Growth and Suitability of Some Tree Species Selected for Planting in Adverse Environments in Eritrea and Ethiopia

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Abstract

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The thesis addresses some important silvicultural issues raised in Eritrea and Ethiopia and the objective was to evaluate various tree species in terms of growth in adverse environments. Three field and two greenhouse studies were performed using the main species *Eucalyptus globulus*, *Cordia africana*, *Casuarina cunninghamiana*, and *Acacia tortilis*, *A. nilotica* and *Leucaena leucocephala.*

Growth of *E. globulus* tree was influenced by altitude and stand density when assessed in a planted stand in Ethiopia. Decreasing altitude increased growth only up to the middle of the valley hillside. Increasing density increased growth. Soil depth had no impact on growth of *E. globulus* and this shows that the species is suitable for planting on shallow soils.

Data from a *C. africana* spacing trial in Eritrea were analysed to improve the management of *C. africana* plantations established on degraded dry lands by evaluating the response of the species to various initial spacings. Planting *C. africana* trees at wider spacing can be advantageous in terms of growth, but not stem quality.

Different provenances of *C. cunninghamiana* were tested in two field trials in Eritrea to identify the provenance matching marginal lands of the Eritrean highlands. For firewood and small pole production, the use of the fast growing provenances 'Coonabarabran' (CN), 'Flag stone' (FS), and 'Rollingstone' (RS) is recommended. However, the use and wide spread of the three provenances must be taken with caution due to the risks involved in the use of exotic tree species.

Two greenhouse experiments investigated the suitability of *A. tortilis* for manure production and rehabilitating salt affected marginal lands. The species has a greater potential to produce mulch rich in nitrogen and phosphorus compared to *L. leucocephala*. Nevertheless, further research under field conditions would be needed to confirm the results and the sustainability of such a practice. *A. tortilis* and *A. nilotica* seem to be sensitive to salinity. However, because the two acacias have a wide distribution covering a large salinity gradient, there could be other provenances or ecotypes of both species that are more tolerant to salinity. Therefore, screening tests involving various genotypes of both species could be promising to find suitable trees for afforestation on salt affected soils in arid and semiarid Africa.

Keywords: Altitude, aspect, branching, biomass, diameter at breast height, initial spacing, green manure, leaf phenology, provenance, root collar diameter, salinity, slope, soil depth, tree height, water potential

Address: Amanuel Mehari, Department of Crop Production Ecology, SLU, P.O. Box 7043, SE–750 07, UPPSALA, Sweden. E–mail: Amanuel.Mehari@lto.slu.se

To

my brother Solomon Mehari Goitom,

my nephew Iyob Geberetensaea Derare, and

my sister in-law Nighisti Minas Gebrekirstos

Contents

Appendix

Paper I-V

The present thesis is based on the following papers, which will be referred to by their Roman numbers:

I. **Mehari, A.** & Näslund B. Å. 1999. Growth performance of *Eucalyptus globulus* as influenced by stand and site factors in Cheleleka catchment, central Ethiopia. *Journal of Tropical Forest Science* 11: 762-774.

II. **Mehari, A.** Mrema, A. F. & Weih, M. 2005. The suitability of *Acacia tortilis* as an alternative tree manure crop to *Leucaena leucocephala* in sub Saharan Africa. *African Journal of Ecology* 43: 162-165.

III. **Mehari, A.**, Ericsson, T. & Weih, M. 2005. Effects of NaCl on seedling growth, biomass production and water status of *Acacia nilotica* and *A. tortilis*. *Journal of Arid Environments* 62: 343-349.

IV. **Mehari, A**. & Habte, B. 2005. Influence of initial spacing on growth and branching characteristics of *Cordia africana* trees established on Eritrean highland. *New Forests* (in press).

V. **Mehari, A.** & Habte, B. 2005. Provenance variation in growth and survival of *Casuarina cunninghamiana* grown at two sites in Eritrea (submitted).

Introduction

Background

The consequences of wood shortage and the need for planting trees in Eritrea and Ethiopia

Wood for fuel and local construction is scarce in both Eritrea (Habtetsion & Tsighe, 2002; MOA, 2002) and Ethiopia (Pohjonen & Pukkala, 1988; Pohjonen, 1989; Pukkala & Pohjonen, 1990; Mekonenen, 1998). Consequently, the life quality of the people is severely affected. When fuelwood is short, people cook less and eat more uncooked foods; they reduce eating foods of higher nutritional and biological values such as meat, beans and grains that are requiring intensive cooking. Especially, eating raw meat containing eggs or reproductive structure of intestinal parasites or pathogens can severely deteriorate the health of the people. Consequently, the efficiency and performance of the human labour declines and so is also the agricultural production.

The development and progress of wood based industries, such as small carpentry shops, tobacco drying, bricks, pottery, steel manufacturing, and tile backing, which are important for creating employment opportunity to the poor in rural and urban areas, are hampered due to the scarcity of fuelwood and other wood products.

In Eritrea and Ethiopia, women have a significant role in household and the process of food production. They fetch water, wash clothes, take care of children and cook meals for the family, and participate in operations of food production processes like planting, weeding and harvesting. In the rural areas, women and children are responsible for collecting firewood. As the fuelwood source is continuously depleted and this energy commodity is becoming scarce, women and children will spend much time and travel long distances to collect fuelwood; for example in Eritrea, they travel up to 10-15 km to collect firewood (Tsighe, 2002). Consequently, the works at home and on farm are often not easily and timely completed. Thus, the work burden on woman increases and her life quality deteriorates. Furthermore, if farm operations such as weeding, planting and harvesting are not done timely, food production declines. Consequently, the two countries may have difficulties to achieve the goal of their millennium food security policy.

The most important problem of economic development of countries in Africa is loss of soil fertility because of erosion caused by forest destruction (Anderson, 1987) and nutrient depletion due to extensive cultivation with short fallows and without fertilizer inputs (Alexandratos, 1995). The average annual soil loss for African soils due to deforestation is estimated at 6 t ha^{-1} (Myers, 1989), which may cause rainfed crop productivity to decline by as much as 20 to 30% during the next 10 years (FAO, 1984). To meet the food need of the growing population, it should be important to replenish the soil fertility of agricultural soils using chemical fertilizers. However, use of chemical fertlizer in subsistence agriculture is not profitable (Kumwenda *et al.*, 1995). The option farmers have is to use green manure harvested from leguminous green manure tree crops and especially their seedlings (Ruthenburg, 1980; Becker *et al*., 1990; Kang *et al*., 1990; Meelu, 1994), because the effective time of using trees for manure is at seedling stage (Meelu *et al*., 1994).

