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Optimal management of the Umbundu traditional land use system in the central Highlands region of Angola

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Academic Dissertation

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ABSTRACT

The study reviews one publication on the traditional land use system in Angolan highlands, three publications on modelling the growth and yield of nine tropical pine and six eucalypt species, and one publication on optimising the land use in Angolan highlands. The sources of data for the land use system analysis were two years field research and a review of previous studies going back to colonial times. The growth models were based on 19,388 radial increments from 1,059 measured pine trees and 10,499 radial increment observations measured on cores taken from 803 eucalypts trees. Linear programming (LP) was used to optimize the combination of alternative production systems. LP problems were formulated and solved for a baseline land use, improved diet, and maximal timber production land uses. The first study has implications for land use management (e.g. regarding length of fallow) and conflict management in Angola and elsewhere. The developed growth and yield model set included dominant height, diameter increment, tree height and self-thinning models for all the studies pine and eucalypt species. The model set makes it possible to simulate stand development on an individual tree basis. They showed good accuracy when the simulated stand development was compared to the observed development. Therefore, they can be used as a management planning tool in tropical pine and eucalypt plantations in Angola. The developed models were used in the last study to calculate the timber production in short- and long-rotation forestry. The last study showed that among the alternative production systems, cash crops under forest fallow showed the highest land expectation value (LEV). Changing diet by diversifying carbohydrate and protein sources increased LEV and reduced the seasonal need for women labour. In the maximal timber production alternative under food sufficiency constraint the optimal share of tree plantations was around 57% of the total land area.

Keywords: Land use management, *Pinus* spp., *Eucalyptus* spp., linear programming, growth models, Umbundu Land Use System (ULUS).

ABSTRAKTI

Väitöskirjan tutkimuskokonaisuus kattaa yhden julkaisun perinteisestä maankäyttösysteemistä Angolan ylänkömailla, kolme julkaisua yhdeksän trooppisen mäntylajin ja kuuden eukalyptuslajin kasvusta ja tuotoksesta, sekä yhden julkaisun maankäytön optimoimisesta Angolan ylänkömailla. Maankäyttösysteemien analyysin aineisto on peräisin kahden vuoden kenttätyöstä ja kirjallisuuskatsauksesta, joka ulottuu aina siirtomaa-aikoihin. Kasvumallit perustuivat 19,388 läpimitankasvuhavaintoon 1,059:sta männystä ja 10,499 läpimitankasvuhavaintoon 803 eukalyptuksesta. Vaihtoehtoisten maankäyttömuotojen optimaalinen kombinaatio haettiin lineaarisella ohjelmoinnilla (LO). LO-ongelmat muodostettiin tämänhetkistä ruokavaliota tavoittelevalle maankäytölle, parannetulle ruokavaliolle sekä vaihtoehdolle, jossa maksimoidaan puuntuotosta niin, että ruuan tuotanto paikalliselle väestölle on samalla riittävää.

Ensimmäisellä tutkimuksella on vaikutuksia maankäytön suunnitteluun (esim. kesannointiajan pituus) ja konfliktien hallintaan Angolassa ja muualla. Kehitetty kasvumallisarja sisältää mallit metsikön valtapituuden ja puun läpimitan kasvulle, puun pituudelle sekä puiden kuolleisuudelle. Mallisarja mahdollistaa metsikön kehittymisen simuloinnin puukohtaisesti. Mallien havaittiin antavan tarkkoja ennusteita, kun simuloitua puuston kehitystä verrattiin havaittuun kehitykseen. Näin ollen malleja voidaan käyttää metsäsuunnittelun työkaluina trooppisten mänty- ja eukalyptuslajien viljelmillä Angolassa. Kehitettyjä malleja käytettiin viimeisessä tutkimuksessa puutavaran tuotannon laskemiseen lyhyen ja pitkän kiertoajan metsätaloudessa. Viimeinen tutkimus osoitti, että parhaan taloudellisen tuloksen tuotti maankäyttö, jossa vuorottelivat puiden kasvatus lyhyellä kiertoajalla ja myytävien viljelykasvien (cash crops) kasvatus. Ruokavalion muuttaminen monipuolistamalla hiilihydraatti- ja proteiinilähteitä paransi tuotannon kannattavuutta ja vähensi kausittaista naistyövoiman tarvetta. Puutavaran maksimaalista tuotantoa tavoiteltaessa optimaalinen osuus puuviljelmien osuus maa-alasta oli 57 %, kun samalla tuotettiin riittävä määrä ravintoa paikalliselle väestölle.

Avainsanat: Maankäytön suunnittelu, *Pinus* spp., *Eucaliptus* spp., Lineaarinen ohjelmointi, kasvumallit, Umbundu-maankäyttösysteemi (ULUS)

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Finally, thanks to all my family, including aunts, uncles, cousins, but most special to my parents, Maria and Cristòbal, and my sister Juana.

LIST OF ORIGINAL ARTICLES

This doctoral thesis is based on the following five articles, which are referred to in the text by the Roman numerals I-V. Articles I to V are reproduced with the kind permission of the publishers.

I Delgado-Matas C., Mola-Yudego B., Grittens D., Kiala-Kalusinga D., Pukkala T. (2015) Land use evolution and management under recurrent conflict conditions: Umbundu agroforestry system in the Angolan Highlands. Land Use Policy, 42: 460-470.
doi: 10.1016/j.landusepol.2014.07.018

II Delgado-Matas C., Pukkala T. (2010) Growth models for *Pinus patula* in Angola, Southern Forests: a Journal of Forest Science, 72(3-4): 153-161.
doi: 10.2989/20702620.2010.547267

III Delgado-Matas C., Pukkala T. (2013): Growth models based on radial increment observations for eight pine species in Angola, Southern Forests: a Journal of Forest Science, 75(1): 19-27. doi:10.2989/20702620.2013.743766

IV Delgado-Matas C., Pukkala T. (2015) Growth models for six *Eucalyptus* species in Angola. Southern Forests: a Journal of Forest Science, 71(1): 1-12.
doi:10.2989/20702620.2014.984266

V Delgado-Matas C., Pukkala T. (2014) Optimisation of the traditional land-use system in the Angolan highlands using linear programming, International Journal of Sustainable Development & World Ecology, 21(2): 138-148.
doi: 10.1080/13504509.2013.863238

Cristobal Delgado-Matas was primarily responsible for the study design, execution, data analysis and writing of all papers. In all papers, data analysis was performed together with Prof. Timo Pukkala. In paper I, the other co-authors contributed by commenting the manuscript.

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1. INTRODUCTION

1.1. Land use changes in Angolan Highlands

Angola is in the process of recovering from 30 years of exhausting civil war, and natural resources and resource management play a pivotal role in this rehabilitation and reconstruction process. The Angolan highlands have been one of the most densely populated areas in the country since early colonial days (Pössinger 1973). During the colonial rule, about 1.96 million people lived in the area, including 150,000 European settlers. While Europeans, mostly colonial authority officials, business leaders and farm owners lived in the urban centres, Africans mostly remained as subsistence farmers in the rural areas. Just before the independence, most of the country's arable land was under European colonial farm regimes, while around 1.7 million ha of small farms remained under traditional land uses (MIAA 1971). When independence came in 1975, most of the European settlers fled the region. The former colonial farms remain mostly unproductive, and some have been grabbed by political and high administrative officials (Pacheco 2005).

At present, cultivated land is limited to traditionally-farmed Umbundu land. The former colonial farms remain uncultivated. There is a handful of tree plantations covering around 100,000 ha and native forest patches in the remote mountain ranges (Delgado-Matas and Pukkala 2011). The military conflict during 1961 to 2002 drove mass migrations from rural areas to the region's urban centres and coastal cities, including the capital Luanda. This exodus created strong commercial ties between the highland region and the coastal economic centres (Delgado-Matas and Pukkala 2012). The highlands are currently home to around 2.86 million people, mostly from the Umbundu ethnic group, of which 48.7% live in rural areas (INE 2012).

Diamonds and especially oil are the most profitable resources of the country. With a daily production of close to 2 million barrels, oil production is the main economic sector of Angola, which ranks the second highest producer in the South-Saharan region after Nigeria (VAM 2005). However, instead of increasing population-wide social welfare, the profits from these resources have only widened the social and geographic disparities in the country (FAO 1996). The agriculture sector could play the role of capital redistribution, especially in rural areas, while also increasing exports. Timber, agriculture products such as corn, sugar cane and soya beans, and fresh products for local markets are among the main opportunities for the agricultural sector.

The Central Highlands were traditionally the breadbasket of Angola, producing corn, beans, wood, and vegetables (Diniz 1973). Then, the demand for timber and other forestry products increased, pulled by a booming building sector in the urban centres. At the time of independence, November 11 1975, Angola was one of the main African exporters of agricultural commodities, especially coffee (3rd-biggest producer worldwide), sisal, sugar and corn. Before independence, agricultural production was structured into commercial and traditional farming (CARE 2004). Commercial farming, ruled by Portuguese and German descendants, produced the main export goods. Traditional farming runs by local communities with strong support from rural extension services produced food for the internal market but gained importance also in the export economy. This system was supported by an agricultural research network (Silva 1971). Over the last 30 years, hindered by years of war and mismanagement, Angolan agriculture, especially in the Highlands, slumped to a point where it no longer covers the primary needs of the populace. With the consolidation of the peace process, solid steps have been taken with the promulgation of a new Land Law and reactivation of the agriculture schools (FAO 2009).

Angola was home to Africa's largest exotic plantation forest area — about 150,000 ha composed mainly of *Eucalyptus saligna*, *E. grandis*, *E. rostrata*, *Cupressus lusitanica* and *Pinus patula* (FAO 1996). During late years of colonial time, forestry held promise as a fast-growing industry, with the Angolan highlands considered an emerging area for plantations. Angolan forestry was based on importing technical knowledge from neighbour countries, and yields tables for *E. saligna* were developed by colonial researchers. The initial spacing of plantations was 1100 to 2000 trees per ha without subsequent clearing or thinnings. Management consisted of two to three coppice regimens for *E. saligna*, with 7 to 10-year rotations. *P. patula* was managed with longer rotation lengths, 25 to 35-years, with limited clearing and no thinning (Silva 1971). Yields and growths were estimated, not measured, at 10–20 m^3 and 20–40 m^3 per ha per year for pines and eucalypts, respectively (FAO 1996). The lack of systematic analysis and modern management and planning tools was stated by the colonial authorities and it is a legacy of the post-independence instability period when Angola succumbed to military conflict.

