth of seedlings (Duryea 1984).

In some tropical soils where trees have been grown following deforestation, fertilisation has been required to replace nutrients lost by removing plants and/or by soil erosion (Sanchez et al 1985). Irrigation of tropical trees may be undertaken to promote deep rooting in drought-prone areas, or may be applied year-round to decrease the carbon demand of roots and increase above-ground production (Cannell 1985).

There are many ways in which the use of fertiliser and irrigation interact in their effect on plants; obtaining the correct balance of water supply and available nutrients can be difficult. Fertiliser application and irrigation also have a temporal impact and nutrients or water may be withheld or applied at different times of the year in order to avoid drought stress, induce dormancy, or prepare seedings for outplanting (Duryea and Landis 1984).

Individual nutrient elements may have different effects according to whether they are present in high or low amounts. For example, in soils where levels of P are low, drought has little effect on root:shoot relative growth rates, but in soils with high levels of P, longer drought periods are associated with higher root:shoot ratios (Cannell 1985). In drought conditions, high levels of N have been found to increase moisture stress in trees, whereas low levels of N have little effect on tree growth (van den Driessche 1984). In plants which are drought stressed, application of N fertiliser is unlikely to improve productivity

(Binkley 1986:79), or may even increase mortality through enhancing shoot growth and inhibiting root growth (Marschner 1986:213, Black 1984:517).

There is also evidence that the interaction of nutrients and drought stress varies with species. For example, adequate foliar concentrations of K have been shown to increase drought tolerance of Pinus sylvestris and dormant Pseudotsuga menziesii seedlings, but not of Picea abies (van den Driessche 1984). The magnitude of the responses of seedlings to fertiliser and watering regime will also vary within a population of seedlings from a single parent and among seedlings from different parent plants (Harper 1977:751 et seq).

METHODS

The plants used in this study were all 52 ± 2 weeks old and had been grown in the greenhouse from seed collected from three parent plants in Bacla and Endlal villages (Fig. 1.2). Seeds were germinated in petri dishes. When the radicle was >10 mm long and cotyledons had emerged, plants were transferred to 200 cm^3 pots in a 4:2:2:1 by volume mixture of sand, perlite, loam and peat. Fourteen weeks after germination, plants were transferred to 1,700 cm^3 pots. All plants were watered with distilled water and their position in the glasshouse was changed every two weeks prior to the beginning of the experiment.

In April 1990, a total of 96 healthy plants, 32 from each parent, were arranged, by parent, from largest to smallest. Each parent group was then divided into 4 size cohorts with 8 plants per cohort. Individual plants were randomly selected, one from each cohort, to produce 8 treatment groups per parent, with 4 replicates per treatment group. Each treatment group was randomly allocated to one of the eight combinations of fertiliser and watering regimes shown in Table 6.1. Six additional "test" plants were used for foliar

Table 6.1. Number of one year old O. europaea subsp. africana seedlings assigned to four watering intervals and two fertiliser treatments.

	watering interval (days) 7	14	21	28	x 3 parents
fertilised	4	4	4	4	48
un-fertilised	4	4	4	4	48
x 3 parents	24	24	24	24	96

Table 6.2. Dates on which one year old O. europaea subsp. africana seedlings were watered and harvested.

	MAY		JUNE				JULY
watering interval	21	28	4	11	18	25	2 harve -sted
7 days	x	x	x	x	x	x	
14 days	x		x		x		
21 days	x			x			
28 days	x				x		

analysis (two plants from each parent); three of these plants were fertilised and three were not.

For two consecutive weeks the fertilised plants were watered weekly with 2.0 g l^{-1} water-soluble complete fertiliser with B, Cu, Fe, Mn and Zn micronutrients (Stern's 15-30-15 Miracle-Gro™). The unfertilised plants were watered weekly with distilled water. All plants were then watered with distilled water weekly for two weeks. After fertilisation, leaves from the three unfertilised and three fertilised "test" plants were analysed for foliar N and P. For this analysis, nine leaves were taken from each plant, three from the top of the plant, three from the middle and three from the base. Leaves were oven-dried overnight at 70°C and crushed in a mortar and pestle prior to Kjeldahl digest.

The digestion procedure (unpublished) of the Plant Analysis Laboratory of the Department of Crop and Soil Science at Oregon State University was used. From each sample, 0.5 g of leaf material was placed in a Kjeldahl digestion tube. To each tube I added 10 ml of concentrated H_2SO_4 and 3 g of powdered catalyst (a mixture of 100 parts K_2SO_4 to 5 parts $CuSO_4$ to 1 part Se). Samples were predigested for one hour at 150°C and then 10 ml of 50% H_2O_2 was added to each tube. Samples were then digested for 3 to 5 hours at 350°C until the solutions cleared. Digest tubes were removed from the digestion block, cooled overnight following the addition of 10 ml of distilled water, and brought to a final volume of 150 ml with distilled water. Total N and total P in the digests were determined colorimetrically by Autoanalyser, using Technicon method no. 334 74A/A (OSU Plant Analysis Laboratory).

Fourteen days after the last application of fertiliser all plants were subjected to varying lengths of drought. This was achieved by watering pots to field capacity every 7, 14, 21, or 28 d with distilled water as described in Table 6.2. The original intention was to water according to this regime for 84 d but the experiment was shortened since fertilised plants from the 28 d watering interval appeared not to recover upon rewatering after the first 28 d period. The plants were harvested at 42 d.

The following data were obtained for each plant: shoot volume, root volume, root:shoot ratio (by volume), height (from stem base to the terminal bud, nearest 1 cm), percent soil moisture, and the number of leaves > 1.0 cm long on each plant. Shoot volume and root volume were obtained by a displacement method, described below, in which an inclined manometer was used to magnify the volume of water displaced by immersing plants in a column of water (Fig. 6.1). Percent soil moisture was obtained gravimetrically by weighing a subsample of soil from each pot at the time of harvest and weighing again after oven drying for 24 h at 105°C. Soil moisture could not be measured for the 28 d watering regime because of the early termination of the experiment (Table 6.2).

Measurement of Shoot and Root Volume

In order to obtain comparable nondestructive measurements, I measured shoot and root volumes by means of a water displacement apparatus shown in Fig. 6.1. Plant parts were immersed in water contained in a 70-cm tall, 6.4-cm diameter clear perspex cylinder (A, Fig. 6.1). The measure of the vertical rise due to water displaced by plant parts (B, Fig. 6.1) was magnified by taking the linear measure of the movement of the corresponding water meniscus (C, Fig. 6.1) in a shallowly inclined, small-bore, clear plastic tube (D, Fig. 6.1) connected to the base of the vertical cylinder by clear, flexible tubing (E, Fig. 6.1).

Two approaches could have been used to convert displacement measurements to measurements of volume. The first involves a conversion using a magnification factor based on the angle of incline of the small bore tube. I used the alternative method, using standards to obtain a conversion

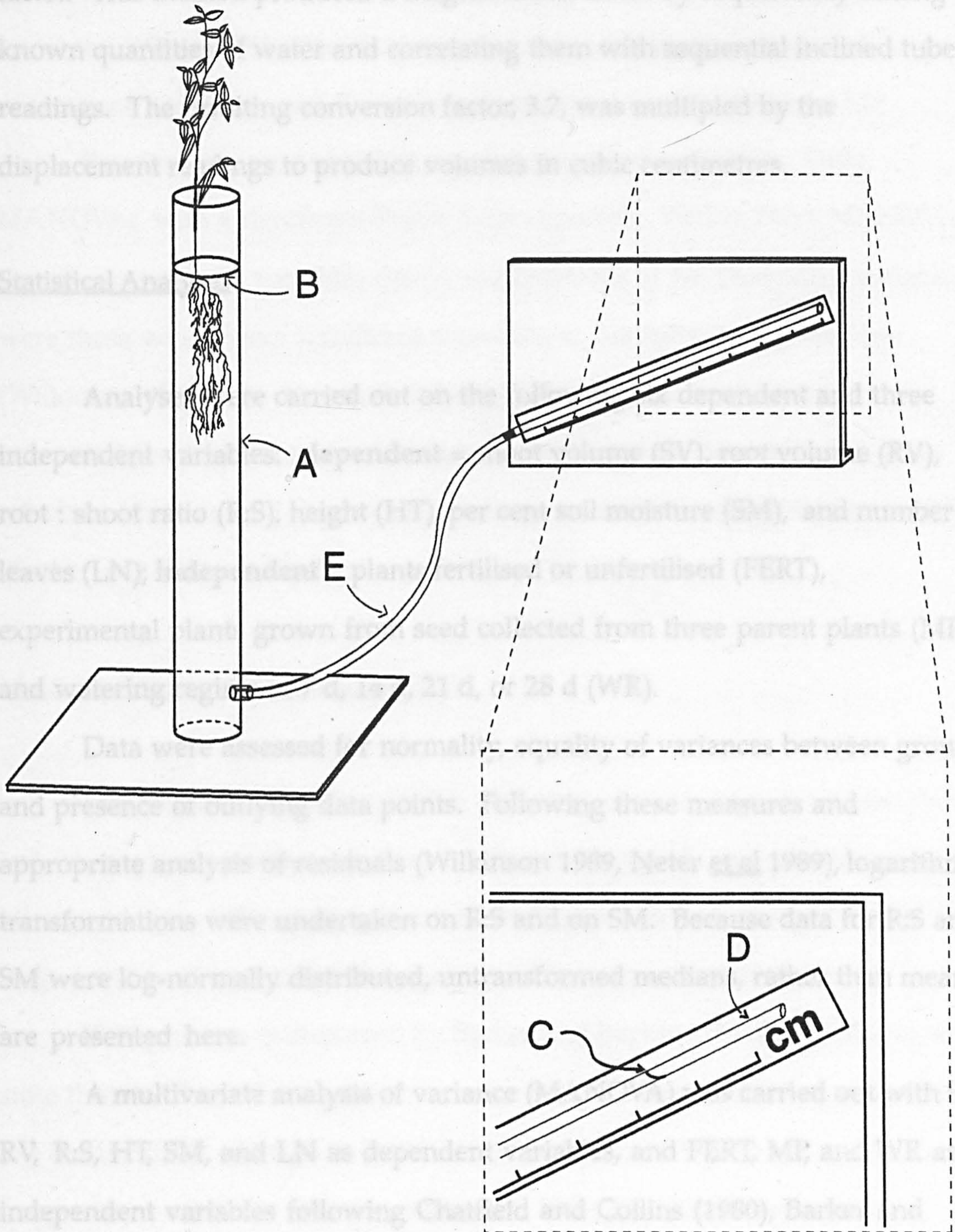

Fig. 6.1. Displacement apparatus used for measuring root and shoot volume of *Olea europaea* subsp. *africana* seedlings in an experiment which studied the effects of fertiliser and drought on various plant parameters.

factor. This method produced a magnification factor by sequentially adding known quantities of water and correlating them with sequential inclined tube readings. The resulting conversion factor, 3.7, was multipled by the displacement readings to produce volumes in cubic centimetres.

Statistical Analyses

Analyses were carried out on the following six dependent and three independent variables: **dependent** = shoot volume (SV), root volume (RV), root : shoot ratio (R:S), height (HT), per cent soil moisture (SM), and number of leaves (LN); **independent** = plants fertilised or unfertilised (FERT), experimental plants grown from seed collected from three parent plants (MP), and watering regime of 7 d, 14 d, 21 d, or 28 d (WR).

Data were assessed for normality, equality of variances between groups, and presence of outlying data points. Following these measures and appropriate analysis of residuals (Wilkinson 1989, Neter et al 1989), logarithmic transformations were undertaken on R:S and on SM. Because data for R:S and SM were log-normally distributed, untransformed medians, rather than means, are presented here.

A multivariate analysis of variance (MANOVA) was carried out with SV, RV, R:S, HT, SM, and LN as dependent variables, and FERT, MP, and WR as independent variables following Chatfield and Collins (1980), Barker and Barker (1984) and Wilkinson (1989). MANOVA was undertaken to determine which uncorrelated dependent variables were most responsible for the differences among the treatments.

Three fully factorial MANOVAs were undertaken using three data sets. The 28-day watering regime (24 cases) was omitted from all three data sets because of missing data. The first data set, with 72 cases, included all six dependent variables and all three independent variables. The second data set, with 36 cases, included only fertilised seedlings and the two independent variables, WR and MP. The third data set, also with 36 cases, included only unfertilised seedlings, and the two independent variables, WR and MP.

Results from the MANOVAs were interpreted as follows. Only MANOVAs with a significant Wilk's Λ are reported. Within these MANOVAs, significant synthetic variables (linear combinations of the dependent variables) were those which were significant according to Bartlett's chi-squared test (Wilkinson 1989:244). Uncorrelated dependent variables which most accounted for the differences between treatments were determined as those which had high (> | 0.3 |) canonical loadings on a significant synthetic variable (Barker and Barker 1984:57).

Multiple Comparisons and MANOVA

The first MANOVA resulted in 42 F-tests, the second in 6, and the third in 6. A single contrast was undertaken to test the significance of differences in NL according to MP, resulting in a total of 55 separate tests of significance. This large number of tests raises the question of how to control type I error.

This problem is discussed by Barker and Barker (1984:28-31, 35-36) who state that the Bonferroni procedure is the simplest appropriate procedure for use in MANOVA, altough its statistical power is limited when a large number of comparisons are made (see also Wilkinson 1989:201-202). A second disadvantage of the Bonferroni procedure is that the significance of some variables may be obscured ("suppressed") because they are correlated with other dependent variables. In other words, the use of the Bonferroni procedure may increase the chance of a type II error. With these caveats in mind, probabilities were Bonferroni-adjusted following Barker and Barker (1984) and Wilkinson (1989) with a denominator **k** = 55 (see also Chapter 5).

RESULTS

Fertilisation nearly doubled the foliar N concentration and increased foliar P by nearly 50%. Foliar N in the three unfertilised plants was 6.4, 7.0, and 7.1 g kg^{-1}, and for the fertilised plants was 8.6, 9.4, 15.5 g kg^{-1}. Foliar P for the unfertilised plants was 0.48, 0.50, and 0.58 g kg^{-1}, and for the fertilised plants was 0.60, 0.70, and 1.00 g kg^{-1}.

This experiment was to have run for 84 days. In the event, all fertilised plants which were watered every 28 days had shed nearly all of their leaves and appeared to be dead by the end of the first watering cycle. At 28 days they were watered according to the schedule in Table 6.2 but they did not recover. Also, a few of the plants which had been watered every 21 days showed signs of moisture stress and one plant in this group died. The experiment was therefore terminated after 42 days.

In the first MANOVA, Wilk's Λ was significant for FERT, MP, WR and FERT * WR but not for the other interactions (Table 6.3). There were significant differences between fertilised and unfertilised seedlings in shoot volume, percent soil moisture in the pots, and the number of leaves (Table 6.4). Fertilised plants had higher mean shoot volume (14.8 cm^3), higher mean leaf number (101), and lower median soil moisture (3%) compared to unfertilised plants (mean shoot volume 7.6 cm^3, mean leaf number 36, and median soil moisture 9%). Parent plant B had fewer leaves (mean = 49) than parent plants A or C (means = 72 and 70). As watering interval increased from 7 to 14 to 21 days, mean shoot volume decreased from 15.1 to 11.2 to 7.0 cm^3, median soil moisture decreased from 12 to 5 to 6%, and the mean number of leaves decreased from 97 to 64 to 44 (Table 6.4). Except for the differences between parents, these results are of little significance, because of the interaction (non-additivity) between FERT and WR. This is why two further MANOVAs were

Table 6.3 Significant Wilk's Λ values from a MANOVA on measurements of one year old Olea europaea subsp. africana seedlings (72 cases). MANOVA was carried out on six dependent variables: shoot volume, root volume, root-shoot ratio, height, per cent soil moisture, and number of leaves and three independent variables: plants fertilised or unfertilised, grown from seed collected from three parent plants, and watered every 7, 14 21, or 28 days. There were four replicates per treatment.