Eritrea and Ethiopia are economically poor. The people of both countries live on less than one US dollar a day. The capacity of both countries to import and ensure the supply of commercial energy commodity such as liquid petroleum gas (LPG) and kerosene to households, the major energy consumers in both countries, is disappearing, because the governments' foreign exchange reserve is declining from year to year. For the same reason, it is also becoming difficult to import timber and other wood products to secure and enhance the construction work in the countries. To alleviate the wood shortage and thus improve the life quality of the poor in rural and urban areas, to encourage employment and community development, and to enhance the construction work in the two countries, increasing the supply of wood from newly established forest plantations and village woodlots would be desirable (Anderson, 1987; Leach and Mearns, 1988; Fuware, 1992; Best, 1992). Nevertheless, like in many countries in the Tropics, suitable land for planting trees is scarce in Eritrea and Ethiopia, because productive lands are always used for food production (Zobel & Talbert, 1984; FAO, 1988; FAO, 1989; Jagger & Pender, 2003; Evans & Turnbull, 2004). Therefore, trees are planted at a large scale in adverse environments (Zobel & Talbert, 1984; FAO, 1988; FAO, 1989; Jagger & Pender, 2003; Evans & Turnbull, 2004) or at greatly reduced scales in agroforestry systems to produce a mixture of products and services for the farming households (Anthofer *et al*., 1998; Lupwayi *et al*., 1999; Kidanu *et al*., 2004).

The use and ecological requirements of some promising tree species

In Eritrea and Ethiopia, native trees such as *Acacia tortilis*, *Acacia nilotica*, *Cordia africana* and exotic ones like *Casuarina cunninghamiana*, *Eucalyptus globulus* and *Leucaena leucocephala* are planted for economic and environmental conservation purposes. Nevertheless, the ecological requirements of all these trees are different (Table 1). Therefore, any decision made on what species to plant must be taken carefully. For very arid sites, *A. tortilis*, *A. nilotica*, *C. cunninghamiana* and *L. leucocephala* might be suitable, but not *C. africana* and *E. globulus* (Table 1). *C. africana* and *L. leucocephala* are intolerant to frost and their use must be restricted to frost free sites. In contrast, *E. globulus* is cultivated on cold marginal tropical highlands of Eritrea and Ethiopia, particularly on degraded mountains and hillsides where frost occurs frequently.

Adverse environments and their silvicultural challenges for cultivating trees

Due to the lack of suitable land, most of the forest plantations in Eritrea and Ethiopia are carried out in adverse environments. Adverse environments are sites that are marginal for growing economic crops due to their extreme climate (e.g. low rainfall, frost etc.) and poor soil conditions (e.g. nutrient deficient, acid, alkaline soils) (Zobel & Talbert, 1984; Evans & Turnbull, 2004).

Table 1. Ecological requirements and use of some selected tree species for planting in Eritrea and Ethiopia

	Ecological requirements					
Species	Soils	Rainfall (mm)	Temperature	Climate type	Uses[†]	References[‡]
Acacia totilis	alkaline, sand, loam-clay, clayey, alluvium shallow (up to 25 cm)	50–1000, tolerates 6-9 months drought	Trees can grow up to 50 ºC; seedlings are sensitive to frost	Arid (AR), and semiarid (SAR) tropics (TR)	1, 2, 3, 4, 5, 6, 7, 10, 11,	1, 5, 7, 9, 10, 11, 12, 14, 15, 17, 18
Acacia nilotica	alkaline, sand, loam-clay, clayey, alluvium	250–1000, tolerates 6-9 months drought	Trees can grow up to 50 ºC; seedlings are sensitive to frost	AR and SAR	1, 2, 3, 4, 5, 6, 7, 8, 10, 11,	1, 5, 9, 11, 14, 15, 19
Casuarina cunninghamiana	Variety of soils	200–1100, riverine	0–40 ºC	AR, SAR, Cool TR and subtropical areas	1, 2, 3, 4, 5, 6, 7, 9	3, 15, 16
Cordia africana	Variety of soils, but do well in light well drained ones	500-1400, tolerates 6-9 months drought	Trees can grow up to 40 ºC; but sensitive to frost	Tropical Africa	1, 2, 3, 4, 5, 6, 9	4, 8, 18, 20
Eucalyptus globulus	well drained, fertile and none calcareous or alkaline and saline loam soils	500-15000, tolerates 2 – 3 months drought	Trees can grow up to 50 ºC; seedling sensitive to frost	Tropical highlands, subtropical and temperate regions	1, 2, 4, 5, 8, 9	1, 2, 6, 13
Leucaena leucocephala	well drained, neutral to slightly alkaline soils	400-1000, tolerates 4–6 months drought	3–40, the species is frost sensitive	AR and SAR, Humid tropics	1, 2, 3, 6, 8	1, 11, 14, 15

[†]Use: 1. Fuel, 2. local construction, 3. fodder, 4. shade, 5. windbreak 6. conservation, 7. hedge 8. pulp, 9. timber, 10. gum and 11. tannin

[‡]References: 1. National Academy of Sciences, 1980; 2. FAO, 1981; 3. Boland *et al*., 1984; 4. White, 1983; 5. Webb *et al*., 1984; 6. Turnbull and Pryor, 1984; 7. Belsky *et al*, 1986; 8. Warfa, 1988; 9. FAO, 1989; 10. Kennenni, 1990; 11. von Maydell, 1990; 12. Vetaas, 1992; 13. Eldridge, 199; 14. Hocking, 1993; 15. Nair, 1993; 16. Weinstein, 1993; 17. Alstad and Vetaas, 1994; 18. Nyberg.and Högberg, 1995, 19. Khristova and Karar, 1999. 20. Mehari and Habte, 2005 (paper III).

Adverse environments are abundant in Eritrea and Ethiopia. Most of the two countries are affected by drought (UNESCO, 1979; Glantz & Katz, 1985; De Pauw *et al*., 2000) and due to night clear skies, frost damage is common on the highlands and lowlands of both countries (Anon., 1988; Griffiths, 1972). Moreover, soils of the Eritrean and Ethiopian highlands are shallow due to erosion. Every year, the region loses about 1500 million tons of its topsoil (Hurni, 1993). The average soil depth for the region is estimated at about 10 cm (e.g. Henrickson *et al*, 1983) and restricted root development and drought are problems associated with these thin soils (Sanchez *et al*., 2003).