The economic importance of fast-growing tree species as a source of pulp, timber and firewood in the intertropical belt has been widely studied. Most studies have focused on predicting the yield of eucalypt and pine plantations. Like in Angola, many of the methods available for tropical plantations are based on yield tables. Yield tables have been developed for pure and even-aged plantations and coppice rotations but they fail to portray the actual growth of a particular stand and, more critically, they are unable to predict the effects of alternative silviculture and harvesting options. Yield tables used in Angola generally come from neighbouring countries such as South Africa (Bredenkamp and Loveday 1984; Kotze and Vonck 1997; Dye 2001; Louw and Scholes 2002; 2006; Kotze and Malan 2007), Kenya (Alder 1977; Tennent 1990; Ngugi 1996), Tanzania (Klitgaard and Mikkelsen 1975; Alder 1979; Pikkarainen 1986; Isango 1994; Malimbwi and Philip 1999) and Zimbabwe (Crockford 1995). *P. patula* has been the most intensively investigated species. There are also reviews covering Southern Africa in general (Pukkala and Eerikäinen 1999; 2000; Pukkala 2000), focusing on *P. oocarpa* (Changala and Gibson 1984; DFSC 2003), *P. kesiya* in Zambia and Zimbabwe (Saramäki 1992; Crockford 1995; Heinonen et al. 1996; Miina et al. 1999; Eerikäinen et al. 2002; Eerikäinen 2003), *P. oocarpa* in Kenya and Zambia (Changala and Gibson 1984; Heinonen et al. 1996), and *P. michoacana* (Heinonen et al. 1996), *P. elliottii* (Poyton 1979; Pienaar and Harrison 1989; Zwolinski et al. 1998) and *P. greggii* in South Africa (Dvorak et al. 1996). Eucalypts have also been well studied in the wider region. Tennent (1990), Shiver and Brister (1992) and Fonweban and Houllier (1997) developed a growth model for *E. saligna* growing in Kenya and the Cameroon highlands, while Saramäki and Vesa (1989), von Gadow and Bredenkamp (1992), Madvurira and Miina (2002) and du Plessis and Cotze (2011) modelled the growth of *E. grandis* in Zambia, South Africa, Zimbabwe and Swaziland. However, there has been no in-depth research on the Angolan plantations, and consequently no modern tools are available to improve analytical decision support in forest management.

In a post-conflict context, new rural development rehabilitation plans are under discussion. As most of the technical references are still based on colonial data, Angola faces a big risk if it attempts to design rural development programmes based on land-use planning from the colonial era. Thirty years of war have changed the conditions that made this schema effective, creating the need to design new land use planning strategies and policies.

On the other hand, information and experience acquired before the conflict is still important for the current development phase. Integrating that information with modern planning methods makes it possible to design new land use strategies according to present-day conditions. One such method is linear programming (LP). LP is a widely used methodology for analyzing land use and natural resource management alternatives (Buongiorno and Gilles 2003). LP has been widely used for optimizing forest management (Dykstra 1984; Pohjonen and Pukkala 1994, Buongiorno and Gilles 2003). However, LP models have also been developed for land-optimized allocation in agriculture and forestry in Finland and Southern Africa (Pukkala and Pohjonen 1990; Muchiri et al 2002).

LP is an easy and flexible method for assessing different ways of using limited resources under variable objectives and constraints. It presupposes that each production alternative, called an activity, is described by parameters used as objectives or constraining variables. These variables include the inputs and outputs of the production process. It is assumed that the utility of the decision-maker depends on the objectives and the constraining variables (Dykstra 1984; Vanclay 1994).

Land use in the Angolan Central Highlands needs based on the fact that optimal allocation of land for arable crops, grazing and forests is related to the proportions of different site fertility classes. Another factor to consider is how food, grass and tree crop growth varies with changes in soil fertility. Land allocation also depends on the species composition of crops, trees and livestock growing or grazing in the area. On other hand, the design of the land use planning system will hinge on integrating local traditional communitarian agricultural knowledge (Chambers 1992; 1995). The population living in the area has requirements that translate into the objective of obtaining maximal income and constraints for ensuring that the land produces enough food, fuel wood and construction timber while also sustaining a fixed amount of livestock for draught and transport power, meat and hides (Pukkala and Pohjonen 1990).

1.2. The Umbundu system

The Umbundu people are originally an amalgamation of ancient pre-Bantu peoples and Bantu migrants. The ethnic group, primarily hunter-gatherers, flourished economically as slave and rubber traders during the 16th to 19th centuries (Edwards 1962; Childs 1969). When the rubber trade collapsed in 1912, the people quickly became cash crop farmers, producing maize and, later, beans, vegetables like garlic, potato, cabbage and onion, and coffee. Production grew fast during the few years before independence (Pössinger 1973; 1986; Morais 1976). The Umbundu continued with cash-crop production, and from the 1920s, many rural people became workers on European farms (Neto 1999; Pacheco 2005). During the last decades of the colonial rule, majority of exportable goods and all fresh products were produced in the small peasant Umbundu plots (MPA 1961; MIAA 1971; Feio 1998; Pacheco 2005).

Cultivation typology in the Umbundu catena

In the Umbundu catena, cultivation varies according to position in the slope (Fig. 1), nature of the field, and human interaction. The whole system can be divided in three main units: the Onaka in lowlands and depressions, the Ongongo or highlands, and the Ombanda situated in the intermediary (Morais 1976). These zones are composed of one or more fertility classes and types of fields (Fig 1).

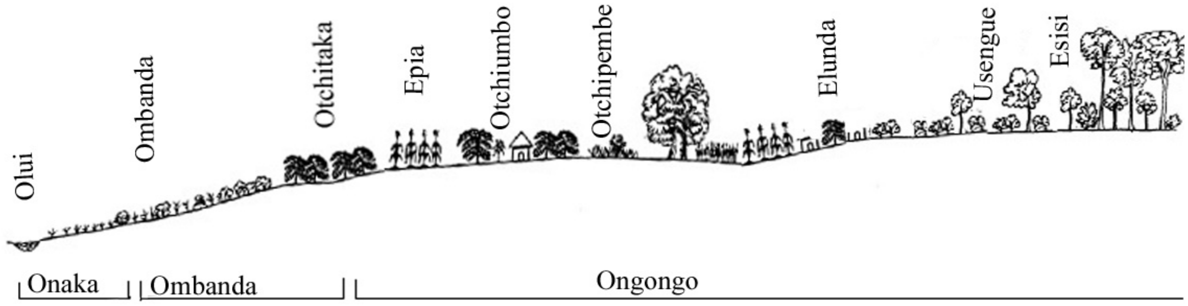


Figure 1: Umbundu catena showing the main site classes.

In the Ongongo, Epia (plural: Ova-pia) is the most abundant site class. It is found over ferralitic soils and some low-fertility paraferralitic soils. Fertility is recovered by fallowing for 15 to 25 years after 5 to 7 years of cultivation (Silva and Morais 1973). The soils are well drained with no irrigation possibilities, and usable only during the rainy season. When the so-called small dry season in early February lasts longer than two weeks, production in these areas is seriously affected (FAO 2006). Poor Epia accounts for the largest cultivated area. Family decides about the use of Epia sites. The main uses are subsistence and cash crop cultivation, and in both cases maize is the main crop. After the harvest, the field is pastured by communal cattle as a community use, which is extended to all the other pastoral plots.

Otchiumbo (plural: Ovi-umbo) fields are small cultivated areas located close to the households. These fields are well drained without irrigation possibilities. They are characterized by their artificially-increased fertility. All human waste is used as manure to increase the naturally poor fertility of the previous Epia soils. Tenure or decision making power on land use in this plot type belongs principally to the family. However, in a few cases it was found that land tenure belongs to the traditional authority, the elders' council. The main crop output is for subsistence, except for tobacco which is traditionally used as currency. Women do almost all the work in Otchiumbo fields (Morais 1976).

Elunda (plural: A-lunda) is a former village abandoned for various reasons, usually epidemic, war, or soil depletion. Former Otchiumbo land still conserves some of the human-induced fertility. Tenure is the same as in Otchiumbo. The main crops for cash purposes are grains and beans. When Elunda soils become exhausted, they enter the same fallow system as the Epia fields.

Otchipembe (plural: Ovi-pembe) is a term used for agriculture areas of exhausted soil. Otchipembe fields are actually cultivated plots of Epia that have entered a fallow period. The Otchipembe area is covered by grass, *Hyparrenia* spp, and some small bushes that survive the cultivation activities. These fields are mainly owned by individuals, belonging to the previous Epia´s owner, but in many cases, when free land is still available, Otchipembe go to communitarian ownership. The main use is for grazing community cattle and as a source of medicinal products.

Esisi (plural: A-sisi) corresponds to forest, usually native miombo forest in an earlier or latest regeneration stage. In general, Esisi sites can be broken down into the Usengue (plural: Ovi-sengue), which corresponds to bush land, and the proper Esisi, which corresponds to high forest. Tenure belongs to the community, and the traditional authority 'Soba', or elders´ council, decides on its conversion to other uses. The main use of Esisi is for providing charcoal, fuel wood, medicines, fruits and mushrooms for family subsistence and commercial gain.

Ongongo and Ombanda feature another sites type, called Otchitaka (plural: Ovi-taka). Otchitaka is characterized by medium-to-high fertility paraferralitic soils. This fertility is supported not only by natural initial conditions but also by manure and artificial fertilizers when available. The soils have sufficient drainage and need a water source for irrigation, usually a spring or river derivation channels. Tenure and decision-making processes are individual and can become a source of rural conflicts if water is scarce (Gritten et al. 2012). The main use is cash-crop production, especially vegetables such as carrot, garlic, cabbage, onions, potato and paprika, with zoned specialization. Mainly men work in Otchitaka cash-crop fields, but women also collaborate.

Ombanda (plural: Olo-mbanda) is situated in slopes close to a river or depression. The soils, usually paraferralitic or in transition to dark hydromorphic soils, are fertile and moderately drained. Uses and tenure are similar to Epia, except that productivity is higher due to the soil's higher fertility and better water retention capacity.

Onaka (plural: Olo-naka) occupies lowlands close to the water lines (Olui). These areas are flooded during the rainy season accumulating rich soil river deposits. During the dry season, the river level descends and the land becomes available for agricultural use for three or four months. The mainly hydromorphic soils with high nutrient content presents serious drainage problems. To combat this problem the Umbundu people repair drainage channels at the beginning of each long dry season to extend the use of the site as long as possible. Nutrient re-deposition occurs naturally each year with the annual floods. Tenure of the Onaka is remarkably individual, and each family of the village usually has at least one Onaka plot. Mainly used for subsistence, this land is worked by women, except the opening of the drainage channels which is done by men. Onaka surface area is small, with each individual parcel being less than 300 m², but at the same time all the usable land is under cultivation. Onaka fields are critically important since they are the only provider of subsistence products. They are also used to produce small amounts of cash crops.