Factor	Wilk's Λ	$p \leq$
Fertiliser	63.3	$1.0 * 10^{-9}$
Parent	2.5	0.006
Watering regime	20.4	$1.0 * 10^{-9}$
Fertiliser x watering regime	8.5	$1.0 * 10^{-9}$

Table 6.4 Means or medians[1] of dependent variables by treatments, and F tests from MANOVA on measurements of one year old Olea europaea subsp. africana seedlings (72 cases). MANOVA was carried out on six dependent variables: shoot volume (SV), root volume (RV), root-shoot ratio (R:S), height (HT), per cent soil moisture (SM), and number of leaves (NL), and three independent variables: seedlings fertilised or unfertilised, grown from seed collected from three parent plants, and watered every 7, 14 or 21 days. There were four replicates per treatment. Data from 28 day unfertilised treatment are omitted because of missing values. Probabilities are Bonferroni adjusted with denominator, k = 55, following Barker and Barker (1984).

FACTOR	SV (cm^3)	RV (cm^3)	R:S[1]	HT (cm)	SM[1] (%)	NL
fertilised	14.8	10.3	0.7	36	3	101
unfertilised	7.6	10.6	1.3	28	9	36
F	41.3	NS	29.5	12.9	318.9	189.4
P <[2]	.00001	–	.0001	.04	$1.0 * 10^{-7}$	$1.0 * 10^{-7}$
mother A	10.2	10.2	1.1	29	6	72
mother B	10.5	10.0	1.0	31	6	49
mother C	11.1	11.1	1.2	34	7	70
F	NS	NS	NS	NS	NS	9.7
P <[2]	–	–	–	–	–	.002
watered @ 7d	15.1	12.0	0.9	36	12	97
watered @ 14d	11.2	11.3	1.2	33	5	64
watered @ 21d	7.0	7.2	1.0	29	6	44
watered @ 28d[3]						
F	18.6	7.3	NS	NS	62.4	45.3
P <[2]	.0001	.072	–	–	$1.0 * 10^{-7}$	$1.0 * 10^{-7}$

undertaken, one using data from the unfertilised plants, the other from fertilised plants.

In the second MANOVA (unfertilised plants), soil moisture was the only dependent variable which differed significantly among watering regimes; there was a significant linear decline from 15 to 9 to 7% as watering interval increased from 7 to 14 to 21 days (Table 6.5).

In the third MANOVA (fertilised plants), as watering interval increased from 7 to 14 to 21 days, there were significant linear declines in mean shoot volume from 21.3 to 15.1 to 7.2 cm^3, in mean height from 43 to 36 to 29 cm, in median soil moisture from 5 to 3 to 2%, and in the mean number of leaves from 154 to 94 to 52 (Table 6.5).

The interactions between fertiliser and watering regime are presented in Figs. 6.2 and 6.3 and in Table 6.5. Root:shoot ratios were significantly lower for fertilised plants than for unfertilised plants although in both treatments there was a trend toward increasing root:shoot ratio with increasing watering interval. Root:shoot ratios were less than 1 for fertilised plants and more than 1 for unfertilised plants (Fig. 6.2).

Soil moisture was significantly lower for all fertilised plants (5% or less) than for all unfertilised plants (7% or more). Soil moisture in pots with fertilised plants had fallen to 5% seven days after watering and 2% twenty-one days after watering, whereas soil moisture in pots with unfertilised plants was 15% 7 days after watering and 7% 21 days after last watering (Fig. 6.2).

Fertilised plants had a mean height of 29 cm or more, whereas unfertilised plants had a mean height of 29 cm or less. The mean number of leaves on fertilised plants ranged from 52 to 154, whilst the mean number of leaves on unfertilised plants was 40 or less (Fig. 6.3).

Table 6.5 Means of dependent variables by treatments, and F tests from two MANOVA on measurements from fertilised and unfertilised one year old Olea europaea subsp. africana seedlings (32 cases in each MANOVA). MANOVA was carried out on six dependent variables: shoot volume (SV), root volume (RV), root-shoot ratio (R:S), height (HT), per cent soil moisture (SM), and number of leaves (NL), and two independent variables: seedlings grown from seed collected from three parent plants, and watered every 7, 14 or 21 days. There were four replicates per treatment. Data from 28 day unfertilised treatment are presented in the last line, although these data were omitted from the MANOVA because of missing values. Probabilities are Bonferroni adjusted with denominator, k = 55, following Barker and Barker (1984).

FACTOR		SV (cm^3)	RV (cm^3)	R:S[1]	HT (cm)	SM[1] (%)	NL
fert	7d	21.3	13.1	0.5	43	5	154
fert	14d	15.1	11.1	0.7	36	3	94
fert	21d	7.2	6.2	0.9	29	2	52
F		56.5	NS	NS	16.4	34.7	110.4
P <[2]		.0003			.02	.0002	$2 * 10^{-7}$
unfert	7d	8.9	10.8	1.1	29	15	40
unfert	14d	7.3	11.6	1.4	29	9	34
unfert	21d	6.8	8.4	1.4	28	7	38
unfert	28d	7.2	11.7	1.8	26	--	33
F		NS	NS	NS	NS	233.2	NS
P <[2]						$2 * 10^{-7}$	

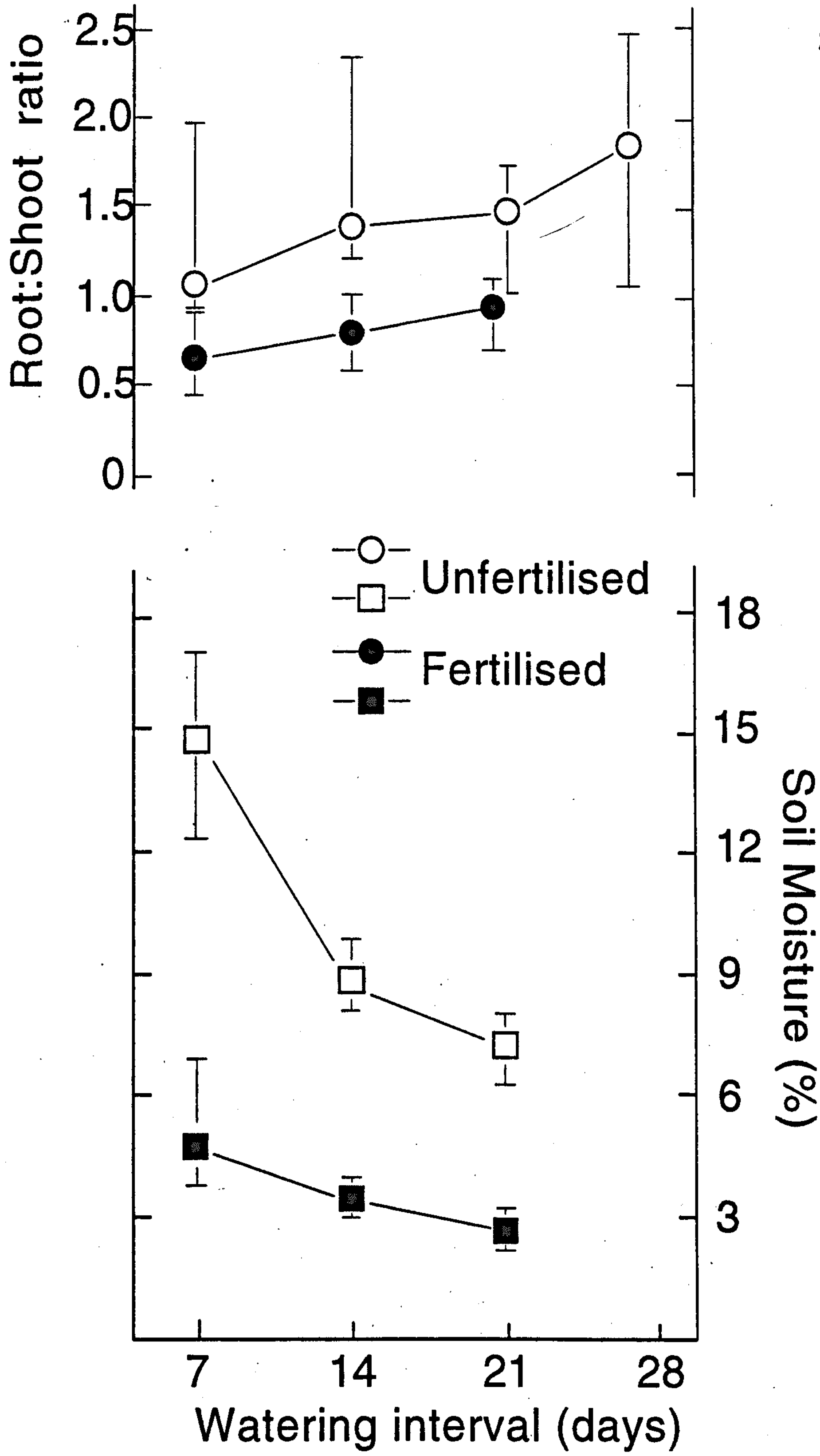

Fig. 6.2. Interactive effect of fertilisation and watering interval on root:shoot ratio and soil moisture of one year old *Olea europaea* subsp. *africana* seedlings. Numbers are medians with interquartile ranges of twelve replicates (four from each of three parents), except that the 21 day watering interval fertilised plants had only eleven replicates because one seedling died.

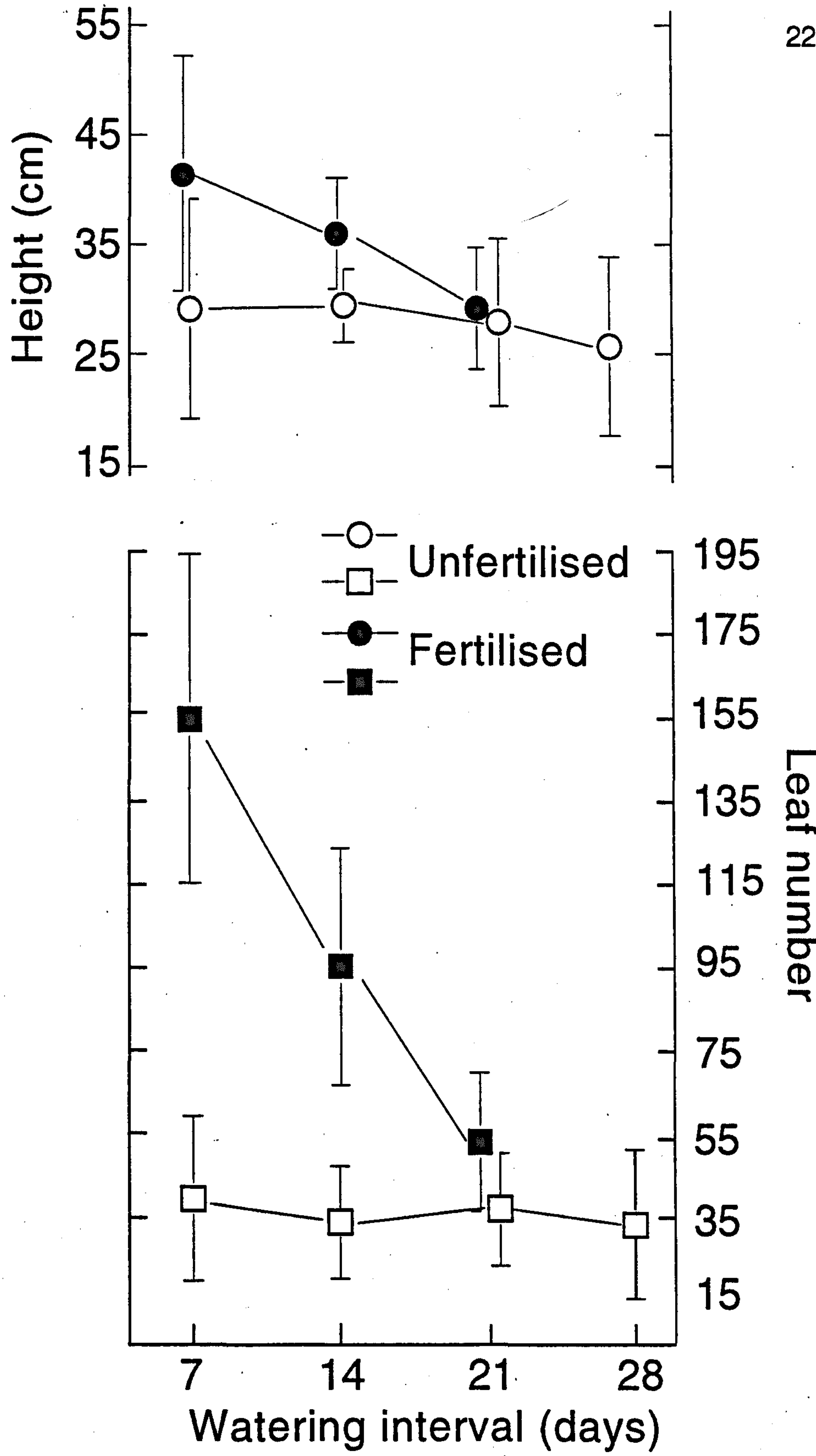

Figure 6.3. Interactive effect of fertilisation and watering interval on height and the number of leaves of one year old *Olea europaea* subsp. *africana* seedlings. Numbers are means (± 1 SD) of twelve replicates (four from each of three parents), except that the 21 day watering interval fertilised plants had only eleven replicates because one seedling died.

DISCUSSION

The most important result of this experiment was that unfertilised olive seedlings showed drought tolerance whilst fertilised seedlings did not. Although fertilised plants watered every 28 days all died, and fertilised plants watered every 21 days showed signs of moisture stress, no unfertilised plant showed any signs of moisture stress such as wilting or leaf roll. The fact that fertilised plants either had dried, shrivelled leaves or else had lost their leaves after 28 days without water indicates that they died of moisture stress. There are three possible explanations, not mutually exclusive, why the 28 day watering interval led to the deaths of fertilised but not of unfertilised plants. Firstly, the greater shoot volumes and numbers of leaves on fertilised plants suggests that they lost more water via transpiration, simply because they had a greater leaf area. Secondly, because photosynthesis and photosynthetic efficiency are greater in plants with adequate nutrition than for under-nourished plants (Kramer and Koslowski 1979), fertilised plants may have dried out their soils faster than unfertilised plants. Thirdly, with improved nutrient status, fertilised plants could have depleted carbon reserves from storage tissues for use in growth, primarily of above ground parts (Kramer and Koslowski 1979:271 et seq); this depletion may have reduced their ability to withstand drought.

Another important result is that plants which were fertilised and watered every week were more than 50% taller, had nearly four times as many leaves and more than twice the shoot volume of unfertilised plants watered weekly. Fertilised plants watered every two weeks also were taller, had three times the number of leaves and nearly twice the shoot volume of unfertilised plants watered weekly. However, fertilised plants watered every 21 days were very similar in their characteristics to unfertilised plants of any watering interval. Fertilisation with adequate watering, therefore, resulted in greatly increased shoot growth but little change in root growth. However, shoot growth declined in fertilised plants watered every 21 days to a point where these plants were very similar to all unfertilised plants. This result implies that fertilisation had little beneficial effect on seedlings which were watered only every three weeks or less often.