Most of the soils on the highlands of the two countries are acidic (Smaling *et al*., 1997) and their pH ranges between 3 and 5.3 (Taddese, 2001). The problems associated with acid soils are well documented (e.g. McBride, 1994; Marschner, 1995).

In Eritrea (Anon., 2000) and Ethiopia (Abebe, 1980; Taddese, 2001), salt affected soils are abundant. The main sources of salinity are salt transported from adjacent highlands due to erosion, shallow ground water tables, and salts from marine origins (Abebe, 1980; Anon., 2000; Taddese, 2001). The salt accumulated in the upper layer of these low lying soils causes salinization and alkalination (Abebe, 1980; Szabolcs, 1989; Anon., 2000; Taddese, 2001) that may create unfavourable conditions for trees (McBride, 1994, Marschner, 1995).

Generally, in the context of this study, adverse environments constitute sites affected by erosion, drought, nutrient depletion, frost, alkalinity and salinity. The extremes of climate and soil are problems for the use of adverse environments for planting trees or forest plantation establishment (Evans & Turnbull, 2004) and the solutions are:

1. to use a species/provenance matching the climate and soil of concern;
2. to introduce technologies that are capable of improving surface stability, water relations and nutritional status of the growing site; and
3. to apply protecting measures to reduce damage on the planted trees.

However, for the success of tree cultivation or establishment of forest plantations in these difficult environments, these solutions must be combined with good forest management and policies.

Aims and objectives

The general aims of this thesis were:

1. To address significant silvicultural issues raised in both countries, in particular the issues of species and provenance selection (Papers II, III & V) and the impact of site and stand factors on tree growth (Papers I, IV & V);

2. To contribute to the improvement of the silvicultural knowledge on some native species (paper II, III & IV).

The general aims were addressed by means of five specific objectives:

1. to identify the site and stand factors influencing growth of *Eucalyptus globulus*, which is often cultivated on marginal lands, particularly on degraded mountains and valley hillsides where variations in site factors such as soil depth, altitude, aspect and slope are markedly observed;
2. to investigate the suitability of *Acacia tortilis* seedlings for use as manure crop in sub-Saharan Africa (SSA);
3. to evaluate the suitability of *A. tortilis* ssp. *radiana* for planting on salt affected marginal lands;
4. to asses the effect of initial spacing on growth and branching habit of *Cordia africana*; and
5. to identify provenances of *Casuarina cunninghamiana* that match the environmental conditions of dry marginal areas in the Eritrean highland.

Information on site and stand factors influencing growth of *E. globulus* will help tree growers to predict yield and understand the limitations for tree cultivation on degraded marginal lands. Moreover, the influence of altitude, aspect and slope on growth of trees has not been demonstrated sufficiently in the tropics and subtropics (Vanclay, 1992).

A. tortilis is a promising tree species for soil conservation in SSA (Belsky *et al*, 1986; FAO, 1989; von Maydell, 1990; Vetaas, 1992; Nair, 1993; Alstad & Vetaas, 1994; Nyberg.& Högberg, 1995), as some of the exotics introduced to the region are susceptible to drought and pests. For example, the use of *Leucaena leucocephala* has decreased because the leucaena psyllid (*Heteropsylla cubana*) is a threat and could wipe out leucaena trees massively in most part of SSA (Bray, 1993; Shayo, 1997).

Soils affected by salt are abundant in the arid and semiarid of Africa as well as in Eritrea and Ethiopia (Abebe, 1980; Szabolcs, 1989; Taddese, 2001; Anon., 2000; Lal, 2002) and these are potential forestry lands in the future, because the productive lands go for food production (El-Lakany, 1983; FAO, 1988). Since selection of suitable species and use of appropriate silvicultural technique determine the success of growing trees on salt affected marginal lands, this study evaluated the salt tolerance of *A. tortilis* ssp. *radiana*. The species is native and drought tolerant and information on its salt tolerance could contribute to the productive use of wastelands in SSA.

C. africana is a native species and improved silvicultural knowledge of the species is critical for its potential use in agroforestry and forestry programmes in both countries. Therefore, we made an effort to show the effect of using various initial spacings on growth and branching characteristics of *C. africana* trees grown on marginal lands on Eritrean highlands. Decisions on initial spacing influences the costs of forest plantation establishment, future silvicultural operations and utilization of the forest products (Evans & Turnbull, 2004).

C. cunninghamiana has an enormous potential as biomass producer and the establishment of profitable forest stands of such an important species is determined by the right choice of provenance, because a high level of genetic diversity exists within the species (Moran *et al*., 1989).

Materials and Methods

Paper I: Growth performance of *Eucalyptus globulus* as influenced by stand and site factors in Cheleleka catchment, central Ethiopia

The study was carried out in a 4 years old *Eucalyptus globulus* fuelwood plantation established in the Cheleleka catchment, central Ethiopia. Data on tree height and diameter were collected from 100 circular temporary sample plots established on 4 altitudinal contours starting from 2850 and ending at 3150 m a.s.l.; the interval between each contour was 100 m. The plot survivor trees, slope, aspect and soil depth were also recorded.

Paper II: The suitability of *Acacia tortilis* as an alternative tree manure crop to *Leucaena leucocephala* in sub Saharan Africa

Seedlings of *Acacia tortilis* (Forssk.) Hayene were tested for their suitability for manure production. The reference species used was *Leucaena leucocephala* (Lam) De Wit, because it is the major supplier of transportable green manure in SSA cropping systems (Brewbaker, 1985; Nair, 1993; Meelu, 1994).The seeds of both species utilized in this experiment were obtained from northeast Tanzania (5°12′ S, 38°29′ E) and central Tanzania (6°20′ S, 36°80′ E) by the Tanzania Forest Research Institute.

The study was carried out on 6 months old seedlings of both species grown in the greenhouse. The seedlings were provided with equal water, liquid fertiliser (Wallco 51-10+43 mikro liquid fertiliser, Cederroth International AB, Sweden) and artificial light during a 12 h photoperiod. The seedlings were watered every third day to field capacity of the soil. Height, root collar diameter and biomass yields of the two species were recorded. The elemental composition, the water-soluble substances and the sulphuric acid lignin (Klason lignin) in the milled plant materials were also determined. Finally, growth, quality and chemical composition of the harvested biomass of both species were compared.