1.3. Fallowing in the Umbundu system

Fallowing is used in the Umbundu system to increase fertility and combat weed (Sanchez et al. 1997; Nair et al. 1999). Sites used as fallow have low fertility, i.e., Epia and Elunda and sometimes also Ombanda. Otchipembe and Esisi are site types that are under fallow. The general configuration of Epia is a traditional long woodland fallow that has some modifications depending on land availability. The fallow cycle can be subcategorized according to the duration of the fallow period and forest, as well as shrub or grassland use during the fallow phase (Silva and Morais 1973).

Originally, the agriculture period begins after the original miombo forest was slashed and burned. The fallow period starts after 4 to 15 years of cultivation. The fallow period is first considered as Otchipembe, which translates to poor land. Otchipembe land may be covered by grass and small shrubs for 2 to 15 years. If natural regeneration is not interrupted, the site is considered Usengue when shrubs and small miombo trees occupy the area. If natural regeneration is left to continue, the natural miombo woodland is harvested and the cultivation period can start again. This case represents the more traditional pattern where the whole process needs more than 25 years to complete. This system needs large areas and is not compatible with high population density. Under increasing population the cycle is shorter, with the cultivation period beginning in Usengue or Otchipembe, which means lower soil fertility recuperation (Morais 1976).

1.4. Planning and decision-making process in the Umbundu system

The Umbundu land use decision-making process is strictly linked to the land tenure regime. The international literature considers that land management is related to the system that defines rights and obligations with respect to the acquisition and use of land in agriculture settlement. There are four major issues concerning land tenure: i) whether to allow individual holdings of arable land or use collective methods of farming; ii) whether to grant permanent ownership rights or only use rights; iii) whether to allow market sale and rental of land or to constrain land transactions; and iv) if land sales to outsiders are unrestricted, whether or not to issue land entitlement (Kinsey 1983; Binswanger and Deininger 1993; 1997; Binswanger et al.1995).

The “formal” Land Law based on European regulations and European framing tradition had been considered to be the paradigm for natural resource management in the Angolan Highlands under the Portuguese colonial rule (Pacheco 2004; 2005; Almeida 2005). The colonial regime used the system to provide European metropolis with farmed raw material as the main concern, as it considered traditional African agriculture and its management rules as unproductive, obsolete and suitable only for subsistence purposes (Fourie 1997; Matemane 1997; Galan 2006). This approach ignores the significance of different conceptions of land ownership and use in the laws and customs of African and settler communities (Klug 1995; 1996). Van Zyl et al. (1996) for South Africa and Pacheco (2004) for the Angolan Umbundu system showed that African family farming based on customary management systems was viable and successfully responded to the increased demand for agriculture products during the early days of colonization in the 19th and 20th centuries. This rise of African commercial farming took place under conditions of relative land abundance and weak and ineffective government interventions. After independence, Angola remained under Marxist regime where natural resources were nationalized, and customary rules were undervalued. During the 1990s, the Marxist regime was dismantled and substituted by a global capitalist economy, but concern for African customary rules has not evolved (Migot-Adholla et al. 1991). Land legislation has only recently included issues pertaining to respecting customary rules, but Land Law is still essentially based on “formal” approach, supporting and promoting the dualistic agriculture structure (Hulme 1988; Birgegard 1993).

The 'diffusionist' theory maintains that traditional institutions play a negative role in the development of rural areas. As affirmed by Muela (2000), traditions and customs, if they relate to land or any other natural resource of social or economic importance, are thought of as backward and a barrier to entrepreneurial behaviour as a vector of improvement aimed at developing agriculture and rural areas.

Along these lines, the liberal theory considers that the tenure reform has to be oriented in a way that privileges the individualization of land rights or recognizes so-called ‘fully-developed’ property rights. Fully developed property rights entail land being privatized to turn it into a commodity. Havnevik (1997) and Adams (1995) believe that such a tenure system will facilitate agricultural development especially where commercial agriculture has significantly developed. Also, transfers in land rights will then be easier for more dynamic farmers, thus leading to enhanced security of tenure and stable investment growth while at the same time providing stronger arguments for credit and new investment.

Taking a different stance, the 'Afro-eternalist' theory suggests that long before the colonists arrived in Africa, the land tenure systems in place were well-adjusted and thus resilient to colonial abuses. In customary systems, land is considered a communal resource upon which every community member has certain rights. According to Muela (2000), land tenure regimes contribute to the harmony of African societies and promote the homogeneity of their social structures. Following this approach, the organizational principles underpinning land matters legislation in an African context have to integrate customary systems.

Finally, the 'evolutionist' theory puts forward reasons demonstrating that these systems have already provided evidence of important changes. Indigenous systems evolve towards individualization, with access to land being deeply rooted in social relations and bearing symbolic meanings when it is transferred under contract to more productive farmers in a more commercially-driven agriculture framework. Furthermore, higher income groups find that land purchases offer attractive investment opportunities without necessarily implying effective use of the land (Kuper and Kuper 1965; Adams 1995; Havnevik 1997).

The Umbundu system has shown a dynamic evolution, highly influenced by Portuguese-imported land law and other formal rules, with many customary principles falling into disuse. Although there are signs that decisions on most plots have started to be taken at individual and family level, woman still have little decision power. Costs and incomes are still considered in a transition phase from subsistence to market-oriented agriculture. Some sunk costs and opportunity costs are overestimated, while the value of woman or family-based labour is underestimated and not considered as cost.

1.5. Objectives

Simulation and optimization, including forest stand development under different management possibilities, are useful tools for modern land-use management planning. Yield and growth models can be used to support decisions on land use, test different alternatives, and find land use options that best meet the objectives of decision makers. The Umbundu land-use system in the Angolan Highlands has been managed based on traditional knowledge but without a clear vision from the decision makers on its importance. The area lacks of a set of models to allow simulations to be run and find the optimal management configuration for agriculture and forestry uses. In addition, there is a lack of tools to evaluate the sustainability of the present system, or evaluate unsustainable land use as a potential source of conflicts. Therefore, it is important to develop a better understanding of the agro-forestry land-use practices in Angola. The scope of this study is the Central Angolan Highlands but the findings can be applied to highlands areas in the inter-tropic regions on South America, Africa and Asia. The hypotheses of this study assume that the nature and dynamics of these conflicts determine the development of the Umbundu Land Use System. Understanding these dynamics and modelling the alternative production systems contribute to optimize the traditional laud use system. The models allow generate scenarios, compare them, defining their trade-offs, potential dynamics and future conflicts. The objective of this study was to characterize the Umbundu system, develop growth and yield models for the main species used in community forestry (i.e. pines and eucalypts) and optimize land use in the Angolan Highlands where forest fallow is an integral part of the land use system.

The specific objectives of this dissertation were as follows (I-V refer to the sub-studies of the thesis):

I) Analyse the characteristics of the Umbundu land use system, stressing its adaptation to the area’s changing socio-economic context. This analysis examines the development of land use systems in the region and identifies potential sources of environmental conflicts inherent to the system.

II, III, IV) Develop individual-tree growth models for the most important pine and eucalypt species under Angolan Central Highland conditions. The pine species were *P.patula, P.chiapensis, P. devoniana, P. elliottii, P. greggii , P. kesiya, P. montezumae , P. oocarpa, P. pseudostrobus,* and the eucalypts were *E. saligna*, *E. camaldulensis*, *E. macarthurii*, *E. resinifera*, *E. siderophloia*, *E. grandis*.

V) Optimize land-use in the Angolan Highlands, considering changes in diet and forestry production alternatives to compare with the existing situation. Study V also analyses in the importance of gender labour roles and seasonal jobs for traditional land-use patterns.

Figure 2 shows the research scheme. Study I characterized the Umbundu land use system and inventoried and analysed its major dynamics and key conflicts. Studies II, III and IV used past growth measurements to build growth and yield models for even-aged plantations of the pine and eucalypt species most widely used in southern Africa. The final stage (Study V) was to develop a land use optimization system for agroforestry uses under the Umbundu land use system. Different scenarios were optimized to illustrate alternative development policies.