In summary, plants need adequate nutrition and water to grow, and irrigating or fertilising plants usually increases their growth where water or nutrients are deficient. In this experiment with potted olive seedlings, fertilisation increased growth in adequately watered plants but resulted in the death of seedlings which were not adequately watered. This may have been due to fertilisation increasing plants' leaf area or improving the efficiency of their photosynthetic apparatus (events which resulted in a lethal decline in soil moisture), or due to rapid growth of shoots leading to a depletion of stored carbon.

CONCLUSION

Notwithstanding the short time scale of this experiment and the fact that plants were grown in pots in the glasshouse, results imply that for these olive seedlings, there was a trade-off between rapid early growth brought about by fertilisation, and subsequent tolerance to moisture stress. In attempting to restore the woodlands of Rora Habab, it will be essential to produce physiologically robust seedlings which can survive drought and grow when moisture and nutrient conditions are favourable. Results presented here indicate that seedlings should not be outplanted shortly after being fertilised, and that fertilisation and irrigation need to be carefully managed to insure optimal growth consistent with post-transplant survival.

The high drought tolerance of olive suggests that it is a good candidate for reforestation in semi-arid zones of Africa such as Rora Habab. Further research is needed into the moisture relations of both wild olive trees and nursery grown seedlings, and their physiological responses to nutrient and moisture stress, particularly in relation to pre-transplant conditioning and root:shoot equilibrium (Cannell 1985:168-175). Some of these questions will be explored starting in 1992. At that time, we will repeat this experiment in Eritrea using local soils and water, various fertilisers, and a range of native tree species, including juniper as well as olive.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

SUMMARY OF CHAPTERS 1 TO 6

The evidence discussed in Chapter 1 shows that the Rora Habab plateau has been modified by people for at least 1000 to 1500 years. In particular, the activities of Italian settlers reduced the wooded area of the plateau in many ways, notably by forest clearance for settled agriculture. Chapter 2 showed that the geology and climate of Eritrea are not uniform and are greatly influenced by the abrupt elevation changes between the eastern and western lowlands. Even within the Rora area, there appear to be differences between Laba in the south and sites further north. There are noticeable differences in rainfall and temperature across the plateau. In Chapter 2, it also became clear that there is no tradition of tree planting on the plateau. Chapter 3 showed that the density and species composition of vegetation is not uniform across the plateau, that even where woodlands are most dense, the distribution of woody perennials is patchy and affected by agriculture, cutting and grazing, and that the distribution of juniper and olive seedlings is restricted to wooded, not agricultural areas. Chapter 4 showed that the soils of the plateau are relatively homogeneous except that fields were different from grazing land with regard to organic carbon and related soil properties, and that the soils of Bacla and Berige were more similar to each other than they were to soils at Laba, where soils were sandier and more sodium-rich. Chapter 5 showed that it is possible to germinate the seeds and vegetatively propagate stem cuttings from olive and juniper, and that germination and rooting exceeded 50% using several methods and reached 75% or more in some cases. Chapter 6 showed that unfertilised olive seedlings were more drought-tolerant than fertilised olive seedlings, that fertilisation and watering regime interact, and concluded that outplanting practices and nursery management should be experimentally determined, taking account of fertiliser and watering regime pre-conditioning as well as soil and site-specific criteria.

IMPLICATIONS FOR RESTORATION

There are three sets of questions to be addressed when considering restoration of the Rora Habab plateau. Firstly, if we accept that it is important to restore the area, what evidence do we have that our efforts will be successful? Secondly, what do we mean by restoration; what is there now, and what was there once that we wish to restore? Thirdly, how do we approach restoration generally and specifically? With regard to this thesis, what have we learned that may guide restoration efforts and identify future research needs? I will consider each of these in turn.

Is Restoration Feasible?

This thesis research grew out of an initial visit to Rora Habab in the summer of 1984, and has developed gradually since then. Over this same period, a literature on restoration ecology and several journals on this topic have come into being. This literature reports the results and lessons learned from a number of case studies, which have demonstrated that it is possible to restore altered or damaged sites in a variety of ecosystems. These include temperate climate prairies, temperate wetlands and woodlands, tropical rain forest, and tropical dry forest (e.g. Soulé 1986, Wilson 1988). Some of the techniques and principles used in these projects, for example the work of Janzen (1988), may be helpful in future restoration efforts on Rora Habab. However, a specific review of these, while important, is not undertaken here.

Rather, the purpose of this section is to discuss some issues of particular relevance to restoration on Rora Habab.

Although soil erosion is severe and the absence of trees in parts of Rora means that seed sources and genetic variability are limited, these are not in themselves sufficient to prevent restoration. Rather, they indicate that restoration should be attempted. The potential impact of climate change, however, is of serious concern in semi-arid marginal lands.

Changes in climate have been attributed to a number of processes, including albedo changes following vegetation clearance (Otterman 1974, Jackson and Idso 1975, Courel et al 1984, Gornitz and NASA 1985, Laval 1986), changes in the flow of the Tropical Easterly Jet Stream (Hulme and Tosdevin 1989), more general, and less well understood changes in the physics of upper atmosphere circulation (Winstanley 1973, Ayoade 1983), and periodic oscillations in sea-surface temperatures, notably the El Niño-Southern Oscillation (Smithson 1988). Many of these mechanisms have been reviewed in Barry and Chorley (1982), Lamb (1988), and Berger et al (1989).

It seems clear that climate change can occur because of human activities or independently of them, that human activities can worsen the consequences of climate change, but that we are some way from clarifying the precise mechanisms, scale of influence, or interactive nature of the processes involved. It is known that Africa has a long history of variation in rainfall, with drought occurring for different lengths of time, and that there may be a periodicity in climatic shifts (Lamb 1988:194 et seq). Lamb (1988:211) concludes that drought is likely to continue or increase in severity over the next several decades.

Some elderly farmers from Rora indicate that recent droughts are more severe than they used to be, while others say that that some droughts have always been severe. There is some evidence to suggest that vegetation clearance, such as has occurred on Rora, results in lower rainfall locally and, with less orographic cloud forming over bare areas, that soil temperatures and evapotranspiration rates are elevated (Otterman 1974, Jackson and Idso 1975).

The most important evidence that a shift toward a drier climate, in itself, should not discourage restoration efforts is that woody and herbaceous plants have continued to thrive and regenerate in a number of protected microsites on Rora. This is particularly the case in cemeteries but also applies to less accessible locations where cutting and grazing pressures are not severe and agriculture is not possible. Nevertheless, the potential problems of even greater aridity than exists today indicates that drought resistance is a key attribute of the native flora which should be studied and incorporated into the restoration programme.

A second set of obstacles to restoration is not related to environment but to social and political factors in Rora and across Eritrea. In this regard, it is of great importance that the history of the Habab people and their current circumstances be well documented and understood.

The farmers on Rora Habab came to Rora about 350 years ago and are the descendants of settled cultivators from the central Eritrean Highlands. They apparently abandoned cereal cultivation soon after settling Rora and relied on their animals for meat and to purchase grains (Chapter 2), taking up cultivation again about 80 years ago.

The transition has not been easy for the Habab for several reasons. Cultivation did not begin voluntarily but was forced upon them by the Italian government just six decades after the Habab had converted from Christianity to Islam. The Rora plateau, indeed most of Sahel province, was politically and geographically marginal to the Italian settlers' main interests so that extension work, the provision of farming implements and other inputs, and other development activities were not regularly provided. Two decades after agriculture was re-introduced, Fascist Italy's expansion into Ethiopia further marginalised Rora and limited its usefulness to the colonists, and in 1941, all development activities on Rora ceased when the British army defeated Italy in Eritrea. Thereafter, neither the British nor the Ethiopian governments showed any interest in Rora's agricultural productivity or the fate of the plateau's natural environment and it was not until eight years ago that any surveys were conducted or any development activities begun. Thus, the people of Rora Habab have had less than 25 years of assistance in converting from pastoralism to agriculture and about 20 years of that time was coerced "help" for the benefit of Italian settlers, not local people.

Despite this fragmented agricultural history, many of the Habab people are very proud of their abilities as farmers and have developed the land classification schemes and farming systems described above and in Chapter 2 within just three generations. In discussing local farming practices, one elder from Bacla showed me his plough and said "..we are the only people in Sahel (an Eritrean Province) who use this. We can make them and we can use them".

Today, the villagers of Rora are very much aware of the declining state of their soils and woodland. Farmers from the northern villages on Rora travel to the south of the plateau and know that the area once was forested. They are keen and willing to involve themselves in restoration, provided that they can be supported to the extent that this work takes them away from cultivating crops or looking after their animals. Moreover, they are supported by a provisional central government which sees the necessity of restoration throughout Eritrea, including Rora Habab, by local extension agents and agricultural experts who speak their language, live and work alongside them, and by a strong, effective relief agency, the Eritrean Relief Association. Thus, there exist no local or national obstacles to restoration of the Rora plateau. In fact, local people, regional and national authorities all wish restoration and sustainable development to take place on Rora Habab.

<u>What are we Restoring?</u>

If we were to state the major problem facing the people of Rora Habab now that the war is over, it would probably go like this. Rora Habab is losing woodlands faster than natural regeneration can replace them, soil erosion is ubiquitous and severe, and the poverty and geographic isolation of the people of Rora means that the woodlands will eventually disappear entirely and Rora will be abandoned. There is a clear role for the ecologist on Rora, as there is in much of semi-arid Africa, where the loss of native woodlands is an economic as well as a biological disaster.

The ecological restoration of Rora Habab will require two complementary activities. Firstly, we must re-establish native trees and other vegetation on the plateau. Secondly, the villagers of Rora and the people who work with them must jointly develop a system of land use and resource management which satisfies economic, social, cultural and political needs but also meets some criterion of environmental stability. In order to plan a restoration programme for Rora, we need first to know what the plateau is like now, and what it was like in the past. The vegetation and soil surveys discussed in Chapters 3 and 4 were an attempt to answer the former question. The only relevant written material that I have found which goes some way to describing what Rora was previously like was in the Archives of the Istituto Agricolo Coloniale Italiano in Florence, Italy. While it would be a mistake to rely solely on a single source of information, this account of Rora as it was observed 80 years ago so closely fits with other archival material, and with the accounts of elderly villagers, that it is worth presenting extended excerpts by way of summary. The following description of Rora Habab was published in <u>L'Agricoltura Coloniale</u> by Emanuele Naldini (1916); the translation is mostly literal with no attempt to alter the rather flowery nature of the archaic Italian prose.

Extracts from: Escursione alle Rore degli Habab ed all'altipiano di Nacfa,
(Excursion to the Roras of the Habab and the Nacfa plain)

The Roras: *These small plateaux which may be spurs of the Ethiopian plateau are so extensive that they merit the interest of the government because of their potential productivity once they are placed under cultivation using methods which even if not perfect will be more advanced than those of the native people.*

Topographic description: *Once you have surmounted the crest of the plateau, Rora is visible as a plateau which is interrupted frequently by small hills and undulations among which wander for many kilometres, little valleys which are more or less wide which constitute the most suitable land for cultivation, but also the hills with shallow slopes could be suited to cultivation.*

The soils: *The soil, which is made up of transported material mixed with many organic substances derived from the litter of the magnificent forests with which Rora is covered, is of an exceptional richness ... The soils are also light and easy to work. The abundant forage which covers the land and the forest vegetation is proof of the soil's richness; ...*

The flora: *The flora which is very rich is not exactly the same on all the Roras. In fact the major part of the flora of Rora Laba is composed of magnificent olives, many of which are young, to which, with a high likelihood of success, we should attempt to graft our olives. A characteristic plant is the rose which I believe is not to be found on other plateaux.*

The herbaceous flora is composed for the most part of Gramineae, Labiateae, Boraginaceae and Leguminoseae. On Rora Tortoret one encounters also an abundance of the Erica *species which are similar to our tree heath (scoparia). On Rora Massal begin to appear the first* **thuie** (Juniperus excelsa) *along with the flora of other Roras. These thuie become more and more* *frequent as we move toward the north, until on Rora Bacla, their number exceeded the other types of tree and their dimensions, truly colossal, reach more than 20 metres in height with a diameter of 60 to 70 or more centimetres at the base, so that they constitute a rich and marvellous forest. I was told that Prof. Fiori did not reach this place as part of his studies on the woods and herbaceous plants from this colony. This is a gap which must be filled. ... But I hope that the wonderful flora of this region will not be ignored any more by the sciences of botany and agronomy.*

The climate: There are no records to characterise Rora's climate but from the altitude, the vegetation, and the information gathered by people who visited the place, we can make an approximate description. The temperature is approximately equal to that of the Ethiopian plateau but the abundance of vegetation notably mitigates solar radiation. The winds are frequent and breezes ascending and descending due to the proximity of the Anseba valley on one side and the Sahel lowland on the other are more frequent than the winds. The humidity is rather marked; in fact because of the immense forests the rains which occur at the same periods as on the other plateaux are more frequent and more abundant than elsewhere. Moreover, the period of the big rains is immediately followed by a long period of fogs due to the rains in the lowlands; the fogs are sometimes so dense that they look like rain. If to all of this we add the great benefit of obstructed runoff and obstructed evaporation both due to the plants, we quickly come to the conclusion that the humidity conditions found here must be exceptional by comparison to other plateaux.

Some people believe, probably correctly, that two crops in one year are possible; the first, the most important, should coincide with the rainy season, the other, the less important, with the subsequent period of fogs ...

Economic and social condition of the region: At this time the region is exclusively devoted to pasture with the exception of a few fields which are cultivated by the Tigre Atacles who, restricted in their territory, got *permission from the government three years ago to cultivate on Rora. ... This year, unexpectedly, their arose among this population* [i.e. the Habab] *a frenzy for cultivation and they requested ploughs and seeds .... Underlying this sudden wish to cultivate was hidden a second goal - to have a reason to contest the ownership of Rora with the Atacles because the Atacles were expanding. But this doesn't matter. ..... the government will have the right to demand that the Habab cultivate Rora and more, that they will cultivate according to the desires of the government. In fact we will be in a good position because the virgin soils will be combined with ignorant farmers who, having no previous uses, customs or cultural prejudices, will be better initiated and directed to a cultivation system which will be more advanced than that of the surrounding populations. I don't intend with this to propose a model of cultivation. It would be an error to expect this from people who were only nomads. None the less, without forgetting the social, economic and ecological conditions, we will always be able to do something which is on the way to what is called agricultural progress. ... It would be a big mistake to permit one or the other tribe to cultivate Rora without imposing new methods of cultivation which could at least safeguard the integrity of the soils and immediately place alongside them a competent functionary who would oversee, direct and look after the application of these methods. For example, it is absolutely necessary to impose terracing of the land without which the soil would be washed away by water to the Anseba valley floor: And after a few years would happen what has happened in other regions; that is to say nothing would remain of the Rore which are today so promising but barren and rocky mountains.*

The necessity of building terraces was grasped initially by Mr. Commissioner for Keren, magg. comm. Fioccardi and he imposed the making of terraces on those few cultivators who were already in Rora, and he would have imposed terracing also on the new farmers this year if considerations of

public order had not forced the suspension of all cultivation for the moment in these contested lands. Fioccardi wanted me to accompany him on his trip in order to build, under my supervision, terraces which would be a model for those to be constructed later by cultivators ; in fact one was built in Rora Laba.
Tree cultivation: *Because of the exceptional climate conditions which we already described of Rora, I think also that some orchards of temperate climate could find satisfactory growth conditions and I think it would be a shame if we did not attempt this experiment.*

The plateau of Nacfa: *To the east of Rora one descends from about 2 400 metres to about 1 600 metres and finds Nacfa in a vast plain, also of great interest. Topographically the fine appearance is similar to Rora .... signor Pontiglione [administrator in Nacfa] (made observations of) precipitation in 1912 which totalled 610 mm distributed as:*

month	*rainfall (mm)*	*month*	*rainfall (mm)*
March	50	Sept.	40
April	3	October	33
June	115	Nov.	2
July	180	Dec.	13
August	172		

Present status of the land: ... this year thanks to active and continuous propaganda they have been able to persuade some, among the least retrograde, to cultivate; for these, making use of some Abyssinian cultivators, they have ploughed a large tract of land ...