Paper III: Effects of NaCl on seedling growth, biomass production and water status of *Acacia nilotica* and *A. tortilis*

The salt tolerance of *Acacia tortilis* (Forsk) Hayne ssp. *raddiana* (Savi) Brenan (accession. No. 01159/83) was tested using *Acacia nilotica* (L.) Wild ex. Del. ssp. *indica* (Benth.) Brenan (accession No. 01441/84) as a reference species, because it is tolerant to salinity (FAO, 1989). The seeds of both species were obtained from the DANIDA Forest Seed Centre, Humlebaek, Denmark.

The salinization experiment was conducted for four weeks on two months old seedlings of *A. tortilis* ssp. *radiana* and *A. nilotica* ssp. *indica*. Seedlings were subjected to three levels of salt treatments. The treatment levels were solutions of 0 mM (control), 150 mM and 300 mM of NaCl. To avoid salt accumulations, seedlings were irrigated daily to field capacity with deionized water and pots were covered with thin plastic sheets to reduce evaporation.

Before the start and at the end of the experiment, we measured height, root collar diameter, stem and root dry biomass of seedlings. Leaf dry weight for *A. tortilis* seedlings grown at 150 mM and 300 mM NaCl could not be recorded, because their leaves were completely shed four weeks after the start of the salinization experiment.

Prior to the onset of any salinity treatment, seedlings of the two species differed in size and morphology. Therefore, the analyses for the seedlings (1) height (HT), (2) root collar diameter (RCD), (3) stem biomass (SB), and (4) root biomass (RB) were carried out by means of relative growth rates since plant growth is related to its initial size (Kozlowski & Pallardy, 1997). Thus, the relative height growth (RGR_{HT}), relative root collar diameter growth (RGR_{RCD}), relative stem biomass growth (RGR_{SB}) and root biomass growth (RGR_{RB}) were computed as:

$$RGR_{HT}\ (\text{cm cm}^{-1}\ \text{d}^{-1}) = (\ln HT_f - \ln HT_i)/(t_f - t_i) \quad (1)$$

$$RGR_{RCD}\ (\text{mm mm}^{-1}\ \text{d}^{-1}) = (\ln RCD_f - \ln RCD_i)/(t_f - t_i) \quad (2)$$

$$RGR_{SB}\ (\text{g g}^{-1}\ \text{d}^{-1}) = (\ln SB_f - \ln SB_i)/(t_f - t_i) \quad (3)$$

$$RGR_{RB}\ (\text{g g}^{-1}\ \text{d}^{-1}) = (\ln RB_f - \ln RB_i)/(t_f - t_i) \quad (4)$$

where HT, RCD, SB, and RB are height, root collar diameter, stem biomass, and root biomass of each seedling at the beginning (subscript i) and end (subscript f) of the salinization experiment, respectively. The t_f-t_i was the period of 30 days during which seedlings were subjected to various levels of NaCl concentration.

Before the final harvest, measurements on shoot water potentials (ψ) were conducted on 6 seedlings of *A. nilotica* and *A. tortilis* from all salt treatments in the morning (8:00 to 10:00 h solar time) and afternoon (13:00 15:00 solar time).

For evaluating RGR_{HT}, RGR_{RCD}, RGR_{SB} and RGR_{RB} of seedlings, we conducted a two-way factorial analysis with main factors species, salt treatment and their interaction. The effects of species, salt treatment and daytime and their interactions on shoot water potential (ψ) of seedlings were also investigated.

Paper IV: Influence of initial spacing on growth and branching characteristics of *Cordia africana* trees established on Eritrean highland

The *Cordia africana* spacing trial was designed systematic (Fig. 1 of paper IV). For the experiment, twenty five (5 × 5) six months old seedlings of *C. africana* were planted at spacings 1 × 1 m, 1.5 × 1.5 m, 2.0 × 2.0 m, 2.5 × 2.5 m, 3.0 × 3.0

m and 3.5 × 3.5 m; these are equivalent to 1 m^2, 2.25 m^2, 4 m^2, 6.25 m^2, 9 m^2 and 12.25 m^2 in growing space per tree (GSPT), respectively.

Tree root collar diameter (RCD) and height (Ht) were measured at the age of 3.5 and 7.5 years. At both ages, survivor trees in each plot (STP) were counted to calculate the plot survival rate (SR). Nevertheless, tree parameters were measured on the innermost survivor trees (IST) in a plot to avoid any edge effect. In addition, tree crown diameter (CD), branch diameter (BD) and number of branches (NB) of trees were assessed 7.5 years after planting. To evaluate the recorded data, we used analysis of variance (ANOVA), correlation and regression analyses.

Paper V: Provenance variation in growth and survival of *Casuarina cunninghamiana* grown at two sites in Eritrea

Casuarina cunninghamiana provenance trials were established at Halhale and Merhano, Eritrea. Six provenances were included (Table 2) and each provenance was represented at both trial sites. The climate and vegetation period of Halhale and Merahano are summarised in papers IV and V. In both trials, a complete block design was used to study the effects of provenance, site and their interaction on tree height and root collar diameter. Each block has the same number of plots and each provenance was assigned randomly within each block. There were 25 trees per plot at 2.0 × 2.0 m spacing.

Table 2. Locations of origin for the six provenances of *Casuarina cunninghamiana* tested at Halhale and Merhano, Eritrea

Locality	Latitude	Longitude	Altitude (m a.s.l.)
Rolling stone	19°10′	146°20′	20
Murumbidgeer	35°05′	147°18′	230
Wcoonabarabran	31°12′	149°11′	670
Brogoriverin	36°37′	149°50′	85
Glennines	29°50′	151°36′	1000
Flagstone	27°38′	152°03′	200

Results and Discussion

Influence of site and stand factors on growth of *Eucalyptus globulus*

Forest plantations in Eritrea and Ethiopia are often established on degraded mountain slopes and valley hillsides where marked changes in site factors such as altitude, aspect, slope and soil depth are experienced. In areas of marked relief, topographic variables such as altitude, aspect and slope could be the dominant forces controlling site productivity and tree growth (Ralston, 1964; Malcolm, 1976), because they influence the climate and soil development on the growing site (Geiger, 1965; Rosenberg *et al*., 1983; Barry, 1992; McGregor & Nieuwolt, 1998). Nonetheless, not only topographic variables, but also competition between the surrounding vegetation and a planted tree affects tree growth and survival (Oliver *et al*., 1996; Jäghagen, 1997).