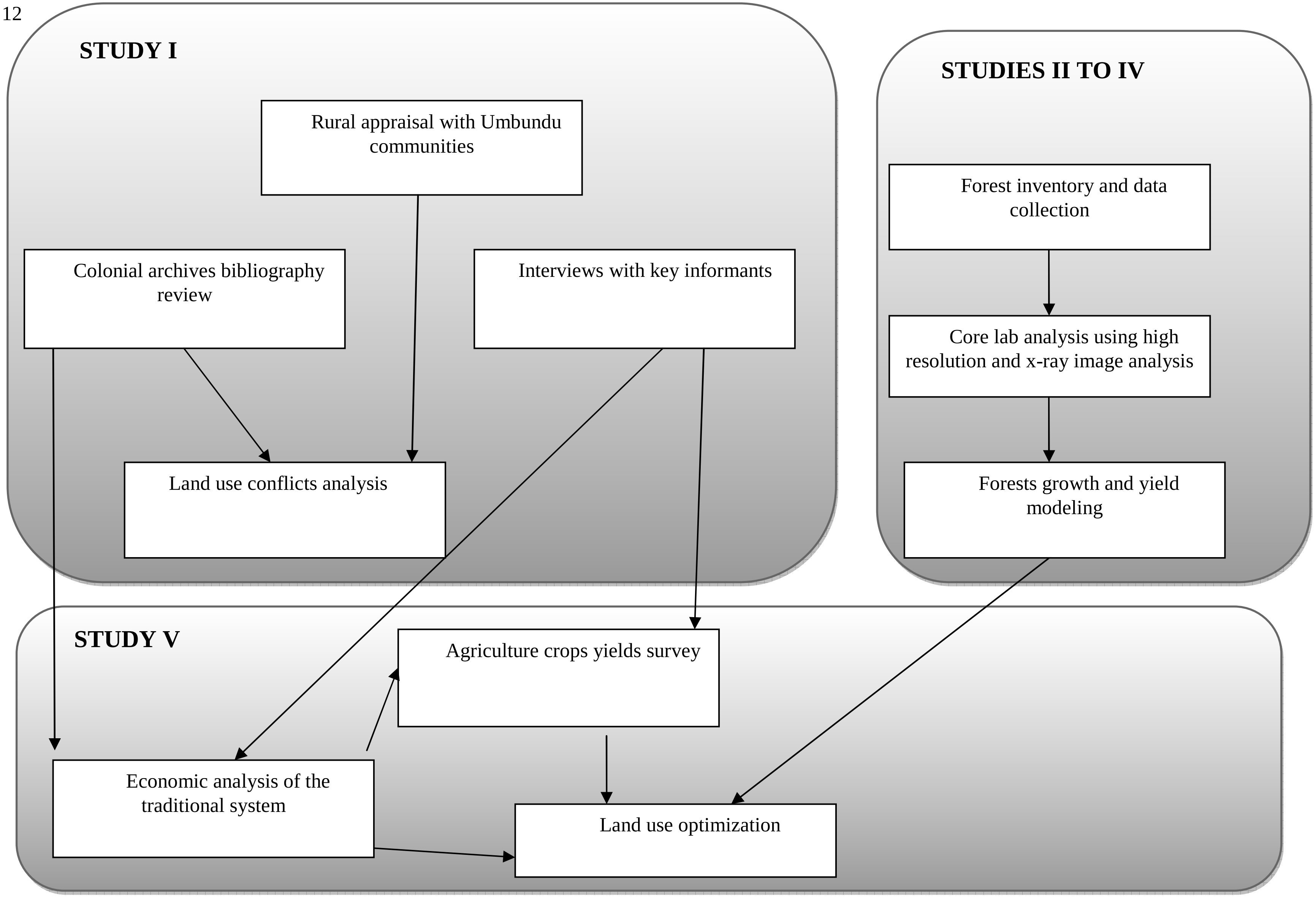


Figure 2: Study scheme showing the successive research steps

2. MATERIAL

2.1. Study area

The study area is located in the Central Highlands of Angola (Fig. 3), situated in the southern African miombo forest region (MIAA 1971; Diniz 1973; 1998). This area covers 7,904,000 ha of flat plateau crossed with valleys and low hills with an altitude of up to 1500 m. Annual precipitation varies between 1100 and 1400 mm. Soils are mainly acidic (pH 5.5–6.5) and have a low nutrient content (Diniz 1973; Delgado-Matas and Pukkala 2012). During the colonial period, the area was densely populated, and inhabited by a third of Angola's rural population. Before the independence of Angola, the region was considered the breadbasket of the country, producing exportable amounts of corn, beans, coffee, manioc and vegetables (MIAA 1971; Delgado-Matas and Pukkala 2011). Eucalypt and pine plantations were established in the region for the local cellulose industry (see Sampaio 1966; Silva 1971). However, following independence, the population was decimated during the 27 years of civil conflict (Pacheco 2004).

2.2. Data origins for Studies I and V

Data were collected to analyse land use patterns, identify conflict typologies and land use constraints, and quantify the revenues, costs, yields, inputs and outputs of alternative production systems. Data collection was organized into three steps. The first step included a systematic review of the technical and scientific colonial documents as well as publications of non-governmental organizations (NGOs) and development agencies. The second step included interviews with rural development officers from state and non-state organizations as well as with different actors, including farmers, community elders and local administration officials. The third step involved field research in different communities in the area. A participatory appraisal was conducted according to FAO (2000) methodology on land uses and the pertinent decision-making processes in 33 rural Umbundu communities located in the province of Huambo. Weekly price checks were carried out over 6 months in the local markets for all the agriculture crops and forestry products. Additional 83 interviews were done with key informants during the period January 2005 to December 2007.

2.3. Data for Studies II, III and IV

The data for tree growth modelling were collected from several forest plantations, including a species introduction experiment established by the Portuguese colonial technicians at the Tchianga Research Station. The species introduction experiment included 31 well-preserved rectangular 306–1031 m² plots with 9 pine and 6 eucalypt species. Three additional 756 m² rectangular plots in three locations were measured for the most commonly planted pine species, *P. patula*, and 12 rectangular plots of 540–1,296 m^2 in six additional locations for the most commonly-planted eucalypt species, *E. saligna*. Diameter at breast height (dbh) was measured on all trees in the plots, and height and bark thickness were measured on 12 trees per plot covering the whole range of tree sizes present in the plot. Three sample trees were selected from among the dominant trees, three from the smallest trees, and the remaining six from medium-sized trees. Five-mm thick radial cores were taken with an increment borer from all eucalypts in the Tchianga experiment and from the fastest growing pine species (*P. patula*, *P. chiapensis*, *P. devoniana*, *P. elliottii*, *P. greggii*, *P. kesiya*, *P. montezumae*, *P. oocarpa*, *P. pseudostrobus*), and every second tree of the remaining pine species was bored to measure radial growth (Table 1, Table 2).

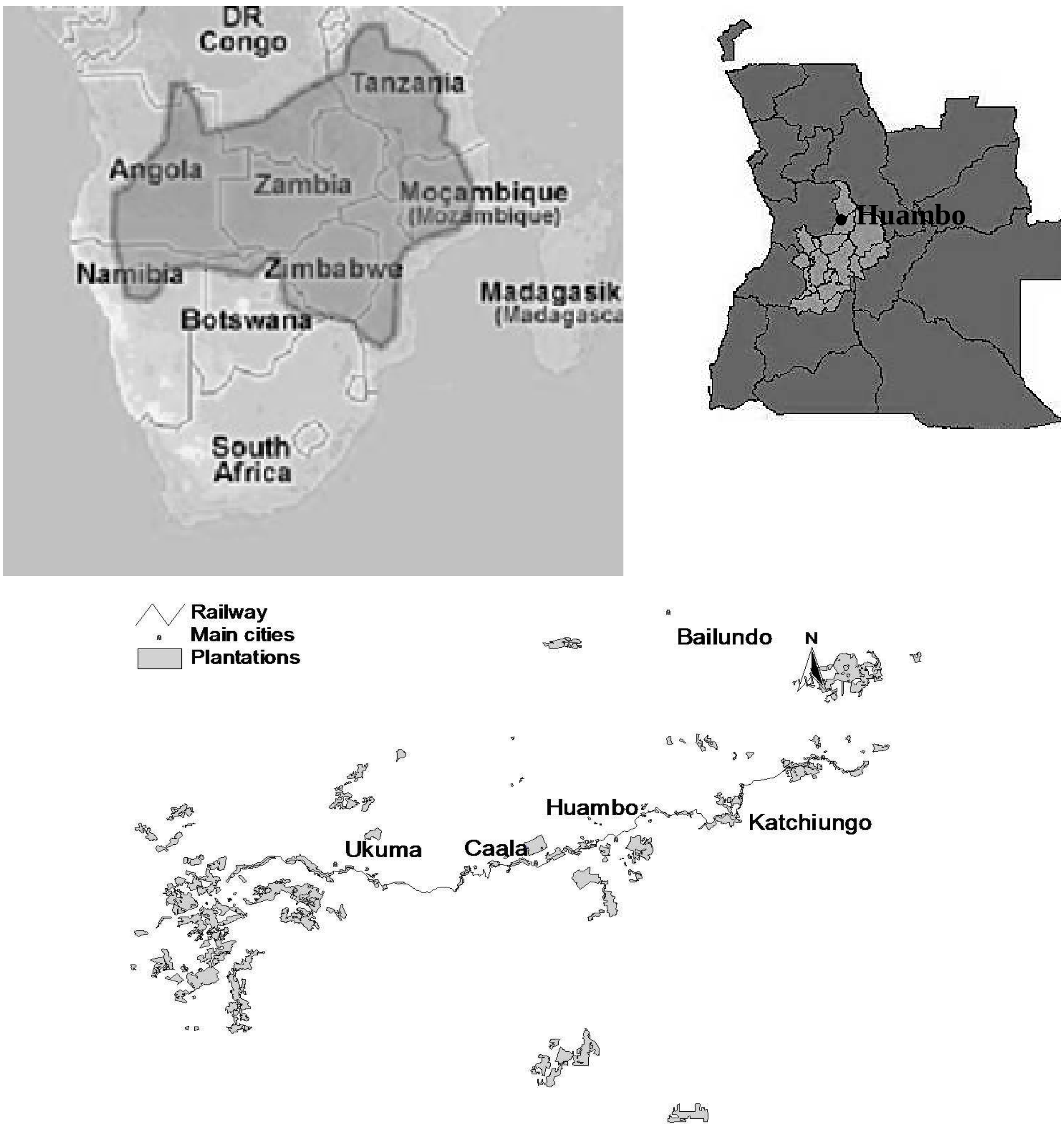


Figure 3. a) Extension of miombo (dark) in southern Africa according to Abdallah and Monela (2007) Imagery © 2013 TerraMetrics, Map data © 2013 AfriGIS(Pty) Ltd. Google. b) Location of the Angolan Highlands in the Republic of Angola. c) Location of the plantations in Huambo province in Angolan Highlands.

The first step of data preparation was to fit a plot-wise model for tree height. This model was used to calculate the height of those trees for which height was not measured. The model was as follows:

$$h = 1.3 + d^2/(a+b \times d)^2 \quad (1)$$

where h is tree height (m), d is dbh (cm) and a and b are estimated parameters.

A species-specific model was fitted between bark thickness (*bark*, mm) and diameter (d, cm). The bark model was as follows:

$$Bark = a_0 + a_1 d \quad (2)$$

This model was used to calculate the bark thickness of all the trees. The calculations assumed that $(d-2 \times Bark)/d$ ratio (underbark/overbark diameter, referred to hereafter as u/o ratio) had been constant for the whole life of the tree.

The increment cores of pines species were taken to the lab to be photographed. The widths of the annual rings were measured from digital photographs using ESRI ARC GIS ® software.

As increment rings were not visible on eucalypt species, data preparation consisted of x-ray analysis. The eucalypt cores were air-dried and scanned with a high-resolution x-ray device, the Itrax ® x-ray densitometer (Cox Analytical Systems, Gothenburg, Sweden). The Density software program (Bergsten et al. 2001) was used to measure annual rings and create a radial increment data file. For all species, the aim was to measure all the annual rings from each tree. However, this was not possible in practice, since some cores did not hit the pith. Some other cores were broken during transport to the laboratory. Therefore, there were some missing radial growths at both ends of some increment cores, i.e. both near the pith and near the bark. Since the purpose was to reconstruct the whole growth history of the stand, which required knowledge of the annual growth of each tree, a linear model was fitted between overbark dbh and the underbark radial growth the previous year, separately for each year and plot. These models were used to calculate the radial growth of the previous year when it was not available as a measurement. The model was as follows:

$$i_{rt-1} = a_t + b_t \times d_t \quad (3)$$

where d_t is overbark dbh at the end of year t (cm) and i_{rt-1} is the underbark radial growth of the previous year (cm).

Using the measurements and the above models, individual tree and stand dimensions for the previous year were calculated as follows:

- Multiply over-bark diameter by the u/o ratio to obtain under-bark diameter;
- Subtract the doubled radial growth (measured or predicted) from under-bark diameter to obtain under-bark diameter one year ago;
- Divide the under-bark diameter by the u/o ratio to obtain over-bark diameter one year ago;
- Calculate 1-year over-bark diameter increment as the difference between current dbh and dbh one year earlier;
- Subtract one year from current tree age to obtain tree age one year ago; and
- Calculate stand characteristics (basal area, mean diameter, etc.) using tree dimensions from one year ago.

The same process was repeated until a young sapling stand state was reached. This back-tracking process resulted in a dataset for modelling future diameter increments (Tables 1 and 2). Only those observations in which the diameter increment was based on measured radial growth were used observations in modelling. The predicted radial growths were only used to back-track the temporal development of stand characteristics and other potential predictors of the diameter increment model, such as the basal area of larger trees.