Reforestation: *Before closing this report I feel the need to make heard my modest applause for the tenacious and meritorious works of reforestation undertaken for some time by signor commissario maggiore comm. Fioccardi, works whose beneficial effects are already apparent. Throughout my travels I* *observed with pleasure the scrupulous respect for the forest and where the land and climate are favourable the trees are already large and luxurious. In the inferior places the results will be delayed but always, as I have observed before, certain and beneficial.*

Naldini's account is the most eloquent of two or three rhapsodic descriptions of Rora Habab published by Italian visitors around the turn of the century. Taken together with the accounts of elderly farmers, it seems beyond doubt that Rora not only had extensive forests and fertile soils, but also a variety of wild animals. While the reintroduction of animals lies beyond the scope of early restoration work, the rehabilitation of the native flora is a reasonable goal.

Where do we go from here?

The restoration of Rora Habab's woodlands will require that native species can be successfully propagated and grown in areas where appropriate protection and management techniques ensure their survival and growth. This may be achieved through natural regeneration, direct seeding of specific plants, or nursery production of seedlings for outplanting. All three approaches would be appropriate for Rora and require experimental investigation. In all three approaches, ecological considerations are important, for example with respect to human ecology, plant-animal interactions, within and between species competition, soil variability, site variability and climatic factors. There are a great many aspects of community ecology and physiological ecology of individual species which, I believe, require an experimental approach to research, not just an empirical one.

Restoration of the plateau also requires an understanding of the social, economic and political circumstances on Rora. People and their animals dominate ecological processes on Rora, and the Habab people subsist almost entirely on its resources. Ecological restoration may well require changes in land management and animal husbandry methods if existing habitat and planted seedlings are to be protected. It is therefore imperative for outsiders, whether Eritrean or not, to work in cooperation with Rora's people, to understand their society, economy, perceptions and options. Eritreans who are not from the plateau but live and work there, have taken the lead in this, so that the developments discussed in Chapters 1 and 2 have taken place in response to problems which the Habab people identify and wish to solve. Future restoration work must find harmony with the Eritrean approach of village-level, integrated development and their philosophy of self-reliance, and also with the Habab people's own agenda.

A major question concerns the level of management which is biologically and socially appropriate in order to avoid the loss of all of Rora's trees, and its eventual abandonment. I believe that without intervention, the woodlands of Bacla and Shamotet will soon disappear, and with them, Africa's most northerly juniper-olive ecosystem. The scope and scale of potential interventions are very diverse, ranging from the relatively passive approach of exclosing land and protecting it, to more active approaches such as nursery production of trees using hand watering and small amounts of fertiliser. Only a cooperative approach to planning, implementation and appraisal will identify a level of intervention conducive to effective, locally acceptable, long-term management and restoration.

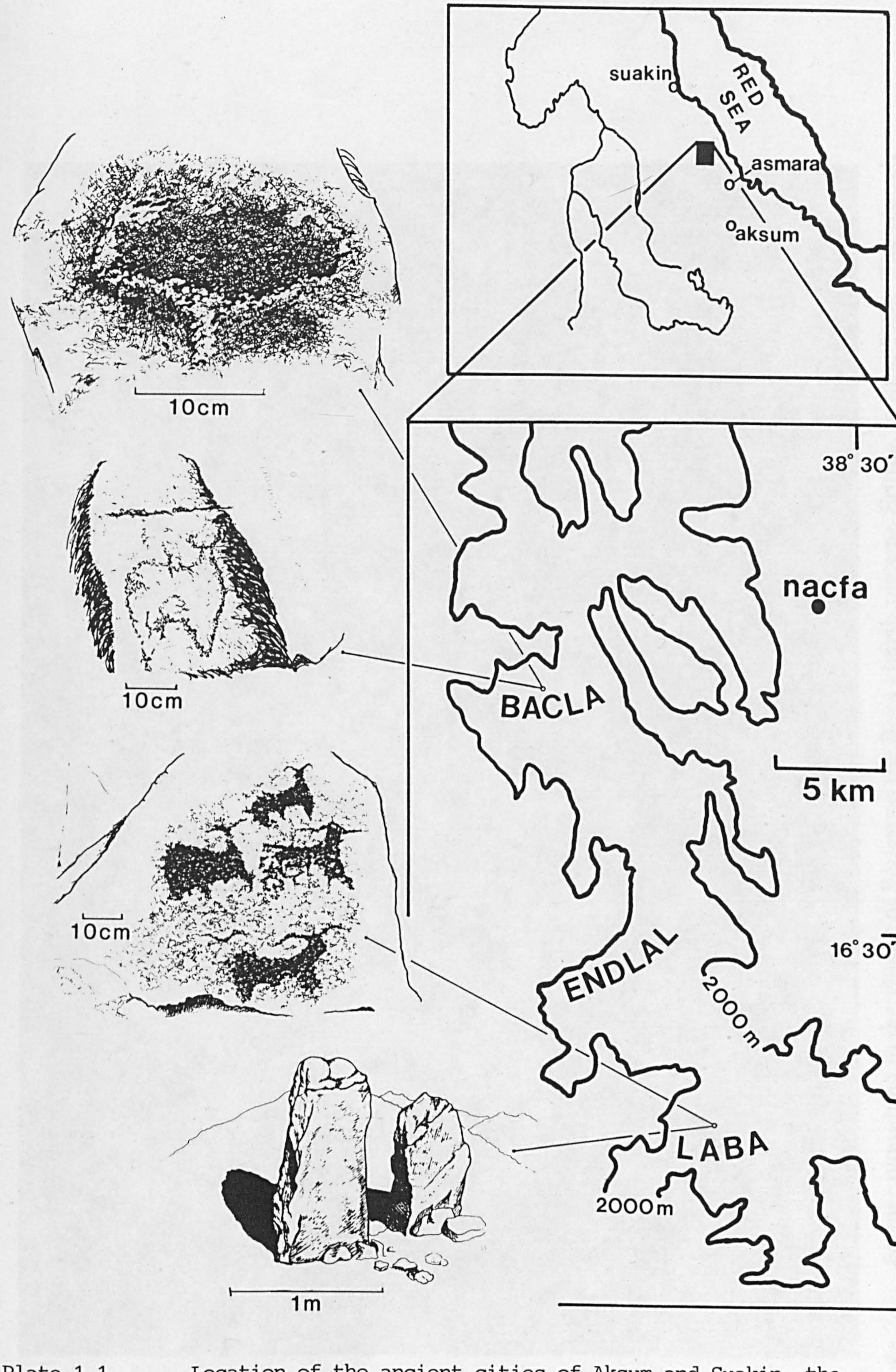

Plate 1.1 Location of the ancient cities of Aksum and Suakin, the Eritrean capital of Asmara, and the villages on the Rora Habab plateau where rock carvings and sculpted stones exist.

Plate 2.1. Farmer ploughing in the village of Berige on the Rora Habab plateau, Eritrea, in June 1984. The plough share was not able to penetrate more than a few centimetres of soil because of the poor health of the animals and the stoniness of the soil. Note the loss of olive woodlands on the hillside.

Plate 2.2. Terracing, completed in 1986, in Laba village on the Rora Habab plateau, Eritrea. Note the large Euphorbia tree, middle left.

Plate 2.3. Farmer using a small scythe to hand-weed a young barley crop in Bacla village on the Rora Habab plateau, Eritrea, August 1987. Note olives adjacent to the cultivated area. Junipers and olives are co-dominant on surrounding hillslopes. The farmer's stick (centre right), made from olive, delimits the work area.

Plate 3.1. Cultivated land, grazing land, juniper and olive trees in Bacla village on the Rora Habab plateau, Eritrea, December 1985. Note the shelter for animals next to a family's home, upper centre.

Plate 3.2. View north-west above Laba village (south transect) on the Rora Habab plateau, Eritrea, January 1989. Note women returning from fuelwood collection, olive stumps and abandoned Ethiopian army defensive positions. Shrubs are Dodonaea viscosa.

Plate 3.3. View east of part of Berige village (central transect) on the Rora Habab plateau, Eritrea, August 1987. Note olive stump, eroded hillsides and cemetery with intact trees (centre left).

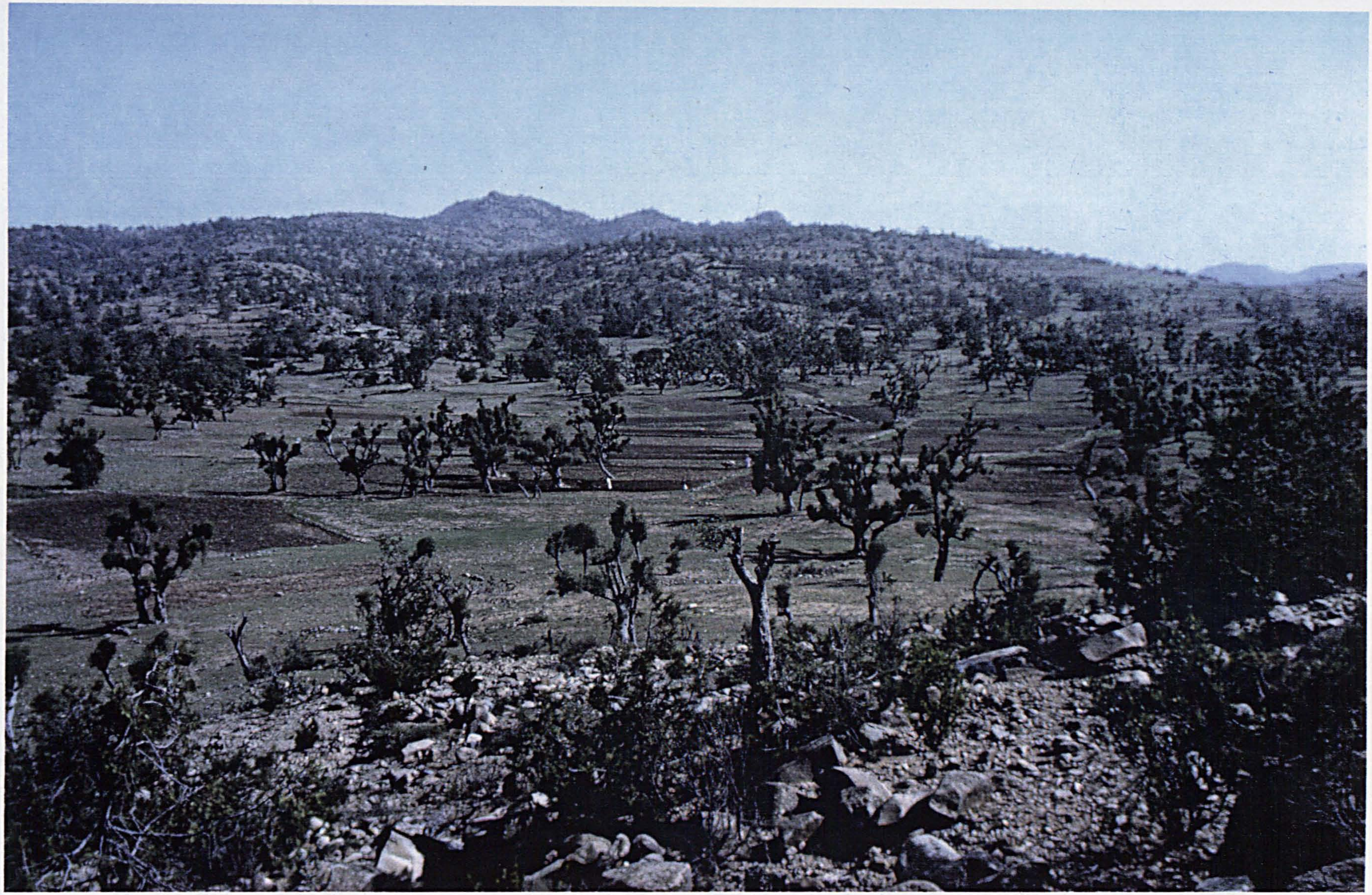

Plate 3.4. View north of part of Bacla village (north transect) on the Rora Habab plateau, Eritrea, August 1987. Note the heavily cut olives in the foreground and pollarded olives within fields.

Plate 3.5. Cemetery in Endlal village on the Rora Habab plateau, Eritrea, August 1987. Note crown closure of uncut olives, regeneration under olive crowns, and eroded, treeless hillslopes to each side.

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Appendix 2 List of Woody and Herbaceous Plants Collected on the Rora Habab Plateau, Eritrea.

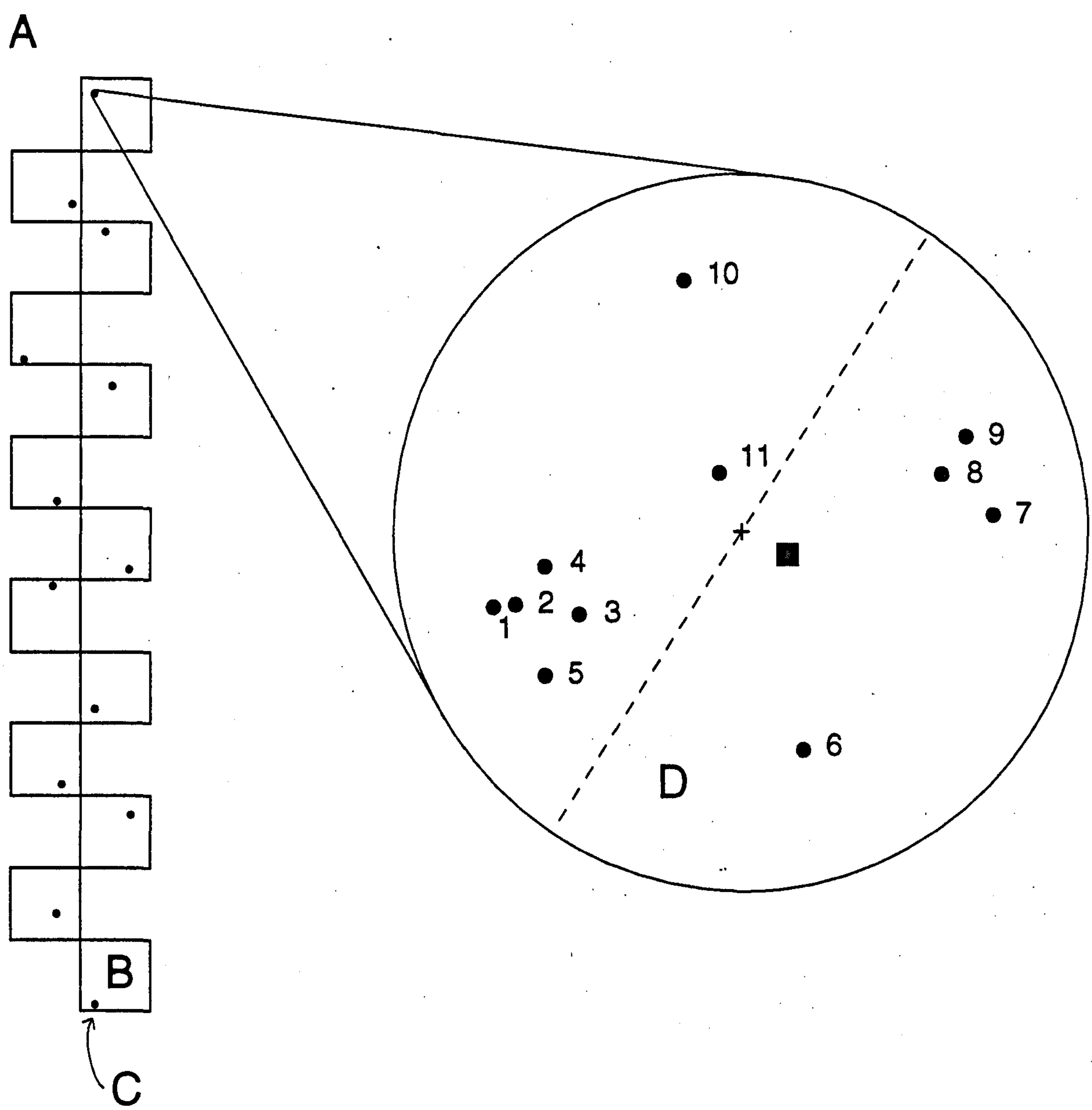
Positive identifications:

Acacia origena Hunde
Anagallis arvensis L.
Asparagus africanus Lam.
Asparagus racemosus Willd.
Bidens setigera (Sch. Bip.) Sherff
Carissa edulis (Forssk.) Vahl.
Chlorophytum tetraphyllum (L.) Baker
Convolvulus sagittatus Thunb.
Cynodon dactylon (L.) Pers.
Dobera glabra (Forsk.) Poir.
Dodonaea viscosa Jacq.
Dyschoriste radicans Nees
Eleusine floccifolia (Forssk.) Spreng.
Eragrostis papposa (R. & S.) Steud.
Felicia abyssinica Sch. Bip. ex A. Rich. subsp. abyssinica
Guizotia scabra (Vis.) Choiv. subsp. scabra
Hyparrhenia hirta (L.) Stapf.
Hypoestes forskaolii (Vahl.) R. B.R.
Hypoxis villosa L.f.
Indigofera amorphoides Jaub & Spach
Juniperus excelsa Bieb.
Justicia lithospermifolia Jacq.
Maytenus arbutifolia (Hochst. ex A. Rich.) Wilczek
Medicago laciniata Forsk.
Momordica pterocarpa A. Rich.
Nuxia congesta R. B.R. ex Fresen
Olea europaea L. subsp. africana (Mill.) P.S. Green
Oxalis obliquifolia A. Rich.
Pennisteum villosum Fresen
Psiardia punctulata (DC.) Vatke
Pulicaria attenuata Hutch. & Burtt
Pycnocycla glauca Lindl.
Rhus abyssinica Hochst. ex Oliv.
Salvia nilotica Juss ex Jacq.
Senecio lyratus Forssk.
Setaria sphacelata (Schumach.) Moss
Solanum piperiferum A. Rich.
Solanum schimperanum Hochst.
Sporobolus pyramidalis P. Beauv.
Tarchonanthus camphoratus L.
Trifolium simense Fresen

Provisional identifications:

Acanthus sp.
Ageratum conyzoides
Alchemilla sp.
Amaranthus hybridus
Ampelocissus sp.
Bidens sp.
Bromus tectorum
Chlorophytum sp.
Clematis sp.
Commelina ?africana
Craterostigma sp.
Cucumis sp.
Cyperus sp.
Cyphostemma sp.
Erodium moschatum
Euphorbia sp.
Ferula sp.
Gomphocarpus sp.
Helichrysum sp.
Hibiscus sp.
Hypoxis sp.
Indigofera sp.
Justicia sp.
Launaea sp.
Panicum sp.
Plantago psyllium
Polygala sp.
Reichardia sp.
Rumex sp.
Solanum sp.
Veronia sp.

Appendix 3. Diagram of random non-aligned transect design used in vegetation and soil surveys (Chapters 3 and 4) on the Rora Habab plateau, Eritrea. Each of three transects (A) in the north, centre, and south of the plateau was 2.6 km long. In each of thirteen alternating 200m square grids (B) a plot of 20 m radius (C) was randomly located. Within this plot (D), a soil pit (solid square) was dug as close to the centre of the plot as vegetation and bare rock permitted. The location of each living and dead tree was charted and numbered in the plot diagram (shaded numbered circles). Other vegetation was sampled along a randomly oriented diameter (shrubs) or radius (herbs) (dashed line). Methods of sampling, measurement, and analysis are given in Chapter 3 (vegetation) and Chapter 4 (soils).



Appendix 4. Profile descriptions and laboratory data from 39 soil profiles sampled along north (Bacla), central (Berige), and south (Laba) transects on the Rora Habab plateau, Eritrea.

Explanatory notes

Entry	Example	Explanation
Profile number	Bacla 1	Name of village and profile number (see Fig. 4.6).
Soil classification	fine, mixed, isomesic **Lithic Ustropept**	Classified to family level following USDA Soil Taxonomy (Soil Survey Staff 1975, 1990).
Topography	uniform, upper slope	Recorded as summit, upper slope, midslope, footslope, terrace or valley bottom and as either uniform or complex (complex = concave, convex or terrace) following Faniran and Areola (1978:101-3).
Slope	29 down, 28 up	Two values are given. The first refers to the angle downslope from the point of measurement, the second to the angle upslope from the point of measurement.
Aspect	260	Compass bearing taken downslope from the point of measurement.
Erosion	moderate	Estimated subjectively and categorised as slight, moderate, or severe.
Land use	woodland, grazing	Major land use classified as woodland, grazing, and/or field (see Table 3.1).
Profile description	A AB Bw R	Horizon designations follow Soil Survey Staff (1975, 1980, 1990). Descriptions of Munsell colour, texture, structure, roots, boundary, and other information follow USDA Soil Conservation Service (1966) and Soil Survey Staff (1980).
Profile data		Depth, percent gravel, particle size, and chemical data by horizon.

Bacla 1	fine, mixed, isomesic **Lithic Ustropept**

Topography:	uniform, upper slope
Slope (degrees):	29 down, 28 up
Aspect (degrees):	260
Erosion:	moderate
Landuse:	woodland, grazing

A	dark yellowish brown (10YR 3/4) moist, light yellowish brown (10YR 6/4) dry; clay; moderate medium angular blocky; very hard (dry), friable (moist); very common fine and very fine roots; boundary abrupt and wavy.
AB	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/6) dry; no analysis; moderate medium angular blocky; very hard (dry), friable (moist); very common fine and very fine roots; boundary gradual and wavy.
Bw	strong brown (7.5YR 5/6) moist, 7.5YR 6/6 dry; clay; moderate medium angular blocky to massive; very hard (dry), very friable (moist); common fine and very fine roots.
R	unweathered rock

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg-1	mg kg-1	g kg-1					
A	6	1	18	40	42	7.6	30	17	4.8	1.0	9.9	0.6	10.2	0.8
AB	22	13				7.1	14							
Bw	28	26	1	30	66	7.4	6		1.0	0.8	4.0	0.4	2.8	0.3
R														

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg-1				
A	0.6	0.2	25.5	4.4	30.2
AB					
Bw	0.1	0.2	9.5	5.1	
R					

Bacla 2	fine, mixed, isomesic **Typic Ustropept**

Topography:	uniform, midslope
Slope (degrees):	9 down, 8 up
Aspect (degrees):	006
Erosion:	severe
Landuse:	woodland, grazing

A	dark yellowish brown (10YR 4/4) moist, light yellowish brown (10YR 6/4) dry; clay loam; moderate medium granular; very hard (dry), very firm (moist); common medium and very common very fine roots; boundary gradual and broken.
AB	strong brown (7.5YR 5/6) moist, 7.5YR 8/2 to pinkish gray (7.5YR 6/2) dry; clay; moderate medium angular blocky; extremely hard (dry), friable (moist); few medium and common fine roots; boundary gradual and wavy.
Bw	red (2.5YR 5/6) moist, light reddish brown (2.5YR 6/4) dry; clay; moderate medium angular blocky; hard (dry), friable (moist); few coarse, medium and fine roots; boundary gradual and wavy.
Cr	red (2.5YR 5/6) moist, light reddish brown (2.5YR 6/4) dry; clay; massive; hard (dry), friable (moist); few medium roots, many medium and large prominent mottles of white (10YR 8/1).

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	5	36	33	29	38	7.2	15	9	2.3	0.5	6.9	0.4	6.5	0.7
AB	18	0	11	37	52	6.7	6							
Bw	114	0	11	36	53	6.6	2		0.1	0.2	12.4	0.3	1.0	0.2
Cr	128+	0	10	38	52	6.1		1	0.4	0.3	10.0	0.3	1.5	0.2

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.6	0.2	16.8	2.7	19.2
AB					
Bw	0.1	0.2	5.8	1.8	
Cr	0.0	0.2	7.3	1.1	10.0

Bacla 3	fine-loamy, mixed, isomesic **Typic Haplustalf**

Topography:	concave, midslope
Slope (degrees):	6 down, 17 up
Aspect (degrees):	205
Erosion:	moderate
Landuse:	grazing

A	dark yellowish brown (10YR 4/4) moist, light yellowish brown (10YR 6/4) dry; clay loam; weak coarse subangular blocky breaking to weak coarse granular; very hard (dry), friable (moist); common fine and very fine roots; boundary clear and irregular.
Bt	yellowish brown (10YR 5/6) moist, very pale brown (10YR 8/4) dry; clay loam; weak coarse subangular blocky; very hard (dry), friable (moist); common fine roots; boundary diffuse and smooth.
Cr	light reddish brown (2.5YR 6/4) to brownish yellow (10YR 6/8) moist, white (10YR 8/2) dry; loam; massive; very hard (dry), firm (moist); very few very fine roots.

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	26	18	35	35	30	6.9	15	12	2.3	0.7	13.1	0.9	15.0	0.9
Bt	55	1	25	38	37	7.4	2		0.4	0.3	13.5	1.0	7.9	0.5
Cr	67+	1	38	39	23	7.4			0.1	0.2	13.7	1.3	11.5	0.4

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.9	0.2	14.3	1.2	17.5
Bt	0.3	0.1	6.3	1.5	
Cr	0.3	0.1	2.8	0.9	

Bacla 4	fine, mixed, isomesic **Typic Haplustalf**

Topography:	uniform, footslope
Slope (degrees):	4 down, 6 up
Aspect (degrees):	355
Erosion:	slight
Landuse:	field

Ap	yellowish brown (10YR 5/6) moist, very pale brown (10YR 7/4) dry; loam; weak fine granular; slightly hard (dry), firm (moist); common fine and very fine roots; boundary abrupt and smooth.
AB	yellowish brown (10YR 5/6) moist, very pale brown (10YR 7/4) dry; clay; moderate medium subangular blocky; hard (dry), very friable (moist); few fine roots; boundary gradual and smooth.
Bt	dark yellowish brown (10YR 4/4) moist, very pale brown (10YR 7/4) dry; clay; strong medium subangular blocky; very hard (dry), very friable (moist); few fine roots; few moderately thick clay films on ped faces.

			-Particle size-						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
Ap	11	10	35	42	23	6.7	4	7	1.3	0.4	12.7	0.4	9.2	0.5
AB	58	7	19	37	44	6.1	7							
Bt	85+	10	13	35	52	6.3	4							

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
Ap	0.3	0.1	7.5	1.4	9.9
AB					
Bt					

Bacla 5	fine, mixed, isomesic **Lithic Haplustalf**

Topography:	valley bottom
Slope (degrees):	4 down, 3 up
Aspect (degrees):	305
Erosion:	slight
Landuse:	field

A	dark yellowish brown (10YR 4/4) moist, pale brown (10YR 6/3) dry; clay loam; weak fine granular; soft (dry), very friable (moist); very common fine and very fine roots; boundary abrupt and broken.
Bt	dark yellowish brown (10YR 4/4) moist, very pale brown (10YR 7/4) dry; clay; strong fine subangular blocky; very hard (dry), friable (moist); common fine and very fine roots; boundary gradual and wavy.
Cr	no sample

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg-1	mg kg-1	g kg-1					
A	5	10	33	34	33	6.5	12	10	3.3	0.6	12.6	0.7	11.9	1.9
Bt	37	11	30	29	41	6.6	5		1.2	0.4	13.9	0.6	11.1	1.4
Cr	38+													

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg-1				
A	1.2	0.1	12.6	3.0	17.9
Bt	0.2	0.2	10.1	3.0	
Cr					

Bacla 6	fine, mixed, isomesic **Typic Ustorthent**

Topography:	valley bottom
Slope (degrees):	3 down, 3 up
Aspect (degrees):	350
Erosion:	slight
Landuse:	field

Ap	dark yellowish brown (10YR 4/4) moist, light yellowish brown (10YR 6/4) dry; clay loam; weak fine to medium granular; hard (dry), firm (moist); common fine and very fine roots; boundary abrupt and smooth.
Ab1	very dark grayish brown (2.5Y 3/2) moist, grayish brown (2.5Y 5/2) dry; clay; moderate medium subangular blocky; very hard (dry), very friable (moist); very few fine roots; boundary abrupt and wavy.
Ab2	black (2.5Y 2/2) moist, very dark grayish brown (2.5Y 3/2) dry; clay; moderate medium angular blocky; very hard (dry), firm (moist); common fine and very fine roots.

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
Ap	6	3	23	38	39	6.4	5	10	1.8	0.5	12.5	0.8	11.7	1.3
Ab1	40	9	21	34	45	5.8	5		1.1	0.4	13.1	0.8	9.9	1.4
Ab2	80+	0	16	26	58	6.3	7		1.0	0.2	11.5	0.8	10.6	1.3

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
Ap	0.7	0.3	11.1	3.6	16.0
Ab1	0.2	0.3	12.1	4.4	
Ab2	0.1	0.1	25.5	7.4	

Bacla 7	fine, mixed, isomesic **Typic Haplustalf**

Topography:	valley bottom
Slope (degrees):	2 down, 2 up
Aspect (degrees):	160
Erosion:	moderate
Landuse:	field

Ap	yellowish brown (10YR 5/6) moist, very pale brown (10YR 7/4) dry; clay loam; weak fine to medium granular; soft (dry), very friable (moist); very common fine and very fine roots; boundary clear and wavy.
Bt	dark yellowish brown (10YR 4/6) moist, light yellowish brown (10YR 6/4) dry; clay; weak medium sub andgular blocky; hard (dry), very friable (moist); very few medium and few fine roots; boundary gradual and wavy.
Bw	olive brown (2.5Y 4/4) moist, very pale brown (10YR 7/4) dry; clay loam; moderate medium subangular blocky; hard (dry), friable (moist); few fine roots.