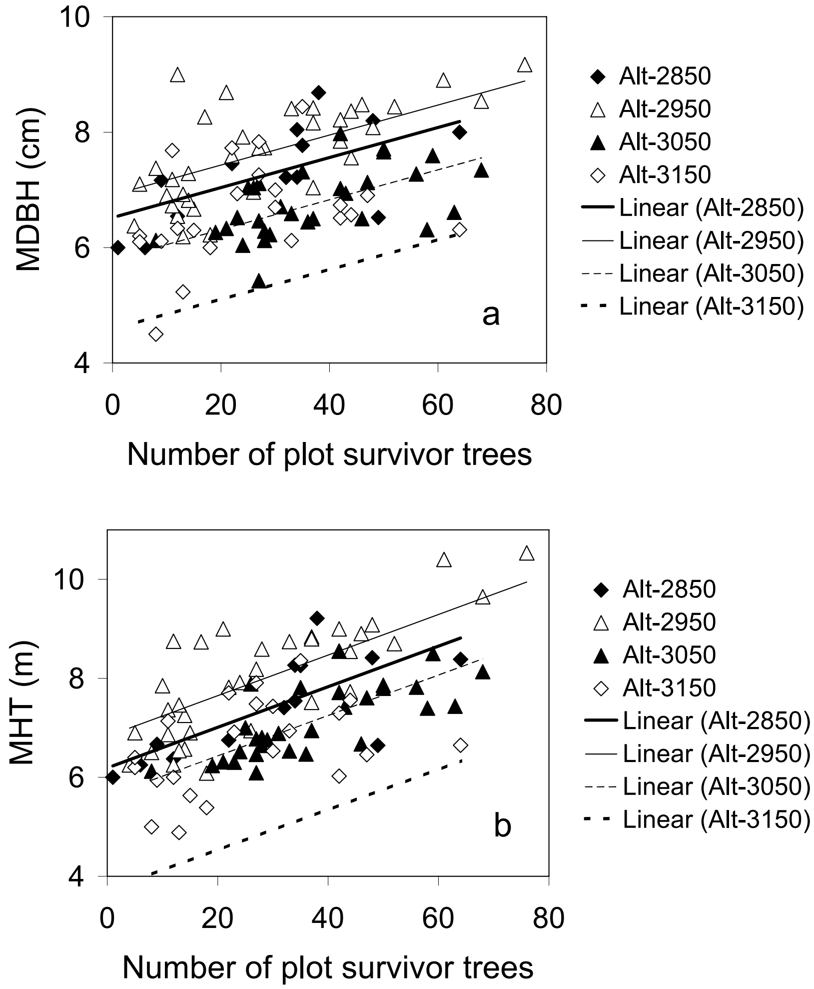

Figure 1. Responses of (a) mean diameter at breast height (MDBH) and (b) mean tree height (MTH) of *Eucalyptu globulus* to density at various topographic positions on the study area. (Data extracted from paper I)

In our study (paper I), height and diameter of trees declined with the number of trees surviving in a plot (Fig 1 on this page, Table 3 on the next page). In other words, we observed poor tree growth in plots where the survival rate was poor and this was contrary to the principle that increasing plant density per unit area reduces tree growth (Daniel *et al*., 1979). The cause for the poor survival rate and growth of the trees in excessively open plots is probably the result of failure in planting and the invasion of weeds. Moreover, the forest plantation where this study was conducted was young and not tended intensively after establishment. Consequently, excessively open plots were infested by weeds.

Except altitude, none of the site factors influenced tree growth in this study, (Table 2c in paper I). The gap between the trend lines in figure 1 (on previous page) indicates the difference caused by the variation in altitude. However, the study is lacking important variables such as habitat type, exposure, soil chemical and physical properties that may have influenced on tree growth performance and site productivity. Therefore, this study suggests further investigation on the impact of site factors on tree growth performance by including the variables that this study has missed out. Such information may improve our knowledge in mountain silviculture and the understanding of the limitations and possibilities for tree cultivation on tropical highlands.

Table 3**.** Estimates of the parameters for the regression equations, showing the relationships between tree growth and number of plot survivor trees (PST) of *Eucalyptus globulus* grown at different altitudes on central Ethiopian highland. (MDBH and MTH are mean diameter at breast height and mean tree height, respectively).

Dependent variable	Parameters	Estimates	Standard error	*t* - Value	*P* - Value
MDBH	Constant	5.95	0.171	34.62	<0.0001
	Altitude				
	2850 m	0.575	0.227	2.53	0.0130
	2950 m	0.965	0.177	5.45	0.0001
	3050 m	-0.158	0.187	-0.640	0.4023
	3150 m	-1,382	.		
	PST	0.062	0.004	6.62	<0.0001
MTH	Constant	5.59	0.185	30..20	<0.0001
	Altitude				
	2850 m	0.605	0.246	2.46	0.0158
	2950 m	1.248	0.191	6.52	<0.0001
	3050 m	0.022	0.203	0.11	0.9143
	3150 m				
	PST	0.041	0.004	9.60	<0.0001

There is evidence for the occurrence of temperature inversions on mountain slopes and in valley hillsides in the Ethiopian highlands (Griffiths, 1972; Gamachu, 1984; Anon., 1988). Therefore, the probable cause for the best growth of *E. globulus* observed at an altitude of 2950 m or on the middle of valley hillsides is the formation of thermal belts or warm zones around this position. The thermal belts are warm zones on valley hillsides arising primarily from the formation of cold air trapped in the valley bottoms and the temperature inversion associated to it (Yashino cited in Kobayashi *et al*, 1994). However, the hypothesis needs to be tested. In addition, to understand the effect of altitude and thermal belt on tree growth, it requires knowledge of wind circulation, energy flow and water balance that have direct impact on the biochemical processes of wood production or tree growth on growing sites.

The soil depth of the study area ranged between 15 and 70 cm. Soils shallower than 50 cm before encountering rock or a hard root-restricting layer pose many constrains to plant growth (Sanchez *et al*., 2003). Therefore, shallow soils are associated to adverse ecological conditions (De Pauw *et al*., 2000). However, growth of *E. globulus* was not influenced by soil depth in this study. This implies that *E. globulus* is a species that can be recommended for planting on adverse environments with shallow soils on Ethiopian highlands. Nonetheless, this study suggests further investigation on the sustainability and profitability of planting *E. globulus* on shallow soils of the marginal lands of the Ethiopian highlands.