The total pine dataset consisted of 19,388 annual ring measurements. Total number of annual rings in the inventoried trees was 38,259 (779 trees x 41 years + 155 trees x 34 years + 105 trees x 10 years = 38,259), which means that about 51% of the annual rings were measured. The total eucalypt dataset consisted of 10,449 annual ring measurements. Total number of annual rings in measured trees was 26,311 (185 trees x 43 years + 116 trees x 42 years + 335 trees x 36 years + 37 trees x 14 years + 21 trees x 12 years + 109 trees x 6 years = 26,311), which means that about 40% of all the annual rings were measured. .

Table 1. Number of observations and plots, and statistics for some variables in the data for modelling the diameter increment of pines.

		P. patula	*P. pseudo-strobus*	*P. kesiya*	*P. devoniana*	*P. chiapensis*	*P. elliottii*	*P. greggii*	*P. montezumae*	*P. oocarpa*
No. of obs.		7,656	4,049	2,744	511	506	937	1,582	478	905
No. of plots	Yield[1]	8	3	3	1	1	2	3	1	2
	Height[2]	8	3	3	1	1	2	3	1	2
Age, year	min.	10	41	41	41	41	41	41	41	41
	mean	18.3	41	41	41	41	41	41	41	41
	max.	41	41	41	41	41	41	41	41	41
	SD	10	0	0	0	0	0	0	0	0
Dominant height, m	min.	15.2	33.7	34.6	33.7	33.1	29.4	24.4	32.5	28.6
	mean	30.0	37.3	37.9	33.7	33.1	29.9	27.3	32.5	29.4
	max.	35.7	43.4	38.1	33.7	33.1	30.4	29.9	32.5	30.1
	SD	7.1	6.3	1.9	0.0	0.0	0.7	2.8	0.0	1.1
Stand basal area, $m^2 ha^{-1}$	min.	0.0	68.2	56.5	58.0	65.8	39.8	37.0	46.8	82.4
	mean	29.4	80.5	75.5	58.0	65.8	44.9	40.8	46.8	83.2
	max.	63.6	94.4	82.1	58.0	65.8	50.0	45.6	46.8	83.9
	SD	14.6	13.1	12.8	0.0	0.0	7.2	4.3	0.0	1.1
Mortality	%	2.5	1.9	2.3	2.2	1.6	2.3	2.6	2.5	1.4
Growth $m^2 ha^{-1} y^{-1}$	mean	20.0	35.0	30.0	20.0	23.0	15.0	12.0	15.0	25.0

Table 2. Mean, range and standard deviation of variables among observations used to model the diameter increment of eucalypts.

		E. saligna	*E. resinifera*	*E. camaldulensis*	*E. macarthurii*	*E. siderophloia*	*E. grandis*
No. of obs.		6,103	1,107	1,435	738	451	615
No. of plots	Yield[1]	11	2	2	1	1	2
	Height[2]	14	2	2	1	1	2
Age, year	min.	6	43	43	43	43	42
	mean	12	43	43	43	43	42
	max.	42	43	43	43	43	42
	SD	12	0	0	0	0	0
Dominant height, m	min.	18.8	42.9	42.5	34.6	31.2	58.3
	Mean	42.9	43.5	42.5	34.6	31.2	62.2
	max.	58.8	44.0	42.6	34.6	31.2	66.2
	SD	11.1	0.8	0.1	0.0	0.0	5.6
Stand basal area, m^2ha^{-1}	min.	0.1	0.2	2.5	2.4	4.8	0.0
	mean	35.9	21.0	16.2	15.7	30.7	18.3
	max.	101.0	36.5	28.5	24.9	53.9	36.9
	SD	22.8	8.7	6.3	6.8	13.1	10.0
Mortality	%	2.1	2.8	3.9	3.9	1.5	2.9
Growth $m^2\ ha^{-1}y^{-1}$	mean	37.0	26.0	15.0	12.0	20.0	25

[1] Number of plots used in growth and yield analyses
[2] Number of plots used for dominant height modelling

METHODS

2.4. System characteristics and conflicts assessment

The initial description and identified main characteristics of the Umbundu system based on the primary information were used for further in-depth investigation. The analysis considered ethnological and socio-economic elements to better understand the system dynamics. The key factor in the data collection and analyses is the long period spent in the field that made it possible to develop trust between the research team and the research targets and facilitate the research. Building long-term relations between communities and the research team makes it possible to get verifiable information and avoid conditioned answers.

Rapid rural appraisal quality analysis tools based on participatory approach was the most common methodology to assess information from communities. Non-structured interviews, participatory mapping, Venn diagram, natural resources matrix and focal informants were the used during the field work. Additionally, colonial archives were analysed.

Due to the variety of the data it was possible to crosscheck information related to the same issue from different sources to eliminate subjectivities and update most of the colonial datasets. All the information was validated at least from two different sources. This was especially relevant in the analyses related to land and environmental conflicts. Geographical information system was used for spatial analysis conflicts mapping.

2.5. Dominant height modelling

The measured or predicted tree heights were used to calculate the dominant height of every plot. Dominant height is defined as the mean height of the 100 largest trees (in terms of dbh) per hectare. For *P. patula*, the ages and dominant heights of all *P. patula* plots were used in modelling. For the remaining pine species, the dominant heights of all pine plots and the dominant heights of 8 additional *P. patula* plots, including young stands, measured in the same region were used to develop a model for average dominant height development (known as the ‘guide curve’). For *E. saligna*, the ages and dominant height of all *E. saligna* plots, including three young stands in Sacaala, Quisala and Kalenga. For the remaining Eucalypts species, the heights observations were used and all *E. saligna* observations added. The Richards-Chapman model had the most logical shape and was therefore selected:

$$H_{guide} = a(1 - \exp(-bT))^{c} \tag{4}$$

where H_{guide} is dominant height (m) and T is stand age (years).

2.6. Diameter increment modelling

Linear regression analysis was used in Studies II, III and IV to model the diameter growth of pine and eucalypt species. The predicted variable was the future 1-year diameter increment *id*. The aim was to develop the following type of model:

$$id = f(\textit{tree size, site, competition}) \tag{5}$$

Tree size was described by dbh, site productivity by site index, and competition by the basal area in larger trees (BAL) and total stand basal area. Due to the hierarchical structure of the data (trees of the same plot were correlated observations), also a mixed model was developed for the eucalypt species:

$$id_{ijk} = f(x_{ijk}) + u_i + u_{ij} + e_{ijk} \tag{6}$$

where id_{ijk} is the diameter increment of tree j of plot i in year k, $f(x_{ijk})$ is the fixed part of the model, x_{ijk} is a vector of predictors calculated for tree j of plot i in year k, u_i is a random plot factor (describing the deviation of plot i from overall growth level), u_{ij} is a random tree factor (describing the deviation of tree j of plot i from overall growth level), and e_{ijk} is the residual (that part of the growth of tree j in plot i and year k that cannot be explained by the model).

Since logarithmic transformation of the predicted variable was used in modelling, a Snowdon (1991) correction factor, i.e. an empirical ratio estimator for bias correction, was calculated for the model, as follows:

$$c = \frac{\sum_i \sum_j \sum_k id_{ijk}}{\sum_i \sum_j \sum_k \exp(y_{ijk})} \tag{7}$$

where id_{ijk} is the measured diameter increment and y_{ijk} is the prediction of the logarithmic model. A prediction of the 1-year future growth (*id*) is calculated as follows:

$$id_{ijk} = c \times \exp(y_{ijk}) \tag{8}$$

For eucalypt species, also Baskerville (1972) and Lappi et al. (2006) correction factors were tested. Corrected predictions were calculated as follows:

$$\text{Baskerville:} \quad id_{ijk} = \exp(y_{ijk} + s_r^2/2) \tag{9}$$

Lappi et al.: $id_{ijk}=(\exp(y_{ijk} + s_r) + \exp(y_{ijk} - s_r))/2$ (10)

where y_{ijk} is the logarithmic prediction and s_r is the standard deviation of the residual.

In Study IV, also a non-linear model for eucalypts was fitted for the non-transformed diameter increment using non-linear regression analysis. Since the predicted variable was non-transformed increment, no correction was required.

2.7. Height modelling

Height measurement data were used to develop individual-tree height models for pines and eucalypts (Studies II, III, and IV). Due to the lack of young stand measurements for most of the species, height models were fitted using combined data for all species of the same genus.

For pines, two types of height models were fitted; one using dominant height as a predictor, and the other without using dominant height. The first type can be used in growth forecasts when the development of stand dominant height is predicted with a dominant height model.

The following model was fitted for the pine species.

$$h = Hdom \times (d/Ddom)^{(b0+(b1+s)\ln(d/Ddom))} \quad (11)$$

where h is tree height (m), $Hdom$ is dominant height (m), d is dbh (cm) and $Ddom$ is dominant diameter in cm (mean diameter of the 100 largest trees per ha). With this model, the height of a tree will be equal to dominant height for a tree with dbh equal to dominant diameter. Trees with dbh less than the dominant diameter will have height predictions that are less than dominant height. The model guarantees that the development of individual tree heights follows the pattern of dominant height development.

For the eucalypt species, the tree height model was slightly different:

$$h = 1.3 + (Hdom - 1.3)\ (d/Ddom)^{(b0+(b1+s)\ln(d/Ddom))} \quad (12)$$

where h is tree height (m), d is dbh (cm), $Hdom$ is dominant height (m), $Ddom$ is dominant diameter (cm), and s is a species-specific coefficient.

2.8. Survival modelling

Studies II, III and IV include equations to account for mortality in pine and eucalypt stands. The measurements do not include temporal mortality data, but knowing the planting density of each plot, N_0, the average mortality rate of each plot could be calculated. This calculated mortality rate then made it possible to gradually return the dead trees to the plot in the backward simulation of stand development. Assuming that annual survival rate is constant, and knowing the remaining number of survivors from the field inventory, N_T, the number of survivors in year, T (N_T), is:

$$N_T = N_0 e^{-kT} \quad (13)$$

Parameter k (average annual mortality rate) can be calculated from N_0, N_T and T as follows:

$$k = (\ln(N_0) - \ln(N_T))/T \quad (14)$$

When back-tracking the development of stand characteristics, it was assume that the most suppressed trees die. Their diameter was assumed to be a weighted average of the minimum and mean diameter of the measured trees in the respective back-tracked year:

$$Dmortality = 0.75Dmin + 0.25Dmean. \quad (15)$$

2.9. Land-use optimization

Study V developed a land-use optimization system for the traditional Umbundu agro-forestry system to support decision making and simulate policy implementation scenarios under Angolan Highland conditions. Linear programing (LP) was used as the optimization method.