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
Ap	16	0	24	41	35	6.1	8	8	2.1	0.5	8.4	0.9	14.5	2.1
Bt	62	13	22	24	54	6.1	6		1.6	0.5	9.8	0.9	11.8	1.1
Bw	93	1	25	37	38	6.5	3		0.5	0.2	9.7	0.9	11.9	0.8

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
Ap	0.3	0.2	12.1	2.9	16.2
Bt	0.1	0.2	14.4	3.8	
Bw	0.1	0.2	10.0	3.9	

Bacla 8	fine, mixed, isomesic **Typic Ustropept**

Topography:	convex, footslope
Slope (degrees):	9 down, 2 up
Aspect (degrees):	185
Erosion:	moderate
Landuse:	field

A	yellowish brown (10YR 5/6) moist, very pale brown (10YR 7/4) dry; clay loam; weak fine granular; soft (dry), very friable (moist); very common fine and very fine roots; boundary abrupt and smooth.
AB	brown (10YR 4/3) moist, light yellowish brown (10YR 6/4) dry; silty clay; weak fine angular blocky; hard (dry), very friable (moist); few coarse, medium and fine roots; boundary gradual and wavy.
Bw	yellowish brown (10YR 5/6) moist, yellow (10YR 8/6) dry; silty clay; weak moderate angular blocky; slightly hard (dry), very friable (moist); few fine roots; boundary gradual and wavy.
Cr	no sample taken

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					$g\ kg^{-1}$	$mg\ kg^{-1}$	$g\ kg^{-1}$					
A	4	3	24	43	33	6.6	17	16	3.3	0.7	12.4	0.7	11.9	0.8
AB	37	2	16	42	42	6.7	13		2.3	0.6	12.8	0.6	10.1	0.7
Bw	72	13	14	41	45	5.7	3		0.6	0.4	14.1	0.6	6.7	0.4
Cr	73+													

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	$cmol\ kg^{-1}$				
A	1.4	0.2	12.2	2.4	17.3
AB	0.3	0.2	15.3	2.7	
Bw	0.1	0.2	7.1	4.2	
Cr					

Bacla 9	fine, mixed, isomesic **Lithic Ustorthent**

Topography:	convex, upper slope
Slope (degrees):	14 down, 4 up
Aspect (degrees):	215
Erosion:	severe
Landuse:	grazing

A	dark yellowish brown (10YR 4/4) moist, light yellowish brown (10YR 6/4) dry; clay loam; weak fine granular; soft (dry), very friable (moist); very common fine and very fine roots; boundary clear and wavy.
AC	dark yellowish brown (10YR 4/4) moist, light yellowish brown (10YR 6/4) dry; clay; weak fine granular to massive; slightly hard (dry), very friable (moist); few medium and fine roots; boundary gradual and broken.
Cr	white (2.5Y 8/2) moist, white (10YR 8/1) dry; no analysis; massive; no analysis; few medium and fine roots; common large prominent mottles of 2.5YR 7/6 moist, yellow (10YR 8/6) dry, few fine prominent mottles of olive brown (2.5Y 4/4) and black (2.5Y 2/1).

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	5	57	38	27	35	7.2	14	30	2.9	0.7	14.0	0.7	10.0	0.9
AC	20	40	30	27	43	6.9	9		1.5	0.4	14.1	0.7	9.6	0.6
Cr	33+													

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	1.1	0.2	14.4	3.4	18.3
AC	0.6	0.2	11.7	2.9	
Cr					

Bacla 10	fine, mixed, isomesic **Lithic Ustorthent**

Topography:	uniform, upper slope
Slope (degrees):	15 down, 15 up
Aspect (degrees):	065
Erosion:	severe
Landuse:	grazing

A	dark yellowish brown (10YR 4/4) moist, light yellowish brown (10YR 6/4) dry; clay loam; weak medium subangular blocky; slightly hard (dry), very friable (moist); common fine and very fine roots; boundary clear and broken.
AC	yellowish brown (10YR 5/4) moist, very pale brown (10YR 7/4) dry; clay; massive; hard (dry), very friable (moist); few fine and very fine roots; boundary clear and broken.
Cr	2.5YR 8/2 moist, white (10YR 8/1) dry; no analysis; massive; no analysis; common prominent large mottles of yellow (2.5Y 7/6) moist and yellow (10YR 8/6) dry.

			-Particle size -						---- TOTAL ----					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	--- % ---					g kg^{-1}	mg kg^{-1}	--- g kg^{-1} ---					
A	11	2	26	35	39	7.3	20	10	4.2	0.6	12.5	0.7	10.9	0.6
AC	36	38	26	33	41	7.5	7		1.0	0.3	15.4	0.5	6.3	0.5
Cr	48+								0.5	0.2	16.1	0.7	3.0	0.5

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	--- cmol kg^{-1} ---				
A	0.8	0.2	19.3	3.7	23.4
AC	0.1	0.2	11.4	2.3	
Cr	0.4	0.2	6.2	0.9	

Bacla 11	fine, mixed, isomesic **Typic Ustropept**

Topography:	convex, upper slope
Slope (degrees):	21 down, 7 up
Aspect (degrees):	243
Erosion:	moderate
Landuse:	grazing

A	strong brown (7.5YR 4/6) moist, brown (7.5YR 5/4) dry; clay; weak fine subangular blocky breaking to moderate fine granular; hard (dry), very friable (moist); common medium and fine and very common very fine roots; boundary clear and irregular.
Bw	reddish yellow (7.5YR 6/6) moist, strong brown (7.yellowish red (5YR 5/8) dry; clay; moderate fine subangular blocky; hard (dry), friable (moist); few medium and very fine and common fine roots; boundary gradual and wavy.
Cr	yellow (10YR 7/8) moist, pink (7.5YR 8/4) dry; clay loam; massive; slightly hard (dry), very friable (moist); common medium and few fine roots.

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg-1	mg kg-1	g kg-1					
A	20	65	19	33	48	6.7	20	7	4.1	0.8	10.1	0.5	11.4	1.1
Bw	45	21	19	30	51	6,6	7		0.9	0.6	10.6	0.4	7.7	3.6
Cr	102 +	5	33	36	31	7.2			0.4	0.5	10.0	0.6	9.6	6.3

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg-1				
A	0.4	0.2	18.1	4.9	25.1
Bw	0.1	0.2	11.5	3.5	
Cr	0.1	0.2	8.2	1.7	

Bacla 12	fine, mixed, isomesic **Lithic Ustorthent**

Topography:	summit
Slope (degrees):	0
Aspect (degrees):	–
Erosion:	moderate
Landuse:	grazing

A	dark brown (7.5YR 3/4) moist, yellowish brown (10YR 5/4) dry; clay loam; weak fine subangular blocky; hard (dry), firm (moist); few coarse, medium, fine, and very fine roots; boundary clear and broken.
AC	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/4) dry; clay; weak fine subangular blocky to massive; hard (dry), firm (moist); few coarse, medium, fine, and very fine roots; boundary clear and irregular.
Cr	pale yellow (2.5Y 7/4) moist, white (10YR 8/1) dry; loam; massive; no analysis; common distinct medium mottles of brownish yellow (10YR 6/8) dry.

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	19-26	69	27	37	36	6.4	25	14	4.3	0.8	11.4	0.7	10.5	4.0
AC	37-44	78	29	30	41	6.2	14		1.9	0.5	12.9	0.6	9.9	3.2
Cr	50+	29	47	28	25	6.6			0.3	0.2	17.1	0.4	7.1	2.4

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	1.5	0.2	14.5	4.4	22.1
AC	0.5	0.2	10.5	5.1	
Cr	0.3	0.2	3.1	1.4	

Bacla 13	very-fine, mixed, isomesic **Typic Haplustalf**

Topography:	convex, upper slope
Slope (degrees):	22 down, 19 up
Aspect (degrees):	230
Erosion:	severe
Landuse:	grazing

A	dark yellowish brown (10YR 3/4) moist, yellowish brown (10YR 5/4) dry; clay loam; weak coarse subangular blocky breaking to weak medium granular; slightly hard (dry), loose (moist); few coarse, common fine and very fine roots; boundary clear and broken.
Bt	dark brown (7.5YR 3/4) moist, reddish yellow (7.5YR 6/6) dry; clay; moderate fine to medium subangular blocky; hard (dry), very friable (moist); few coarse and medium, common fine roots; boundary gradual and broken.
Bw	dark brown (7.5YR 4/4) moist, light brown (7.5YR 6/4) dry; clay; moderate fine to medium subangular blocky; hard (dry), very friable (moist); few coarse and medium, common fine roots.

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	22	1	22	40	38	6.8	24	11	4.5	0.8	12.7	0.6	11.2	5.2
Bt	49	24	3	27	70	6.2	10		1.3	0.6	12.9	0.5	6.5	3.1
Bw	93+	34	9	33	58	6.1	6		1.1	0.5	13.3	0.6	7.4	3.5

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.5	0.0	21.7	4.1	25.5
Bt	0.2	0.0	12.9	7.2	
Bw	0.2	0.0	13.3	7.2	

Berige 1	fine, mixed, isomesic **Lithic Ustorthent**

Topography:	summit
Slope (degrees):	1 down, 3 up
Aspect (degrees):	110
Erosion:	slight
Landuse:	field

Ap	dark brown (10YR 3/3) moist, yellowish brown (10YR 5/4) dry; clay loam; moderate medium subangular blocky breaking to weak fine granular; very hard (dry), very friable (moist); common coarse, fine and very fine roots; boundary clear and wavy.
Cr	light olive brown (2.5Y 5/6) moist, yellow (2.5Y 7/6); no analysis; massive; no analysis.

			-Particle size -						------- TOTAL -------					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	------ % ------					g kg^{-1}	mg kg^{-1}	------ g kg^{-1} ------					
Ap	35	13	30	34	36	7.2	11	6	2.0	0.5	13.4	0.5	5.5	3.1
Cr	48 +								0.3	0.5	16.7	0.2	3.5	1.6

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	------ cmol kg^{-1} ------				
Ap	1.0	0.0	9.0	3.4	15.1
Cr	0.1	0.0	2.5	0.8	

Berige 2	fine, mixed, isomesic **Typic Ustropept**

Topography:	concave, footslope
Slope (degrees):	8 down, 19 up
Aspect (degrees):	350
Erosion:	severe
Landuse:	field

A	dark brown (10YR 3/3) moist, yellowish brown (10YR 5/4) dry; clay loam; moderate medium subangular blocky breaking to weak fine granular; hard (dry), fvery riable (moist); very common coarse, fine and very fine roots; boundary gradual and wavy.
AB	dark yellowish brown (10YR 4/4) moist, brown (10YR 5/3) dry; silty clay; strong fine to medium subangular blocky; very hard (dry), very friable (moist); common medium roots; boundary gradual and wavy.
Bw	dark yellowish brown (10YR 3/4) moist, yellowish brown (10YR 5/4) dry; silty clay; strong medium subangular blocky; very hard (dry), very friable (moist); few fine and very fine roots; boundary gradual and wavy.
BC	dark brown (10YR 3/3) moist, yellowish brown (10YR 5/4) dry; silty clay; strong fine tomedium subangular blocky breaking to weak fine granular; very hard (dry), very friable (moist); very few fine and very fine roots; boundary gradual and wavy.
Cr	no sample taken

			-Particle size -						------ TOTAL ------					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C		N	P	K	Na	Ca	Mg
	cm	----- % -----					g kg-1	mg kg-1	------ g kg-1 ------					
								mg kg-1						
A	30	4	24	42	34	6.8	13	6	2.8	0.6	10.8	0.9	11.0	4.4
AB	42	6	16	40	44	6.2	16		3.2	0.9	10.1	1.0	9.1	4.7
Bw	78	2	15	41	44	6.1	11		2.0	0.7	9.5	0.9	9.0	4.1
BC	95	14	19	37	44	6.2	7		1.3	0.8	8.1	1.0	8.6	4.4
Cr	96+													

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	----- cmol kg-1 -----				
A	0.7	0.1	15.0	3.6	19.6
AB	0.3	0.2	19.4	5.5	
Bw	0.2	0.2	17.4	4.5	
BC	0.2	0.2	16.9	4.8	
Cr					

Berige 3	fine, mixed, isomesic **Lithic Haplustalf**

Topography:	concave, midslope
Slope (degrees):	15 down, 20 up
Aspect (degrees):	304
Erosion:	severe
Landuse:	grazing

A	dark yellowish brown (10YR 3/4) moist, light yellowish brown (10YR 6/4) dry; clay loam; weak medium subangular blocky breaking to weak fine granular; slightly hard (dry), friable (moist); very common fine and very fine roots; few charcoal; boundary clear and broken.
Bt	dark yellowish brown (10YR 4/6) moist, light yellowish brown (10YR 6/4) dry; clay; weak medium subangular blocky; very hard (dry), firm (moist); common fine and very fine roots; boundary clear and broken.
Cr	strong brown (7.yellowish red (5YR 5/8) moist, brownish yellow (10YR 6/8) dry; clay; massive; very hard (dry), firm (moist).

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	13	17	27	35	38	6.4	14	5	1.8	0.5	14.0	0.6	5.8	3.7
Bt	20	38	17	36	47	6.4	9		1.3	0.5	14.1	0.6	6.5	3.4
Cr	80+	9	27	32	41	6.5			0.7	0.7	8.5	0.4	9.4	5.2

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.2	0.1	12.9	4.1	17.1
Bt	0.2	0.2	12.9	4.8	
Cr	0.0	0.2	11.1	6.3	

Berige 4	fine, mixed, isomesic **Typic Ustropept**

Topography:	convex, midslope (between two rock outcrops)
Slope (degrees):	21 down, 15 up
Aspect (degrees):	263
Erosion:	moderate
Landuse:	grazing

A	dark brown (10YR 3/3) moist, yellowish brown (10YR 5/4) dry; silty clay; moderate medium subangular blocky; hard (dry), very friable (moist); very common fine and very fine roots; few casts (no worms seen); boundary gradual and wavy.
Bw	dark brown (10YR 3/3) moist, light olive brown (2.5Y 5/6) dry; silty clay; moderate fine subangular blocky; very hard (dry), friable (moist); common fine and very fine roots; few casts (no worms seen); boundary gradual and wavy.
BC	brown (10YR 4/3) moist, yellowish brown (10YR 5/6) dry; silty clay; massive; very hard (dry), very friable (moist); common fine and very fine roots.

			-Particle size -						---- TOTAL ----					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	---- % ----					g kg^{-1}	mg kg^{-1}	---- g kg^{-1} ----					
A	20	1	14	40	46	7.1	13	9	2.0	1.4	9.1	0.7	12.1	4.8
Bw	40	0	11	40	49	7.4	10		1.5	1.3	8.5	0.7	10.4	4.9
BC	86+	1	8	40	52	7.5	7		1.1	1.2	7.8	0.7	9.2	5.5

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	---- cmol kg^{-1} ----				
A	0.6	0.2	20.2	6.0	26.2
Bw	0.5	0.2	20.7	6.4	
BC	0.3	0.1	20.0	6.8	

Berige 5	fine, mixed, isomesic **Lithic Haplustoll**

Topography:	concave, terrace
Slope (degrees):	0 down, 3 up
Aspect (degrees):	342
Erosion:	slight
Landuse:	field

Ap	very dark grayish brown (10YR 3/2) moist, grayish brown (10YR 5/2) dry; clay loam; strong medium granular; soft (dry), friable (moist); very common fine and very fine roots; few casts (no worms seen); boundary abrupt and broken.
AC	very dark gray (10YR 3/1) moist, grayish brown (10YR 5/2) dry; clay loam; moderate medium subangular blocky; soft (dry), very friable (moist); common fine and very fine roots; boundary clear and wavy.
Cr	grayish brown (10YR 5/2) moist, light gray (10YR 7/2) dry; silty clay; massive; soft (dry), very friable (moist); very few fine and very fine roots.

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					$g\ kg^{-1}$	$mg\ kg^{-1}$	$g\ kg^{-1}$					
Ap	10	0	29	37	34	7.3	21	356	7.6	7.3	10.3	0.6	21.3	4.6
AC	27	4	28	36	36	7.3	13		2.9	2.9	12.6	0.6	15.4	2.9
Cr	55 +	16	26	36	38	7.9			1.1	3.0	13.3	0.5	9.2	2.0

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	$cmol\ kg^{-1}$				
Ap	3.1	0.2	33.9	7.8	30.5
AC	2.4	0.3	20.1	7.5	
Cr	2.1	0.2	12.4	5.8	

Berige 6	fine, mixed, isomesic **Lithic Ustorthent**

Topography:	convex, midslope
Slope (degrees):	14 down, 8 up
Aspect (degrees):	094
Erosion:	severe
Landuse:	grazing

A	olive brown (2.5Y 4/4) moist, 1light olive brown (2.5Y 5/4) dry; clay loam; weak medium angular blocky breaking to weak fine granular; slightly hard (dry), very friable (moist); few very fine roots; boundary abrupt and broken.
Cr	very pale brown (10YR 8/3) dry; sandy loam; massive; hard (dry), firm (moist); few medium roots.