Suitability of *Acacia tortilis* for green manure production and afforestation of saline marginal lands

The concentration of water-soluble substances (sugars, amino acids, and proteins; Marstorp, 1996) is an important factor affecting quality of green manure (Reinertsen *et al*., 1984; Collins *et al*., 1990; Palm & Rowland, 1997). Water-soluble extracts were significantly greater concentrated in the leaves of *Leucocephala leucocephala* than in those of *Acacia tortilis* (Paper II). This indicates that more degradable carbon is released from *L. leucocephala* leaves in the early stages of litter decomposition to support the growth of microorganisms compared to *A. tortilis* (Palm & Rowland, 1997). Consequently, there might be a high risk of losing a large fraction of nutrients (e.g. N, K and Mg) in the early stages of manure decomposition (Gosz *et al*.; 1973; Slapokas & Granhall, 1991; Takahashi, 1996; Villegas-Pangga *et al*., 2000). Therefore, the use of green manure with a high content of water-soluble components in sub-Sharan Africa (SSA) rainfed agriculture could be disadvantageous. Nutrient loss immediately after the rains start is possible, because young crops do not have well-developed root systems to take up nutrients released from the added green manure.

The amounts of nitrogen (N) and phosphorus (P) accumulated in *L. leucocephala* were not significantly different from those in *A. tortilis* (paper II). No significant difference was also found in the biomass yield of the two species. This suggests that *A. tortilis* may be used to produce green manure rich in N and P that are the most crop-production-limiting nutrients in the Tropics (Mugwira & Haque, 1993). However, further studies under field conditions are recommended to confirm the results of this study and the sustainability of such a practice.

Acacias are often used for plantation on dry saline soils (Oba *et al.*, 2001; Tomar, *et al*., 2003). In paper III, we evaluated the tolerance of *Acacia tortilis* ssp. *radiana* to salinity compared with a known salt tolerance reference species *Acacia nilotica* ssp. *indica*, which is extensively used for rehabilitating alkaline and saline soils (Young, 1989; Dagar *et al*., 2001; De & Mitra, 2002; Goel & Behl, 2004) and can tolerate root zone salinity of up to 3% (approximately 520 mM NaCl salinity)

(FAO, 1995). However, when both species were subjected to salinity, we found them similar in terms of growth, but different in terms of changes in seedling morphology (paper III); the canopy of the control seedlings was dense compared to those of the salt treated ones (Fig 2 on this page). Seedlings of *A. tortilis* treated with 150 mM and 300 mM NaCl started to exhibit stunted growth and begun to shed their lower leaves in the second week of the experiment, and shed their leaves completely in the fourth and third week after the start of the salinization experiment, respectively. In contrast to *A. tortilis,* seedlings of *A. nilotica* started to show stunted growth from the third week of the experiment and it was in the fourth week that those subjected to 300 mM salt concentration began to shed their leaves.

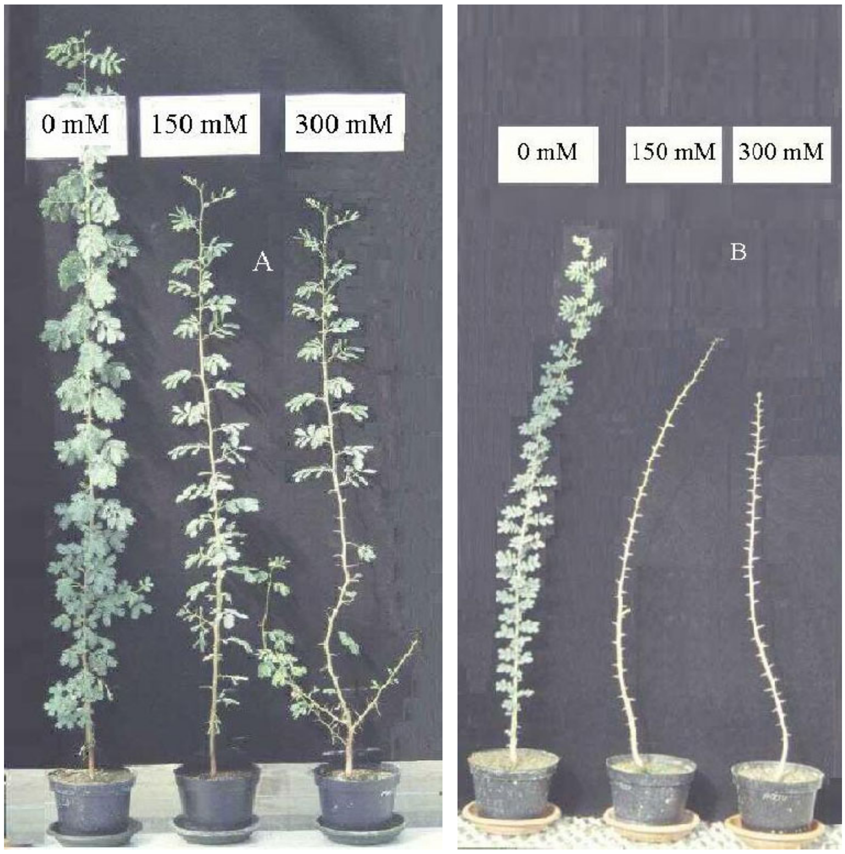

Figure 2. Morphological variation between treatments observed on seedlings of *Acacia nilotica* (A) and *A. tortilis* (B) four weeks after the start of various NaCl treatments.

The mechanisms how salt injures plant tissue and slows down growth are not yet fully understood (Munns, 1993; Allen et al., 1994; Fung et al., 1998). However, there is evidence for an impact of soluble salt on plant water relations (Allen et al., 1994; Fung et al., 1998). Increased soluble salt causes drought and nutrient stress, because it reduces the osmotic potential of soil solutions and hampers plant water and nutrient uptake (Greenway & Munns, 1980; Allen et al., 1994). In this study, though seedlings were watered daily and the soil on which they grew was always kept moist to field capacity, their shoot water potential (ψ) decreased with salinity. This supports the hypothesis that increased soluble salt in the root zone affects plant water potential negatively (Greenway & Munns, 1980; Allen et al., 1994).