LP has been used for general land allocation problems in commercial and traditional agriculture and forestry since the 1950's (Heady 1958). Most of its applications are related to optimizing land use combinations carrying diverse constraints, including agroforestry system optimization with a single objective (Raintree and Turray 1980; Pukkala and Pohjonen 1990; Pukkala 2000). The first step is to identify the objective function and the constraining equations for the system.

The variables used as objective or constraining variables were land expectation value (LEV), net present value (NPV), costs, self-subsistence crop requirements (in tn), draught animal needs (in TLU: Tropical Livestock Unit), carrying capacity (in TLU), forest product needs (in m^3), available area of each site class (in ha) and labour availability by gender (in working days), including seasonal labour peaks. The decision variables were the areas of different production systems. Three different alternatives were optimized under 5% and 10% discount rates: baseline and two alternative strategies. The alternatives were compared with the current situation (baseline), and included changes in basic diet in the self-subsistence agriculture system and transitioning into forestry-based economy.

3. RESULTS

3.1. Land use characteristics and conflicts

The Umbundu land use system can be divided into three main units: the Ongongo or highlands, the Onaka in the lowland and depressions, and the Ombanda situated in the intermediary. In each particular case, the catena can feature a varying number of field types depending on the ecological and socio-economic conditions (Fig. 1). Onaka and Otchiumbo, which are used for subsistence production, are the smallest, averaging less than 100 m^2 in size, while Epia and Otchipembe are the largest, 1 to 2 ha maximum.

Since its origins, the system has evolved under continuous conflicts of varying intensities. In the early days there were tribal wars between Mumuila and Tchoqwe Bantu people searching for new and more fertile land. Under Portuguese occupation, conflicts between European settlers and Umbundu farmers were common. Nationalism and revolutionary guerrilla warfare characterized the Cold War period, followed by civil war in the wake of independence and, more recently, land grabbing by political and economic lobbyists. Throughout these phases, the system continued evolving by diversifying field typologies, adopting new crops and technologies, including new cash crops introduced by European settlers, and shifting gender roles and land tenure.

During each phase the major factors dictating land use allocation were conflict intensity and increasing population. The forest uses, Esisi and Usengue, declined rapidly even before the first colonial settlements, transferring ground to extensive cultivation like Epia and fallow systems such as Otchipembe. New techniques and crops allowed the expansion of cash crop production in most fertile Ombanda and Onaka. European settlers and colonial enterprises established forest plantations, and after seeing these plantations, Umbundu farmers started to include planted forest as fallow in the system. During post-independence period of military conflicts, many areas occupied by Epia went to fallow and forest was allowed to recuperate in the most inaccessible and insecure zones.

Fallowing is an inherent component of the Umbundu system enabling natural fertilization of exhausted cultivated soils. Cattle are necessary as draught power, and thus play a vital role in keeping the system functional. Fallows can be used for grazing in naturally regenerated shrub and wood lands, or plantation forestry, mainly pines and eucalypts. These cycle types diverge in terms of time under fallow, which ranges from less than 10 years when the fallow period includes just short grass and shrub to more than 25 years when it changes into natural forests (Esisi plots) or is used for long-rotation plantation forestry. The cultivation period can run from 3 to 7 years depending on time under fallow and natural site fertility. Crop species also change during the cycle based on their nutrient demands, pH needs and market value. Crops residues are used for cattle grazing after the harvest.

3.2. Growth models for tree plantations

Dominant height models for pines

The model for the average dominant height development (guide curve) of *P. patula* was as follows:

$$Hdom = T^2/(0.867+0.148\,T)^2 \qquad (16)$$

where *Hdom* is dominant height (m) and *T* is stand age (years). The R^2 of the *P. patula* model is 0.950 and the standard error (standard deviation of residuals) is 1.84 m.

For the other pine species, a common average dominant height was developed. The model (guide curve) is as follows (Fig. 4):

$$Hdom = T^2/(0.791+0.154\,T)^2 \qquad (17)$$

The R^2 of the latter model is 0.495 and the standard error is 4.33 m. The site index was calculated considering using 35 years as the index age, which is a reasonable rotation length for pine species in Angola (Melo 1974). The site index of the studied species varied from 26.3 m for *P. greggii* to 37.7 m for *P. kesiya*.

Dominant height models for eucalypts

The Chapman-Richards model was found to be the most logical model for describing average dominant height development of eucalypt species growing in the Angolan Highlands (Fig. 5). It is as follows:

$$Hdom = 47.278\,(1 - \exp(-0.111T))^{1.424} \qquad (18)$$

If the age index was taken as 10 years, which is a reasonable rotation length for short-rotation eucalypt species management in Angola (Silva 1971). The site index of the sample plots of the studied species varied from 17.89 m for *E. macarthurii* to 37.96 m for *E. grandis*.

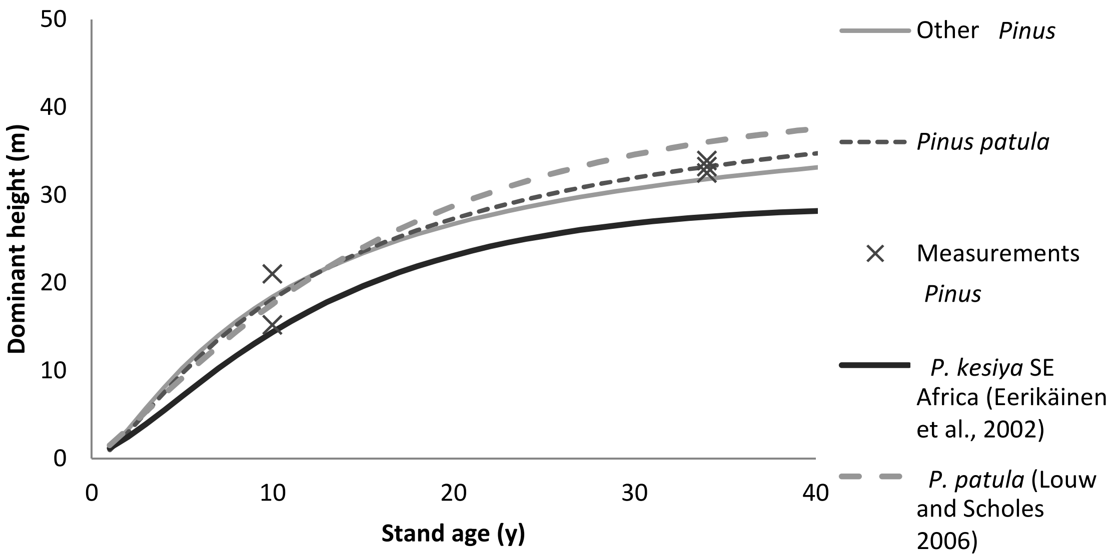


Figure 4. The dominant height models developed for pines in Angolan highlands and the shape of the two other dominant height models.

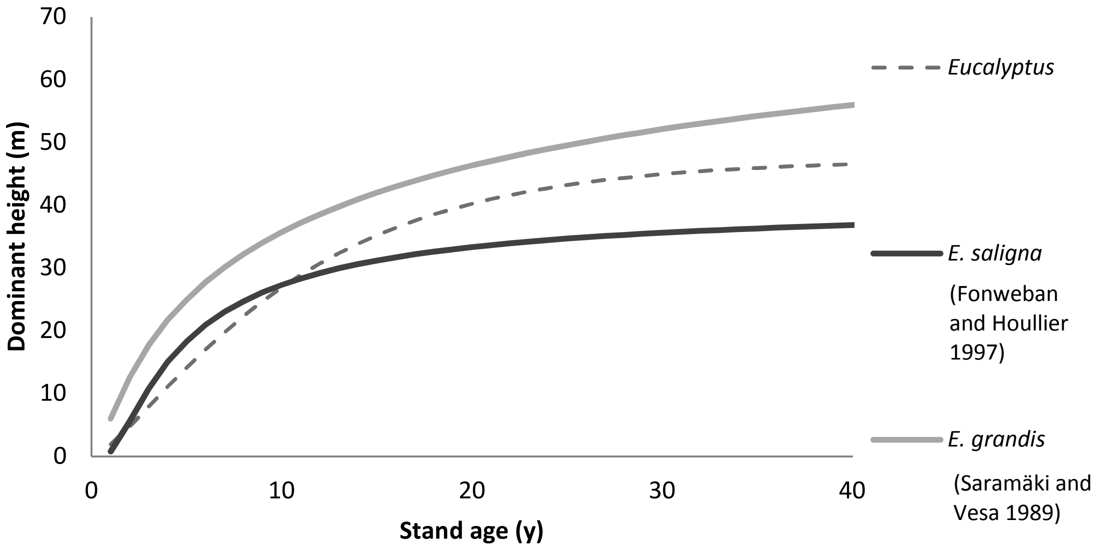


Figure 5. The developed dominant height model for eucalypts and the shape of the two other dominant height models.

Diameter increment models for pines

The models for the future annual diameter increment (cm) for pine species (Fig. 6) were as follows:

P. patula

$$id_{ijk} = 1.113 \times \exp(-1.674+18.880/(T_{ik}+5)+7.087/(d_{ij}+5) -0.0286BAL_{ij})) + u_i \quad (19)$$

P. pseudostrobus

$$id_{ijk} = 1.096 \times \exp(0.829+5.636/(d_{ijk}+5)-0.023BAL_{ijk}-0.726\ln(T_{ik})+0.024SI_i) \quad (20)$$

P. kesiya

$$id_{ijk} = 1.118\times\exp(0.480+6.901/(d_{ijk}+5)-0.018BAL_{ijk}-0.771\ln(T_{ik})+0.029SI_i) \quad (21)$$

P. devoniana

$$id_{ijk} = 1.075\times\exp(2.068-0.035BAL_{ijk}-0.779\ln(T_{ik})) \quad (22)$$

P. chiapensis

$$id_{ijk} = 1.094\times\exp(2.187-0.024BAL_{ijk}-0.859\ln(T_{ik})) \quad (23)$$

P. elliottii

$$id_{ijk} = 1.095\times\exp(-1.530+11.045/(d_{ikj}+5)-0.030BAL_{ijk}-0.513\ln(T_{ik})+0.071SI_i) \quad (24)$$

P. greggii

$$id_{ijk} = 1.147\times\exp(0.892+7.609/(d_{ijk}+5)-0.026BAL_{ijk}-0.611\ln(T_{ik})) \quad (25)$$

P. montezumae

$$id_{ijk} = 1.174\times\exp(1.356-0.050BAL_{ijk}-0.523\ln(T_{ik})) \quad (26)$$

P. oocarpa

$$id_{ijk} = 1.203\times\exp(2.075-0.011BAL_{ijk}-0.910\ln(T_{ik})) \quad (27)$$

where id_{ijk} is the diameter increment of tree *j* of plot *i* in year *k*, id_{ijk} is the annual overbark diameter increment of tree *j* in plot *i* and year *k* (cm), *T* is the stand age, *BAL* is the basal area of trees larger than the subject tree (m² ha^{-1}), and u_i is a random factor for plot *i* in *P. patula* model.