			-Particle size -						------------- TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	-------- %					g kg^{-1}	mg kg^{-1}	------------- g kg^{-1} -------------					
A	13	4	30	34	36	7.2	5	7	1.0	0.4	12.6	0.8	13.7	2.8
Cr	49+	45	54	23	23	6.5	7		0.6	0.2	12.4	0.9	11.5	2.1

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	------- cmol kg^{-1} -------				
A	0.2	0.3	12.1	1.9	13.0
Cr	0.0	0.2	7.0	2.1	

Berige 7	fine, mixed, isomesic **Lithic Ustorthent**

Topography:	uniform, midslope (below nose of ridge)
Slope (degrees):	9 down, 8 up
Aspect (degrees):	096
Erosion:	severe
Landuse:	grazing

A	brownish yellow (10YR 6/8) moist, yellow (10YR 7/8) dry; clay loam; weak fine granular; soft (dry), loose (moist); few fine and very fine roots; boundary clear and wavy.
Cr	yellowish brown (10YR 5/8) moist, yellow (10YR 8/6) to reddish yellow (7.5YR 7/8) dry; clay; massive; slightly hard (dry), friable (moist); few fine and very fine roots; common prominent large mottles of yellowish red (5YR 6/8) moist and yellow (10YR 7/8) moist.

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg-1	mg kg-1	g kg-1					
A	18	17	28	36	36	7.3	5	3	1.1	0.6	3.9	0.5	18.4	2.5
Cr	56 +	1	15	39	46	7.6	2		0.3	0.5	5.7	0.6	16.4	2.7

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg-1				
A	0.2	0.2	9.0	1.7	11.5
Cr	0.1	0.1	7.3	2.0	

Berige 8	fine, mixed, isomesic **Typic Haplustalf**

Topography:	uniform, upper slope
Slope (degrees):	32 down, 34 up
Aspect (degrees):	288
Erosion:	severe
Landuse:	grazing

A	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/6) dry; clay loam; moderate medium granular; slightly hard (dry), loose (moist); common fine and very fine roots; boundary diffuse and broken.
Bt	dark brown (7.5YR 4/4) moist, yellowish brown (10YR 5/6) dry; clay; moderate medium granular; slightly hard (dry), friable (moist); common fine and very fine roots; boundary gradual and wavy.
Bw	yellowish red (5YR 5/8) moist, reddish yellow (7.yellowish red (5YR 6/8) dry; clay; weak coarse angular blocky breaking to weak fine granular; slightly hard (dry), very friable (moist); few coarse, fine and very fine roots; boundary clear and broken.
B/C	yellowish red (5YR 6/8) moist, reddish yellow (7.yellowish red (5YR 6/8) dry; clay; weak coarse angular blocky breaking to weak fine granular; slightly hard (dry), very friable (moist); boundary clear and broken.
Cr	yellowish red (5YR 6/8) moist, reddish yellow (7.5YR 7/8) dry; clay; massive; soft (dry), friable (moist); few coarse and fine roots; common prominent medium mottles of white (10YR 8/1) moist and 2.yellowish red (5YR 5/8) moist.

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	22	4	21	39	40	6.8	17	4	2.5	0.6	7.3	0.6	8.4	4.0
Bt	42	7	13	34	53	6.3	11		1.5	0.6	7.1	0.7	4.3	3.2
Bw	90	1	11	32	57	6.1	6		0.6	0.4	3.6	0.4	1.3	2.2
B/C	112	1	15	35	50	6.0	5		0.4	0.3	3.9	0.5	1.3	1.3
Cr	131+	0	18	32	50	5.9			0.3	0.3	2.5	0.5	1.2	1.5

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.4	0.2	15.7	4.4	22.9
Bt	0.2	0.2	12.3	5.4	
Bw	0.1	0.2	7.2	4.1	
B/C	0.1	0.2	5.8	2.4	
Cr	0.1	0.2	4.5	2.6	

Berige 9	fine, mixed, isomesic **Lithic Ustropept**

Topography:	convex, footslope (below small rock outcrop)
Slope (degrees):	8 down, 22 up
Aspect (degrees):	053
Erosion:	severe
Landuse:	field

A	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/6) dry; clay loam; weak fine granular; slightly hard (dry), very friable (moist); common fine and very fine roots; boundary clear and wavy.
Bw	dark yellowish brown (10YR 4/4) moist, yellowish brown (10YR 5/6) dry; clay loam; weak to moderate medium subangular blocky breaking to weak fine granular; hard (dry), friable (moist); few fine and common very fine roots; boundary clear and broken.
BC	yellowish brown (10YR 5/8) moist, brownish yellow (10YR 6/6) dry; silty clay; weak medium subangular blocky to massive; slightly hard (dry), very friable (moist); few fine and very fine roots; boundary gradual and wavy.
Cr	yellow (10YR 8/6) moist, yellow (10YR 7/8) dry; silty clay; massive; slightly hard (dry), very friable (moist).

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	17	25	31	37	32	6.7	12	4	1.8	0.6	8.7	0.9	12.8	3.4
Bw	32	4	23	38	39	6.8	10		1.5	0.6	7.7	0.9	11.0	2.8
BC	45	11	9	42	49	7.0	8		0.5	0.5	2.2	0.8	6.0	2.7
Cr	97 +	2	3	44	53	8.0			0.2	0.4	5.1	0.8	4.5	1.4

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.3	0.2	11.8	2.9	15.2
Bw	0.2	0.2	11.5	2.9	
BC	0.1	0.2	7.5	2.0	
Cr	0.0	0.2	11.1	2.8	

Berige 10	fine, mixed, isomesic **Typic Ustropept**

Topography:	terrace
Slope (degrees):	4 down, 3 up
Aspect (degrees):	055
Erosion:	slight
Landuse:	field

Ap	yellowish brown (10YR 5/6) moist, brownish yellow (10YR 6/6) dry; clay loam; weak fine granular; soft (dry), loose (moist); very common fine and very fine roots; boundary abrupt and wavy.
AB	light yellowish brown (10YR 6/4) moist, brownish yellow (10YR 6/6) dry; clay; strong fine subangular blocky breaking to weak fine granular; hard (dry), friable (moist); common fine and very common very fine roots; few charcoal fragments; boundary clear and wavy.
Bw	yellowish brown (10YR 5/6) moist, brownish yellow (10YR 6/6) dry; clay; strong medium to coarse subangular blocky; hard (dry), firm (moist); few medium and fine roots; few casts (no worms found); boundary clear and wavy.
BC	yellowish brown (10YR 5/6) moist, brownish yellow (10YR 6/6) dry; clay; strong medium subangular blocky; hard (dry), firm (moist); few medium and fine roots.

			-Particle size -						------ TOTAL ------					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	---- % ----					g kg^{-1}	mg kg^{-1}	---- g kg^{-1} ----					
Ap	11	1	22	41	37	7.2	13	30	1.7	0.9	9.9	0.7	15.3	2.7
AB	24	1	18	40	42	6.6	20		3.9	1.9	10.5	0.7	13.4	3.4
Bw	49	3	18	37	45	6.8	7		1.1	1.3	12.0	0.7	4.1	2.3
BC	93+	10	15	35	50	7.5	6		0.6	1.2	12.9	0.9	10.9	2.4

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	---- cmol kg^{-1} ----				
Ap	1.0	0.1	11.6	2.7	15.6
AB	1.5	0.2	19.4	5.8	
Bw	1.7	0.2	11.1	3.3	
BC	2.4	0.1	9.4	3.8	

Berige 11	fine, mixed, isomesic **Lithic Ustorthent**

Topography:	concave, footslope (above road)
Slope (degrees):	13 down, 19 up
Aspect (degrees):	248
Erosion:	severe
Landuse:	grazing

A	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/4) dry; clay loam; weak fine to medium granular; soft (dry), loose (moist); very common fine and very fine roots; boundary clear and broken.
AC	light yellowish brown (10YR 6/4) moist, pale brown (10YR 6/3) dry; clay loam; weak fine granular to massive; soft (dry), very friable (moist); common very fine roots; boundary abrupt and broken.
Cr	white (10YR 8/2) moist, very pale brown (10YR 7/4) dry; clay loam; massive; slightly hard (dry), very friable (moist); very few very fine roots.

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	14	17	25	38	37	7.3	8	8	2.6	0.6	12.3	0.9	12.3	5.9
AC	26	76	28	40	32	7.4	5		1.3	0.4	13.8	1.1	10.9	3.6
Cr	63+	8	23	46	31	7.5			0.5	0.2	11.0	1.1	11.5	3.1

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.2	0.2	21.3	2.0	22.5
AC	0.1	0.2	16.3	1.5	
Cr	0.0	0.2	9.5	1.8	

Berige 12	fine, mixed, isomesic **Typic Haplustalf**

Topography:	uniform, footslope
Slope (degrees):	2 down, 2 up
Aspect (degrees):	120
Erosion:	slight
Landuse:	field

Ap	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/8) dry; loam; weak fine granular; soft (dry), loose (moist); few medium and very common fine and very fine roots; boundary clear and wavy.
Bt	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/4) dry; clay; strong coarse granular; very hard (dry), friable (moist); few coarse and common fine and very fine roots; boundary gradual and broken.
Bw	yellowish brown (10YR 5/8) moist, olive yellow (2.5Y 6/6) dry; clay loam; weak medium granular to massive; very hard (dry), friable (moist); very few coarse and common fine roots; boundary clear and wavy.
Cr	very pale brown (10YR 8/4) moist, pale yellow (2.5Y 8/4) dry; silty clay loam; massive; slightly hard (dry), very friable (moist).

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
Ap	12	4	40	35	25	7.4	7	10	1.3	0.6	9.0	0.8	17.6	2.6
Bt	48	6	20	38	42	7.2	13		2.4	1.0	9.5	1.7	18.7	4.8
Bw	85	36	32	33	35	7.6	4		0.6	0.6	5.6	2.1	22.2	7.7
Cr	97 +	3	19	43	38	8.0		1	0.1	0.2	15.2	1.8	30.0	7.6

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
Ap	0.4	0.0	10.0	0.9	12.7
Bt	0.2	0.0	25.4	7.6	
Bw	0.1	0.0	22.3	7.9	
Cr	0.0	0.0	19.4	7.5	7.5

Berige 13	fine, mixed, isomesic **Lithic Ustropept**

Topography:	summit
Slope (degrees):	0
Aspect (degrees):	–
Erosion:	moderate
Landuse:	field

A	dark yellowish brown (10YR 4/4) moist, yellowish brown (10YR 5/6) dry; clay loam; weak fine granular; soft (dry), friable (moist); common fine and few very fine roots; boundary clear and wavy.
Bw	brownish yellow (10YR 6/6) moist, yellow (10YR 7/6) dry; clay ; weak subangular blocky; slightly hard (dry), friable (moist); few medium, fine and very fine roots; boundary clear and broken.
Cr	2.yellowish red (5YR 6/8) moist, pink (7.5YR 8/4) dry; clay ; massive; slightly hard (dry), very friable (moist); very few very fine roots.

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
A	7	19	39	33	28	7.5	5	7	0.8	0.4	12.1	0.6	6.6	3.4
Bw	44	12	20	35	45	7.6	3		0.4	0.5	16.2	0.7	3.9	3.0
Cr	76	43	10	37	53	8,3			0.1	0.2	18.1	0.6	8.9	4.7

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
A	0.2	0.0	8.0	1.4	10.0
Bw	0.1	0.2	7.5	1.4	
Cr	0.1	0.2	19.9	2.1	

Laba 1	fine-loamy, mixed, isomesic **Lithic Ustropept**

Topography:	convex, upper slope
Slope (degrees):	16 down, 10 up
Aspect (degrees):	320
Erosion:	moderate
Landuse:	grazing

A	dark yellowish brown (10YR 3/6) moist, dark yellowish brown (10YR 4/4) dry; loam; strong medium granular; hard (dry), friable (moist), not sticky and not plastic (wet); few coarse roots; boundary gradual and broken.
Bw	dark yellowish brown (10YR 4/6) moist, brownish yellow (10YR 6/6) dry; silt loam; moderate medium angular blocky to massive; slightly hard (dry), friable (moist), sticky and plastic (wet); few fine roots; boundary gradual and broken.
Cr	dark yellowish brown (10YR 4/6) moist, brownish yellow (10YR 6/6) dry; no analysis; massive; no analysis; few fine roots.

			-Particle size -						---- TOTAL ----					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	---- % ----					g kg^{-1}	mg kg^{-1}	---- g kg^{-1} ----					
A	14	74	42	36	22	6.8	14	4	2.3	1.0	3.2	1.2	17.2	2.0
Bw	50	1	25	51	24	6.5	9		0.9	0.8	3.6	0.8	38.4	3.9
Cr	64 +					6.4	7		0.6	0.8	3.6	0.8	38.8	3.9

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	---- cmol kg^{-1} ----				
A	0.4	0.7	15.3	4.7	20.5
Bw	0.1	0.9	7.4	2.8	
Cr	0.1	1.0	6.1	2.3	

Laba 2	fine-loamy, mixed, isomesic **Lithic Ustorthent**

Topography:	convex, upper slope
Slope (degrees):	21 down, 17 up
Aspect (degrees):	320
Erosion:	severe
Landuse:	grazing

A	very dark grayish brown (10YR 3/2) moist, dark brown (10YR 3/3) dry; loam; moderate to strong medium subangular blocky; hard (dry), friable (moist), slightly sticky and slightly plastic (wet); moderate fine roots and pores; boundary clear and broken.
Cr	no analysis; massive; no analysis; few fine roots and pores.

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					$g\ kg^{-1}$	$mg\ kg^{-1}$	$g\ kg^{-1}$					
A	40	24	49	31	20	6.5	11	4	2.0	0.6	5.0	1.0	10.0	1.3
Cr	57 +					6.7	5		0.8	0.2	5.8	0.9	0.5	0.1

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	$cmol\ kg^{-1}$				
A	0.2	0.7	11.8	3.3	15.5
Cr	0.1	0.6	3.7	1.0	

Laba 3	coarse-loamy, mixed, isomesic **Lithic Ustorthent**

Topography:	concave, midslope
Slope (degrees):	25 down, 30 up
Aspect (degrees):	313
Erosion:	severe
Landuse:	grazing

A	dark yellowish brown (10YR 4/4) moist, very pale brown (10YR 7/4) dry; sandy loam; massive; soft (dry), friable (moist), not sticky and not plastic (wet); few fine roots; boundary clear and broken.
Cr	no analysis; massive; no analysis; few fine roots.