The two acacias in this study exhibited a rapid change in phenology with no symptoms of necrosis detected on their dead fallen leaves. According to Munns (1993), leaves of sensitive genotypes die because salts arrive faster or because cells are unable to compartmentize the salt in vacuoles to the same high concentration compared to tolerant genotypes. However, both *A. tortili*s and *A. nilotica* are drought-deciduous tree species (Ross, 1979; Webb *et al*., 1984). During drought seasons when plants suffer from water deficit or water stress, they abscise their leaves. This sort of leaf abscission is characteristic for arid plants and helps them to control water relations and avoid drought-induced water deficits. In this investigation, we observed *A. tortilis* (Fig. 2A) and *A. nilotica* (Fig. 2B) shedding their leaves after both species were subjected to salt stress. From the results of this study, it is not clear whether salt-induced drought or the toxic effect of the salt ions or both caused the leaf abscission. Nonetheless, loss of these leaves affects the supply of assimilates to the growing regions and thereby affects growth and biomass accumulation.

Field trials with acacias grown on salt affected marginal lands indicate that both species are tolerant to salinity (e.g. Tomar, *et al*., 2003). However, we found both species sensitive to salinity values within the tolerance range previously reported for *A. nilotica*. The reason for the discrepancy of results might be the variation between the genetics and seed sources of the materials used in both trials, because plant tolerance to salinity is controlled by genetics (van der Moezel *et al*., 1991; Heth & Macrae, 1993; Nabil & Condret, 1995; Fung *et al*.; 1998; Marcar, *et al*., 2002) as well as seed source environment (Sands, 1981; Crang *et al*., 1990). Seeds from non-saline environments have poor germination and subsequent seedling growth when subjected to salinity (Sands, 1981; Craig *et al*., 1990). The results from this study suggests screening tests involving various ecotypes and genotypes of both species, because it is promising to find suitable trees for the afforestation of salt affected soils in arid and semiarid Africa. In addition, there might be other provenances and/or ecotypes of both species that are more tolerant to NaCl salinity, for example among the *A. tortilis* genotypes growing naturally around soda lakes (Fagg & Stewart, 1994; Gates & Brown, 1988).

Effect of growing space on growth and branching habit of *Cordia africana* trees

C. africana trees planted at wider spacing grew faster than those grown at narrow spacing (Figs 3a & 3b on the coming page; Table 4 on page 21). Therefore, planting *C. africana* trees at wider spacing on dry marginal lands could be beneficial in terms of growth; it avoids competition for soil moisture, light and nutrients in dry regions (FAO, 1989; Lamprecht, 1989). However, growing *C. africana* trees at wider spacing could be disadvantageous in terms of stem quality. Trees at wider spacing had bigger branches or knots than those at narrow spacing

(Fig. 4a on this page; Table 5 on the next page) and bigger branches or knots are factors that degrade the value and quality of its logs (Daniel *et al.*, 1999; Zobel & van Buijtenen, 1989; Haygreen & Bowyer, 1996). Therefore, it is necessary to minimize the effects of these factors to increase the quality and value of wood from *C. africana* trees. To improve stem quality and enhance growth of *C. africana* trees, this study suggests the establishment of closely spaced plantations followed by thinnings as soon as the water and nutrient requirements of the planted trees increase.

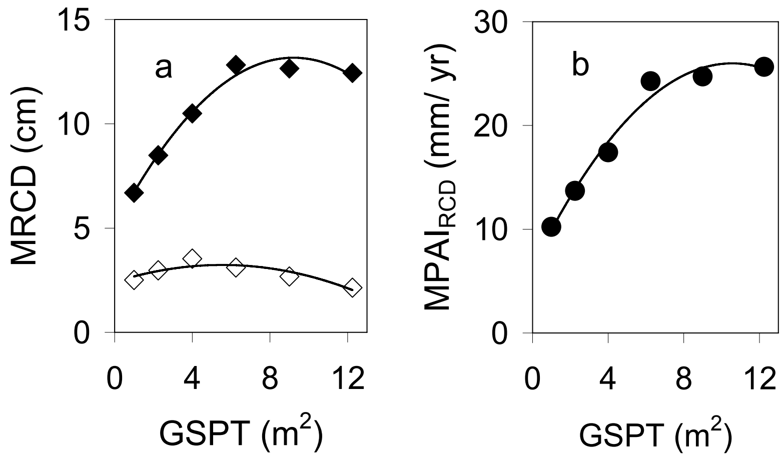

Figure 3. The influence of growing space per tree (GSPT) on (a) mean tree root-collar-diameter (MRCD) at the age of 3.5 (◊) and 7.5 years (♦), (b) mean periodic annual increment in tree root-collar-diameter ($MPAI_{RCD}$), for *Cordia africana* trees.

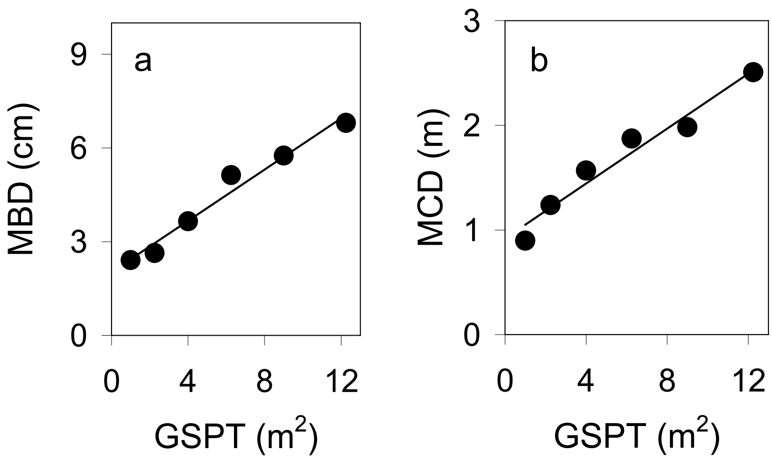

Figure 4. The influence of growing space per tree (GSPT) on (a) mean branch diameter (MBD) and (d) mean crown diameter (MCD) for *Cordia africana* trees.

Table 4. Regression equations, depicting the relationships between growth characteristics and growing space per tree (GSPT) for trees of *Cordia africana* established on Eritrean highland, following the equation Y = $\alpha + \beta_1$ (GSPT) + β_2 (GSPT)^2. Y is the dependent variable, i.e., mean tree root-collar-diameter (MRCD) 3.5 (subscript i) and 7.5 (subscript f) years after planting and mean periodic annual increment in tree root-collar-diameter ($MPAI_{RCD}$); α, β_1 and β_2 are regression coefficients; n is the number of assessed plots; R^2 is the coefficient of determination.