According to the models, increasing tree diameter decreases the annual diameter increment while increasing competition decreases growth counteracting with the effect of dbh (Fig. 6). Site index was a significant predictor only for three species. As expected, improving site index increased diameter increment. Site index affected growth much more in *P. elliottii* than in *P. pseudostrobus* and *P. kesiya*. Since the BALs of the trees increase as the stand develops, and the differences in the BALs of the trees also increase, the models predict that once competition among trees starts, the growth of the dominated trees decreases most, and the size differences between trees start to increase. All the models also predict that when a stand is thinned, smaller trees improve their growth more than larger trees. In fact, the largest tree in the stand does not react to thinning at all. In a very sparse stand, the smallest trees grow the fastest. There is a certain relatively low stand density at which all trees have nearly the same growth rate. In a dense stand, the largest trees grow fastest.

Based on the location of the plots in the slope catena it was possible to classify the *P. patula* plots into the three categories of the land use system traditionally used in forestry farming. Ombanda is considered to be the best site for agriculture, and poor Epia the worst. The mean plot factor (u_i) of the fitted diameter increment model was -0.059 for Ombanda, 0.1768 for Good Epia, and -0.1178 for Poor Epia. The plot factors suggest that, for *P. patula* growth, Good Epia is the best site whereas Ombanda and Poor Epia are almost equal. The mean site indices for the three different sites were 33.6 m for Ombanda, 35.0 m for Good Epia, and 32.8 m for Poor Epia.

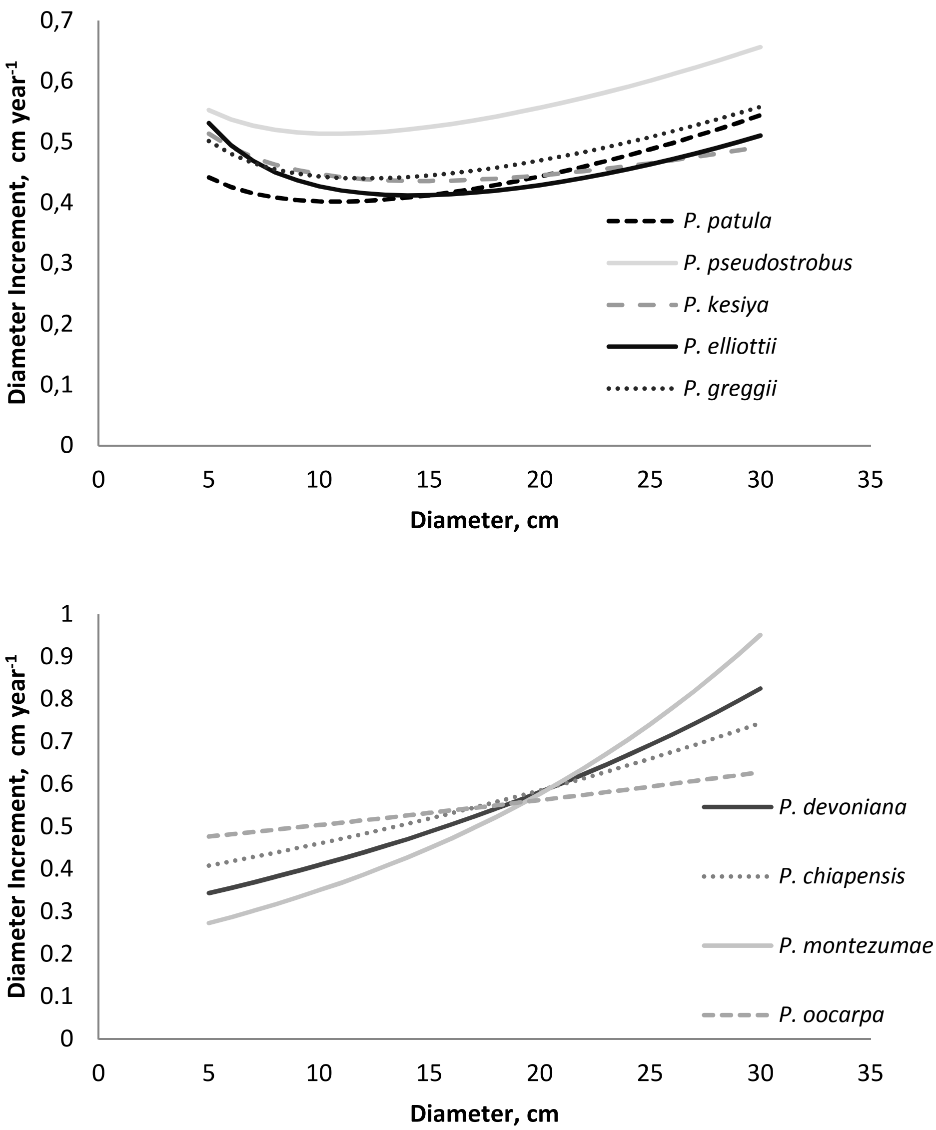


Figure 6. Combined effect of diameter and BAL on 1-year diameter increment in 9 different pines species according to equations 19 – 27 when *SI* is 28 m and stand age is 20 years, BAL decreases from 25 to 0 m^2 ha^{-1} when diameter increases from 5 to 30 cm.

Diameter increment models for eucalypts

The linear mixed-effects model of diameter increment for eucalypt species was as follows (Fig. 7):

$$\ln(id_{ijk}) = 1.468 + 0.0035SI_i - 0.00783\ln(BAL_{ijk} + 1) - 0.505\ln T_{ik} + 0.103\ln d_{ijk} - 0.205\sqrt{d_{ijk}} + 0.373S_{ij} + u_{ij} \quad (28)$$

where id_{ijk} is the annual overbark diameter increment of tree *j* of plot *i* in year *k* (cm), *d* is dbh (cm), *T* is the age (years) of the stand, *BAL* is the basal area of trees larger than the subject tree (m^2 ha^{-1}), S_{ij} is an indicator variable for *E. saligna* (*S* = 1 if the tree species is *E. saligna*, and 0 otherwise), and u_{ij} is random tree effect. The random plot effect, u_i, was not significant and was therefore not included in the model.

The Snowdon correction factor of the diameter increment model (Equation 28) was 1.026 when u_{ij} was not used in prediction (i.e. only the fixed part of the model was used, as is usually the case when the model is used in routine forestry practice). The standard deviation of the residual of the logarithmic prediction was 0.547, leading to a Baskerville (1972) correction factor of 0.1495.

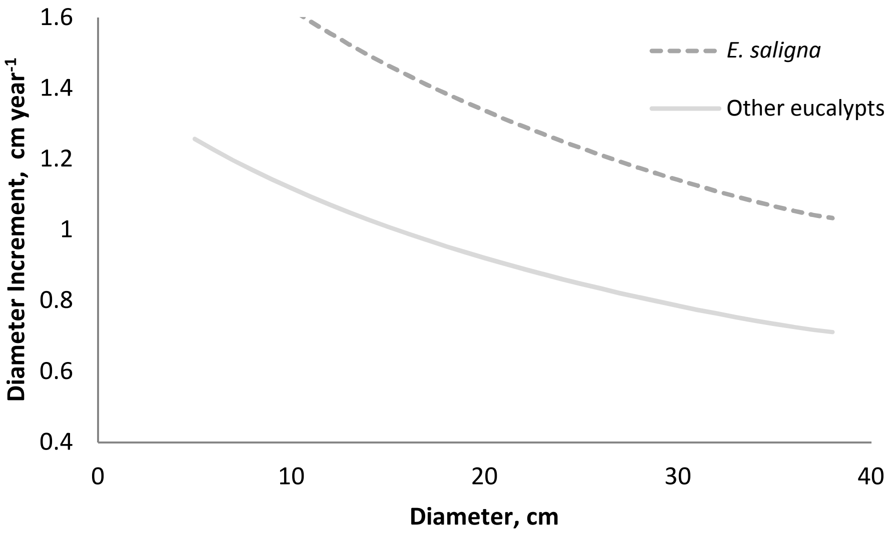


Figure 7. Effect of predictors on 1-year diameter increment in 6 different eucalypts species according to the mixed-effects model. *SI* is 30 m, BAL ranges from 0 to 33 m^2ha^{-1} and *Age* is 8 years.

The RMSE of the non-transformed diameter increment was 0.702 with Snowdon (1991) correction, 0.6981 with Baskerville (1972) correction, and 0.6978 with Lappi et al. (2006) correction for the fixed part of the mixed model (when only the fixed part was used). Without any correction, the RMSE was 0.816.

The non-linear version of the diameter increment model was:

$$id_{ijk} = \exp(1.753 + 0.00939SI_i - 0.0105\ln(BAL_{ijk} + 1) - 0.872\ln T_{ik} - 0.0455\sqrt{d_{ijk}} + 0.503S_{ij}) \quad (29)$$

The effect of site index is much stronger in the non-linear fixed-effects model, most probably because the random tree factors of the mixed-effects model explain a major part of the site effect. Therefore, the fixed part of the mixed model predicts less site variation than the non-linear fixed-effects model. The RMSE of the non-linear model was 0.6552, which is less than the RMSE obtained for the fixed part of the mixed-effects model. The RMSE of a non-linear mixed model was 0.8775 with random plot factor and 1.0299 with random tree factor. Therefore, the fixed-effects non-linear model was better in terms of RMSE than the fixed part of non-linear mixed-effects model. On the basis of RMSE, the ranking of alternative models was as follows: (i) non-linear fixed-effects model, (ii) fixed part of the linear mixed-effects model with Lappi et al. (2006) correction, (iii) Baskerville (1972) correction, (iv) Snowdon (1991) correction, (v) without correction, and (vi) fixed part of non-linear mixed-effect model.

Height models for pines

The tree height models of pines using dominant height as a predictor are (Fig. 8):

P. patula

$$h = Hdom \times (d/Ddom)^{0.960-0.384d/Ddom-0.0134T} \quad (30)$$

P. pseudostrobus

$$h = Hdom \times (d/Ddom)^{0.292-0.294\ln(d/Ddom)} \quad (31)$$

P. kesiya

$$h = Hdom \times (d/Ddom)^{0.367-0.122\ln(d/Ddom)} \quad (32)$$

P. devoniana

$$h = Hdom\times(d/Ddom)^{0.219-0.354\ln(d/Ddom)} \quad (33)$$

P. chiapensis

$$h = Hdom\times(d/Ddom)^{(-0.041-0.609\ln(d/Ddom))} \quad (34)$$

P. elliottii

$$h = Hdom\times(d/Ddom)^{0.359-0.148\ln(d/Ddom)} \quad (35)$$

P. greggii

$$h = Hdom\times(d/Ddom)^{0.402-0.085\ln(d/Ddom)} \quad (36)$$

P. montezumae

$$h = Hdom\times(d/Ddom)^{0.083-0.172\ln(d/Ddom)} \quad (37)$$

P. oocarpa

$$h = Hdom\times(d/Ddom)^{0.017-0.759\ln(d/Ddom)} \quad (38)$$

where *h* is tree height (m), *Hdom* is stand dominant height (m), *d* is dbh (cm), *Ddom* is dominant diameter (cm), and *T* is stand age (a). The degree of explained variance (R^2) was 0.846, and the standard error of estimate was 5.248 m.