			-Particle size -						---- TOTAL ----					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	---- % ----					g kg^{-1}	mg kg^{-1}	---- g kg^{-1} ----					
A	6	49	57	32	11	7.1	4	2	0.7	0.2	5.5	0.8	9.5	0.7
Cr	45 +					7.3	2		0.3	0.1	10.0	0.8	1.6	0.2

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	---- cmol kg^{-1} ----				
A	0.3	0.5	5.4	1.4	6.1
Cr	0.1	0.6	3.0	0.9	

Laba 4	fine-loamy, mixed, isomesic **Lithic Ustorthent**

Topography:	concave, midslope
Slope (degrees):	28 down, 30 up
Aspect (degrees):	280
Erosion:	severe
Landuse:	grazing

A	dark brown (10YR 3/3) moist, dark yellowish brown (10YR 4/4) dry; loam; strong fine angular blocky to weak fine granular; very hard (dry), friable (moist), slightly sticky and slightly plastic (wet); frequent fine to medium roots; boundary abrupt.
R	unweathered rock

			-Particle size -						---------------- TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	--------- %					g kg^{-1}	mg kg^{-1}	---------------- g kg^{-1} ----------------					
A	20	23	44	32	24	6.8	9	3	1.7	0.4	3.4	0.8	9.7	1.3
R	21+													

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	-------- cmol kg^{-1} ---------				
A	0.3	0.6	12.0	3.9	18.0
R					

Laba 5	coarse-loamy, mixed, isomesic **Lithic Ustorthent**

Topography:	uniform, footslope
Slope (degrees):	19 down, 19 up
Aspect (degrees):	305
Erosion:	severe
Landuse:	grazing at edge of field

A	dark brown (7.5YR 3/4) moist, strong brown (7.5YR 4/6) dry; loam; strong fine to moderate medium subangular blocky; hard (dry), friable (moist), sticky and slightly plastic (wet); common very fine and fine roots; boundary abrupt and wavy.
Cr	yellowish brown (10YR 5/8) moist, yellow (10YR 7/8) dry; no analysis; massive; no analysis; very few fine roots.

			-Particle size -						---------------- TOTAL ----------------					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	--------- % --------					g kg^{-1}	mg kg^{-1}	---------------- g kg^{-1} ----------------					
A	15	7	48	37	15	7.2	11	16	1.4	0.5	2.2	0.9	18.9	1.1
Cr	48 +					7.0	3		0.2	0.8	1.2	0.8	8.0	3.9

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	--------- cmol kg^{-1} ----------				
A	0.3	1.0	12.4	3.9	14.9
Cr	0.1	0.8	9.5	4.3	

Laba 6	fine-loamy, mixed, isomesic **Typic Ustifluvent**

Topography:	valley bottom, (edge of seasonal stream)
Slope (degrees):	5 down, 5 up
Aspect (degrees):	198
Erosion:	slight
Landuse:	field

Ap	black (10YR 2/1) moist, dark yellowish brown (10YR 4/4) dry; loam; moderate to strong coarse subangular blocky breaking to moderate fine granular; hard (dry), friable (moist), sticky and plastic (wet); numerous fine and very fine roots; boundary clear and wavy.
Ab1	black (10YR 2/1) moist, brown (10YR 4/3) dry; loam; moderate to strong coarse subangular blocky breaking to moderate fine granular; hard (dry), firm (moist), sticky and plastic (wet); few medium roots; boundary clear and wavy.
Ab2	dark brown (10YR 3/3) moist, brown (10YR 4/3) dry; loam; weak coarse subangular blocky; slightly hard (dry), friable (moist), very sticky and plastic (wet); few large roots.
	note: Profile continues to > 3 m, with six stone lines at 20 to 80 cm intervals and angular boulders up to 40 cm in diameter.

			-Particle size -						---- TOTAL ----					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	---- % ----					g kg^{-1}	mg kg^{-1}	---- g kg^{-1} ----					
Ap	15	8	45	34	21	6.9	8	4	1.1	0.5	2.9	1.0	14.8	1.8
Ab1	65	8	43	36	21	7.4	6		0.8	0.5	3.2	1.0	13.0	2.2
Ab2	120	2	40	40	20	7.6	7		0.8	0.5	3.2	1.0	14.1	2.2

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	---- cmol kg^{-1} ----				
Ap	0.2	0.7	13.9	4.2	15.9
Ab1	0.2	0.6	14.1	5.4	
Ab2	0.2	0.8	16.9	5.0	

Laba 7	fine-loamy, mixed, isomesic **Typic Haplustalf**

Topography:	valley bottom
Slope (degrees):	4 down, 3 up
Aspect (degrees):	220
Erosion:	slight
Landuse:	field

Ap	brown (10YR 4/3) moist, yellowish brown (10YR 5/6) dry; clay loam; moderate medium subangular blocky breaking to strong coarse granular; very hard (dry), friable (moist), very sticky and very plastic (wet); numerous fine to medium roots; boundary clear and wavy.
AB	brown (10YR 4/3) moist, yellowish brown (10YR 5/4) dry; loam; moderate medium subangular blocky breaking to moderate medium granular; hard (dry), friable (moist), very sticky and plastic (wet); numerous fine to medium roots; boundary clear and wavy.
Bt	dark yellowish brown (10YR 4/4) moist, yellowish brown (10YR 5/4) dry; clay loam; moderate coarse subangular blocky to massive; very hard (dry), not friable (moist), very sticky and very plastic (wet); numerous fine to medium roots; few thin clay films on roots and pore faces.

			-Particle size -						---- TOTAL ----					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	--- % ---					g kg^{-1}	mg kg^{-1}	--- g kg^{-1} ---					
Ap	11	0	30	42	28	6.7	9	6	1.4	0.6	4.6	0.9	15.4	2.0
AB	79	1	29	44	27	6.4	8		1.1	0.6	4.8	0.9	18.0	2.1
Bt	94 +	2	28	36	36	6.6	5		0.5	0.5	4.9	1.0	21.5	2.2

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	--- cmol kg^{-1} ---				
Ap	0.3	0.6	14.9	5.7	20.9
AB	0.2	0.7	17.5	6.6	
Bt	0.2	0.7	15.7	9.5	

Laba 8	coarse-loamy, mixed, isomesic **Typic Haplustalf**

Topography:	convex, upper slope
Slope (degrees):	11 down, 4 up
Aspect (degrees):	203
Erosion:	slight
Landuse:	field

Ap	dark yellowish brown (10YR 4/4) moist, light yellowish brown (10YR 6/4) dry; sandy loam; moderate to weak medium subangular blocky breaking to granular; very soft (dry), very friable (moist), not sticky and not plastic (wet); common fine to medium roots; boundary gradual and wavy.
Bt	yellowish brown (10YR 5/4) moist, yellow (10YR 7/6) dry; loam; weak medium angular blocky breaking to granular; slightly hard (dry), very friable (moist), slightly sticky and slightly plastic (wet); common fine roots; boundary gradual and wavy.
Cr	light olive brown (2.5Y 5/4) moist, pale yellow (2.5Y 8/4) dry; no analysis; massive; no analysis.

			-Particle size -						---------------- TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	--------- %					g kg^{-1}	mg kg^{-1}	------------- g kg^{-1}					
Ap	12	27	57	32	11	6.8	4	3	0.7	0.4	3.2	0.9	23.6	1.5
Bt	54	10	48	34	18	6.8	2		0.4	0.4	5.0	1.0	24.4	2.0
Cr	87 +					7.0			0.4	0.9	4.3	1.4	21.3	1.1

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	--------- cmol kg^{-1} ----------				
Ap	0.2	0.7	7.6	2.4	8.6
Bt	0.1	0.8	8.5	4.0	
Cr	0.0	1.2	11.0	4.7	

Laba 9	coarse-loamy, mixed, isomesic **Typic Ustorthent**

Topography:	uniform, upper slope (small ridge)
Slope (degrees):	4 down, 5 up
Aspect (degrees):	290
Erosion:	slight
Landuse:	field

Ap	dark brown (10YR 3/3) moist, light olive brown (2.5Y 5/4) dry; sandy loam; weak fine subangular blocky breaking to weak fine granular; hard (dry), friable (moist), not sticky and not plastic (wet); common fine to very fine roots; boundary gradual and wavy.
Ab	brown (10YR 4/3) moist, light olive brown (2.5Y 5/4) dry; sandy loam; weak fine subangular blocky breaking to moderate fine to medium granular; hard (dry), friable (moist), slightly sticky and slightly plastic (wet); few fine roots; boundary abrupt and wavy.
R	unweathered rock

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
Ap	15	25	58	29	13	6.5	3	6	0.8	0.6	4.2	0.9	16.0	2.4
Ab	54	7	57	27	16	6.8	1		0.5	0.5	3.5	0.9	14.1	2.3
R														

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
Ap	0.2	0.8	7.1	2.5	9.0
Ab	0.1	0.7	9.0	3.8	
R					

Laba 10	fine-loamy, mixed, isomesic **Typic Ustorthent**

Topography:	uniform, midslope
Slope (degrees):	5 down, 6 up
Aspect (degrees):	120
Erosion:	slight
Landuse:	field

Ap	dark yellowish brown (10YR 4/4) moist, light olive brown (2.5Y 5/4) dry; sandy loam; weak medium subangular blocky breaking to weak to moderate medium granular; slightly hard (dry), friable (moist), not sticky and not plastic (wet); common fine and very fine roots; boundary clear and wavy.
Ab1	brown (10YR 4/3) moist, yellowish brown (10YR 5/4) dry; sandy loam; weak medium subangular blocky breaking to weak fine granular; slightly hard (dry), friable (moist), slightly sticky and slightly plastic (wet); few fine roots; few charcoal; boundary clear and wavy.
Ab2	brown (10YR 4/3) moist, yellowish brown (10YR 5/4) dry; sandy loam; weak medium subangular blocky breaking to weak fine granular; hard (dry), friable (moist), sticky and slightly plastic (wet); few fine roots; boundary clear and wavy.
Cr	dark yellowish brown (10YR 4/6) moist, yellowish brown (10YR 5/6) dry; no analysis; massive; no analysis.

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
Ap	12	4	63	28	9	6,6	2	6	0.9	0.7	3.2	0.9	18.2	2.9
Ab1	32	3	57	31	12	6.6	3		0.6	0.7	3.3	1.1	18.8	3.1
Ab2	83	27	53	32	15	6.8	1		0.4	0.8	3.2	1.1	18.4	3.1
Cr	102+					7.0			0.3	0.7	3.7	1.1	18.2	3.2

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
Ap	0.2	0.6	9.3	3.2	10.0
Ab1	0.1	0.5	10.0	3.5	
Ab2	0.1	0.6	11.0	4.1	
Cr	0.1	0.6	9.8	4.3	

Laba 11	coarse-loamy, mixed, isomesic **Typic Haplustalf**

Topography:	concave, midslope
Slope (degrees):	4 down, 9 up
Aspect (degrees):	280
Erosion:	slight
Landuse:	field

Ap	dark brown (10YR 3/3) moist, light olive brown (2.5Y 5/4) dry; sandy loam; weak coarse angular blocky breaking to weak fine granular; soft (dry), friable (moist), not sticky and not plastic (wet); few fine and very fine roots; boundary gradual and wavy.
Bt	dark brown (10YR 3/3) moist, brown (10YR 5/3) dry; loam; weak to moderate medium subangular blocky breaking to weak fine granular; hard (dry), friable (moist), very sticky and slightly plastic (wet); few fine and very fine roots; few thin clay films on ped faces; boundary clear and wavy.
Cr	yellowish brown (10YR 5/4) moist, light yellowish brown (2.5Y 6/4) dry; sandy loam; massive; loose (dry).

			-Particle size -						TOTAL					
horizon	depth	gravel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg-1	mg kg-1	g kg-1					
Ap	32	6	62	28	10	6.7	3	7	0.7	1.0	4.0	0.9	23.6	3.3
Bt	73	7	41	41	18	6.9	8		0.7	1.0	5.8	1.1	22.5	4.1
Cr	104 +		56	35	9	7.1		2	0.1	2.8	8.9	1.1	28.1	2.9

	- EXCHANGEABLE -				
horizon	K	Na	Ca	Mg	CEC
	cmol kg-1				
Ap	0.2	0.5	7.2	2.5	9.5
Bt	0.2	0.5	13.5	5.3	
Cr	0.1	0.8	11.2	4.8	8.8

Laba 12	fine-loamy, mixed, isomesic **Typic Haplustalf**

Topography:	valley bottom
Slope (degrees):	2 down, 2 up
Aspect (degrees):	360
Erosion:	slight
Landuse:	field

Ap	brown (10YR 4/3) moist, light olive brown (2.5Y 5/4) dry; loam; strong coarse angular blocky breaking to granular; hard (dry), friable (moist), sticky and slightly plastic (wet); common medium, fine and very fine roots; boundary clear and wavy.
AB	brown (10YR 4/3) moist, light olive brown (2.5Y 5/4) dry; loam; weak to moderate fine subangular blocky breaking to weak to moderate fine to medium granular; hard (dry), friable (moist), sticky and slightly plastic (wet); common medium, fine and very fine roots; few thin clay films on ped faces; boundary clear and wavy.
Bt	very dark grayish brown (10YR 3/2) moist, brown (10YR 5/3) dry; clay loam; strong medium to coarse subangular blocky breaking to strong fine to medium granular; very hard (dry), friable (moist), very sticky and plastic (wet); few fine and very fine roots; common thick clay films on ped faces; boundary clear and wavy.
BC	brown (10YR 4/3) moist, light yellowish brown (2.5Y 6/4) dry; clay loam; moderate medium subangular blocky to massive; very hard (dry), friable (moist), very sticky and plastic (wet); few fine roots; boundary gradual and wavy.
R	unweathered rock

			-Particle size -						------------- TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	------- %					g kg^{-1}	mg kg^{-1}	------------- g kg^{-1} -------------					
Ap	12	2	46	39	15	6.6	6	6	1.0	0.9	5.3	1.0	19.6	3.3
AB	40	5	45	37	18	6.3	7		0.8	0.8	5.6	1.0	18.7	3.2
Bt	85	2	38	34	28	6.3	4		0.8	0.8	6.0	1.1	16.7	3.3
BC	91	5	37	36	27	6.5	9		0.6	0.8	6.2	1.0	16.3	3.0
R	92 +													

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	--------- cmol kg^{-1} ---------				
Ap	0.2	0.7	9.4	3.2	12.5
AB	0.2	0.6	10.0	3.7	
Bt	0.2	0.6	12.4	4.8	
BC	0.2	0.7	11.5	5.7	
R					

Laba 13	coarse-loamy, mixed, isomesic **Typic Ustropept**

Topography:	convex, upper slope
Slope (degrees):	9 down, 6 up
Aspect (degrees):	270
Erosion:	slight
Landuse:	field

Ap	very dark grayish brown (2.5Y 3/2) moist, light olive brown (2.5Y 5/4) dry; sandy loam; weak coarse angular blocky breaking to weak fine granular; soft (dry), friable (moist), not sticky and not plastic (wet); few fine roots; boundary clear and wavy.
Bw	light olive brown (2.5Y 5/4) moist, pale yellow (2.5Y 7/4) dry; sandy loam; weak to moderate medium subangular blocky breaking to weak fine granular; soft (dry), friable (moist), slightly sticky and not plastic (wet); few very fine roots; boundary gradual and wavy.
Cr	light olive brown (2.5Y 5/6) moist, light yellowish brown (2.5Y 6/4) dry; sandy loam; massive; loose (dry).

			-Particle size -						TOTAL					
hori-zon	depth	gra-vel	sa	si	cl	pH	org. C	avail P	N	P	K	Na	Ca	Mg
	cm	%					g kg^{-1}	mg kg^{-1}	g kg^{-1}					
Ap	15	22	57	31	12	7.0	23	13	0.8	1.7	5.5	1.0	22.5	3.4
Bw	64	10	53	35	12	7.6	3		0.2	1.3	5.6	1.2	21.7	3.3
Cr	76+		63	30	7	7.5			0.0	1.4	6.0	1.5	24.0	3.4

	- EXCHANGEABLE -				
hori-zon	K	Na	Ca	Mg	CEC
	cmol kg^{-1}				
Ap	0.3	0.5	7.4	2.4	9.6
Bw	0.1	0.7	10.0	3.7	
Cr	0.1	1.3	11.4	4.6	