Dependent variable	n	Estimated parameters and coefficients					
		α	β_1	β_2	F	P	R^2
$MRCD_i$	6	2.41**	0.296 NS	- 0.0267 NS	5.91	0.0911	0.798
$MRCD_f$	6	5.05***	1.762**	- 0.096**	89.88	0.0021	0.984
$MPAI_{RCD}$	6	6.40**	3.71**	- 0.176*	73.18	0.0028	0.9791

NS= not significant, * significant at $P \leq 0.05$ and ** significant at $P \leq 0.01$

Table 5. Regression equations, depicting the relationships between the stem quality indicators and growing space per tree (GSPT) for trees of *Cordia africana* grown on Eritrean highland, following the equation Y = $\alpha + \beta_1$ (GSPT). Y is the dependent variable, i.e., mean tree crown diameter (MCD) and mean tree branch diameter (MBD); α, and β are regression coefficients; n is the number of assessed plots; R^2 is the coefficient of determination.

Dependent variable	n	Estimated parameters and coefficients				
		α	β	F	P	R^2
MCD	6	0.919**	0.131**	87.02	0.0007	0.996
MBD	6	2.02**	0.410**	134.93	0.0003	0.971

** significant at $P \leq 0.01$

C. africana is an indigenous tree that farmers deliberately preserve on their farm, because it improves soil fertility (Mugendi & Nair, 1997). However, the increasing canopy size with growing space (Fig. 4b; Table 5) can be disadvantageous in agroforestry applications, because it might reduce the light intensity reaching the crops through shading that may ultimately lead to reduction in crop yield. Therefore, the results of this study suggest further research on the potential of the species to alter the surrounding light, moisture and its impact on crop production to improve the traditional agroforestry practice using *C. africana* trees.

Provenance variation in growth and survival of *Casuarina cunninghamiana*

There are several studies suggesting that early survival, height and volume growth of *C. cunninghamiana* are influenced by provenance, site and their interaction (e.g.

El-Lakany, 1990; El-Lakany & Shepherd, 1983; Merwin *et al*., 1995; Weinstein, 1993). We observed an effect of provenance on height growth rate of *Casuarina cunninghamiana* (paper V; Fig 5 on this page).

In general, *C. cunninghamiana* grows faster than leguminous and none-leguminous indigenous trees planted for biomass production in dry marginal lands of Eritrean highlands (Fig. 3 in paper V). Nonetheless, within the species, the provenance of 'Bega' (BG) grew slower in height than provenances of 'Coonabarabran' (CN), 'Flag stone' (FS), and 'Rollingstone' (RS) across the sites (Fig 5). Its least square (LS) means for plot mean relative periodic annual increment in tree height (LSM_{RPAIHT}) was significantly different from those of CN (P = 0.0033), FS (P = 0.0456) and RS (P = 0.0093). Moreover, early vigour, survival and adaptability of these provenances were above the average (paper V). Therefore, these three provenances should be considered for use in the future afforestation and agroforestry programmes in dry regions of SSA with climate and soil conditions similar to the Eritrian highland. However, the use of the three provenances must be controlled, because they can behave as weeds especially along canals and watercourses (Nair, 1993).

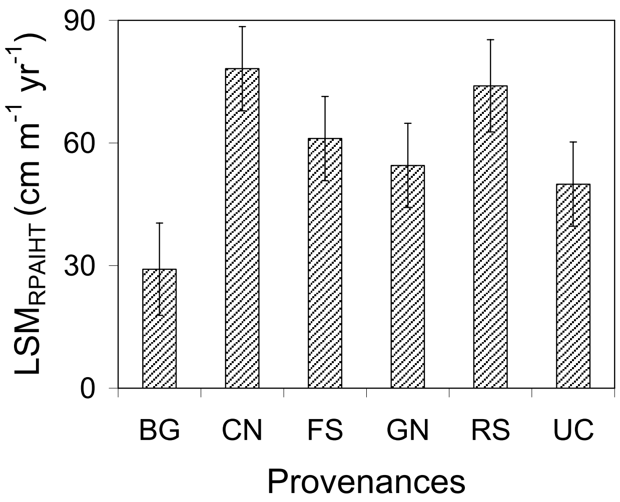

Figure 5. Least square means of relative periodic annual increment in height (LSM_{RPAIHT}) for various provenances of *Casuarina cunninghamiana* grown for 3.5 years after establishment at Halhale and Merhano on Eritrean highland. BG, CN, FS, GN,' RS and 'UC are 'Bega', 'Coonabarabran' ,'Flag Stone' , 'Glen Innes' , 'Rolingstone' and 'Uriarra Crossing' provenances of the species, respectively.

If the purpose of the management is to produce high valued timber, the decision which of the provenances of *C. cunninghamiana* should be used must be made carefully, because the good initial performance of the CN, FS and RS provenances could be followed by a later slowdown, lack of vigour, dieback, poor form or even death (Zobel *et al*., 1987). Therefore, it is important to make long-term investigations on the suitability and stability of the provenances before they are widely spread in the region.

Conclusions

The thesis gives recommendations for the appropriate choice and silviculture of some tree species and provenances to be used for the afforestation of adverse sites in Africa, especially Eritrea and Ethiopia.

Growth of *Eucalyptus globulus* was influenced by altitude and stand density (i.e., the number of survivor trees per plot), but not by aspect, soil depth and slope. The insignificant impact of soil depth on growth of *E. globulus* in this study implies that the species is suitable to plant in adverse environmental conditions associated with shallow soils on the Ethiopian highlands. Nevertheless, this needs further investigation on the sustainability and profitability of planting *E. globulus* on shallow soils in the region.

Acacia tortilis may be used to produce green manure rich in N and P that are the most crop-production-limiting nutrients in the Tropics, because both biomass production and nutrient contents were similar compared to *Leucaena leucocephala*. However, the sustainability of a practice using *A. tortilis* as green manure should be confirmed in the field.

Acacia tortilis ssp. *raddiana* originating from Gezira, the Sudan, was sensitive to salinity. However, the species is widely distributed in the SSA and there might be other provenances and/or ecotypes of the species that are more tolerant to salinity. Screening tests involving various ecotypes and genotypes of the species should be performed.

Planting *Cordia africana* trees at wider spacings could enhance growth, but this practice still can be disadvantageous, because it increases the branch (knot) size and therefore has negative impact on stem quality.

Provenances of *Casuarina cunninghamian* varied in terms of growth and the provenances ‘Coonabarabran’ (CN), ‘Flag stone’ (FS), and ‘Rollingstone’ (RS) performed best among the material tested in semiarid areas of the Eritrean highlands. These three provenances could be used for firewood and small pole production, if their distribution can be controlled particularly along canals and watercourses.

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