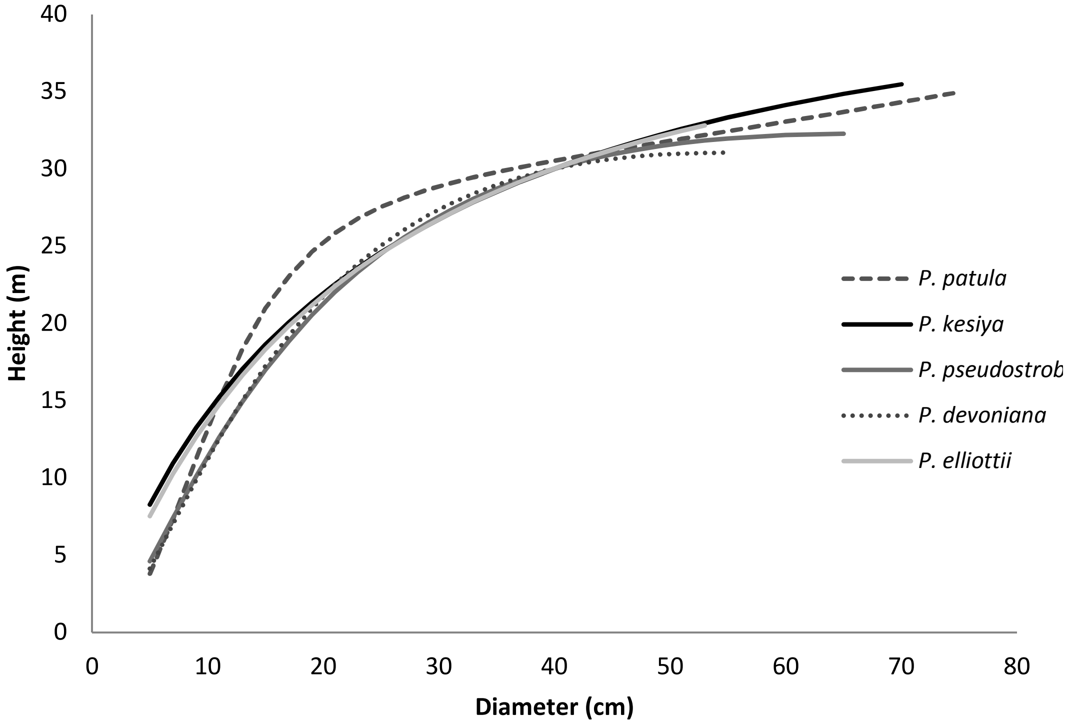
The degree of explained variance (R^2) ranges from 0.30 for *P. montezumae* to 0.83 for *P. pseudostrobus*, and the standard error of estimate ranges from 1.81 m for *P. montezumae* to 4.39 m for *P. devoniana*. For *P. patula*, the degree of explained variance (R^2) of the model is 0.897, while standard error is 3.028 m.

A height model for *P. patula* without using dominant height as a predictor is as follows:

$$h = \frac{10515.8 + 583.8T + 8362.8(d / Ddom)}{1392.0 - 13609.6 / d + 225515.9 / d^2} \quad (39)$$

The R^2 of the height model (equation 39) is 0.884 and the standard error is 3.269 m.

a



b

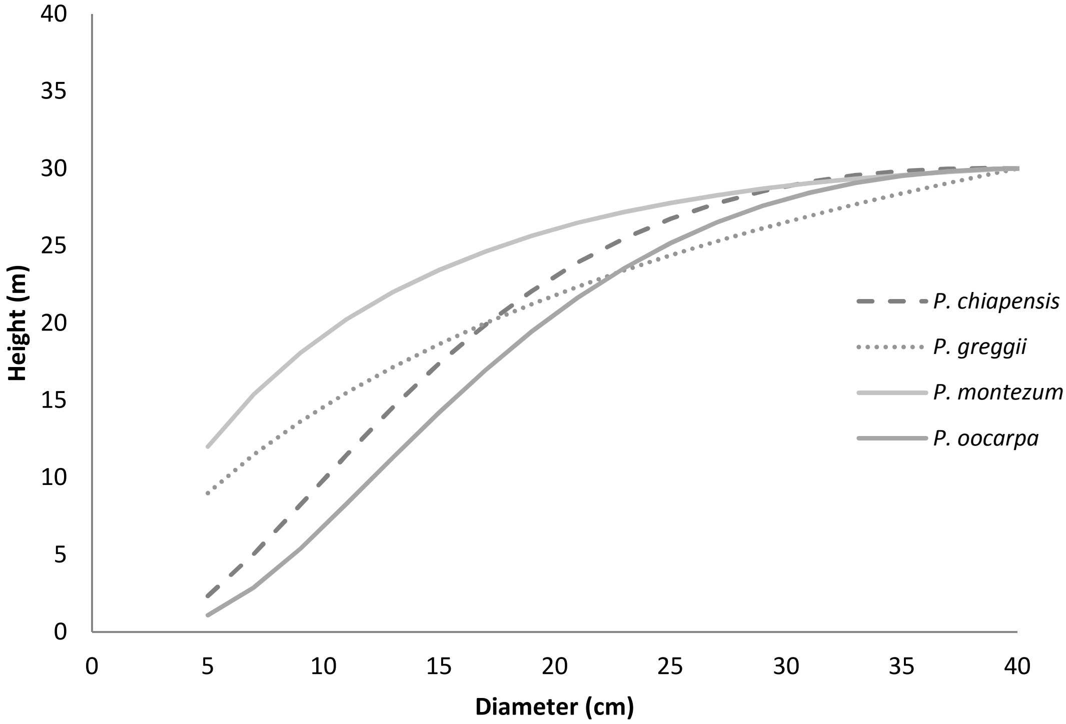


Figure 8. Relationship between height and diameter for tropical pines in Angolan Highlands when dominant height (*Hdom*) is 30 m and dominant diameter (*Ddom*) is 40 cm.

Heights models for eucalypts

The height model for the eucalypt species is as follows:

$$h = 1.3 + (Hdom - 1.3)\ (d/Ddom)\ (0.241 + (-0.165 + s)\ \ln(d/Ddom)) \quad (40)$$

where h is tree height (m), $Hdom$ is stand dominant height (m), d is dbh (cm), $Ddom$ is dominant diameter (cm), and T is stand age (a) (Fig. 9). The degree of explained variance (R^2) is 0.846, and the standard error of estimate is 5.248 m.

The eucalypts height model includes a species-specific coefficient, s, which is 0.158 for *E. saligna*, 0.304 for *E. resinifera*, 0.408 for in *E. camaldulensis*, and zero for the other three species. The degree of explained variance (R^2) is 0.846, and the standard error of estimate is 5.248 m.

Survival of pines

According to the model, the number of survivors at 50 years is 35 to 50% of the number of trees planted. The model for the surviving number of trees in non-thinned stands (N_T) is as follows (Fig. 10):

$$N_T = N_0\ e^{-kT} \quad (41)$$

where N_0 is initial number of trees per ha, k is mean mortality rate per year, and T is stand age (a).

The mean annual mortality rates of the 8 species ranged from 0.014 (1.4% mortality per year) to 0.026 (Table 4). The mortality rate is lowest in *P. oocarpa* and highest in *P. greggii*. For *P. patula*, the mean annual mortality rate of all plots is 0.025 (i.e. 2.5%).

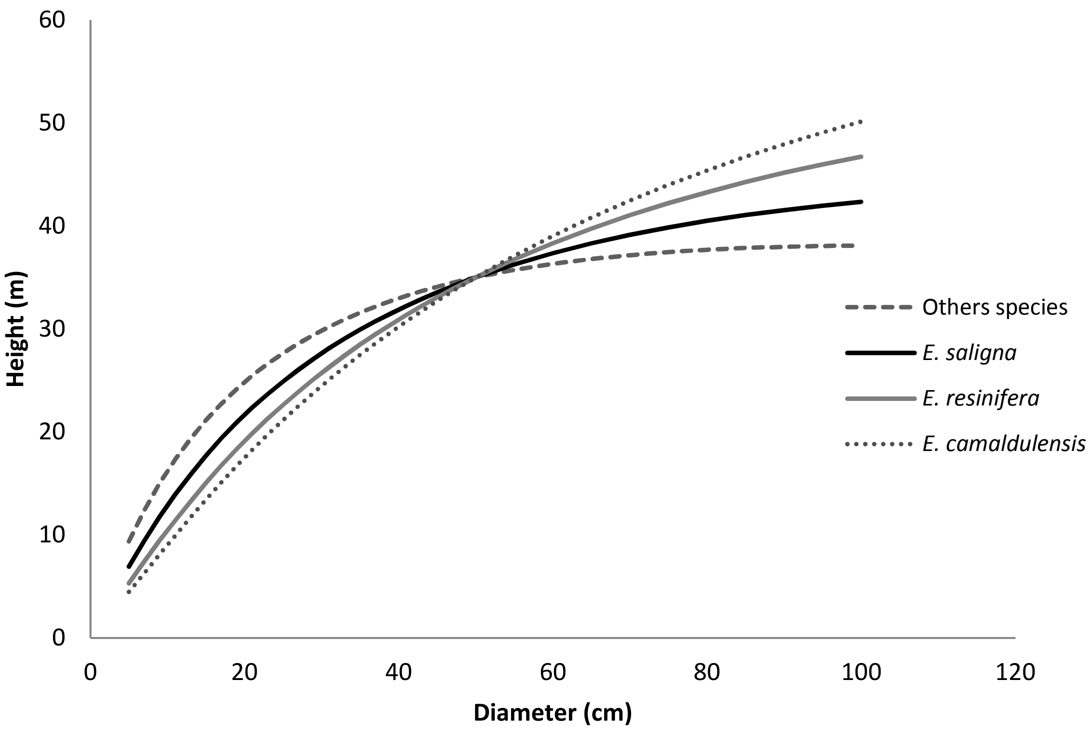


Figure 9. Relationship between height and diameter for tropical eucalypts in Angolan Highlands when *Hdom* is 35 m and *Ddom* is 50 cm.

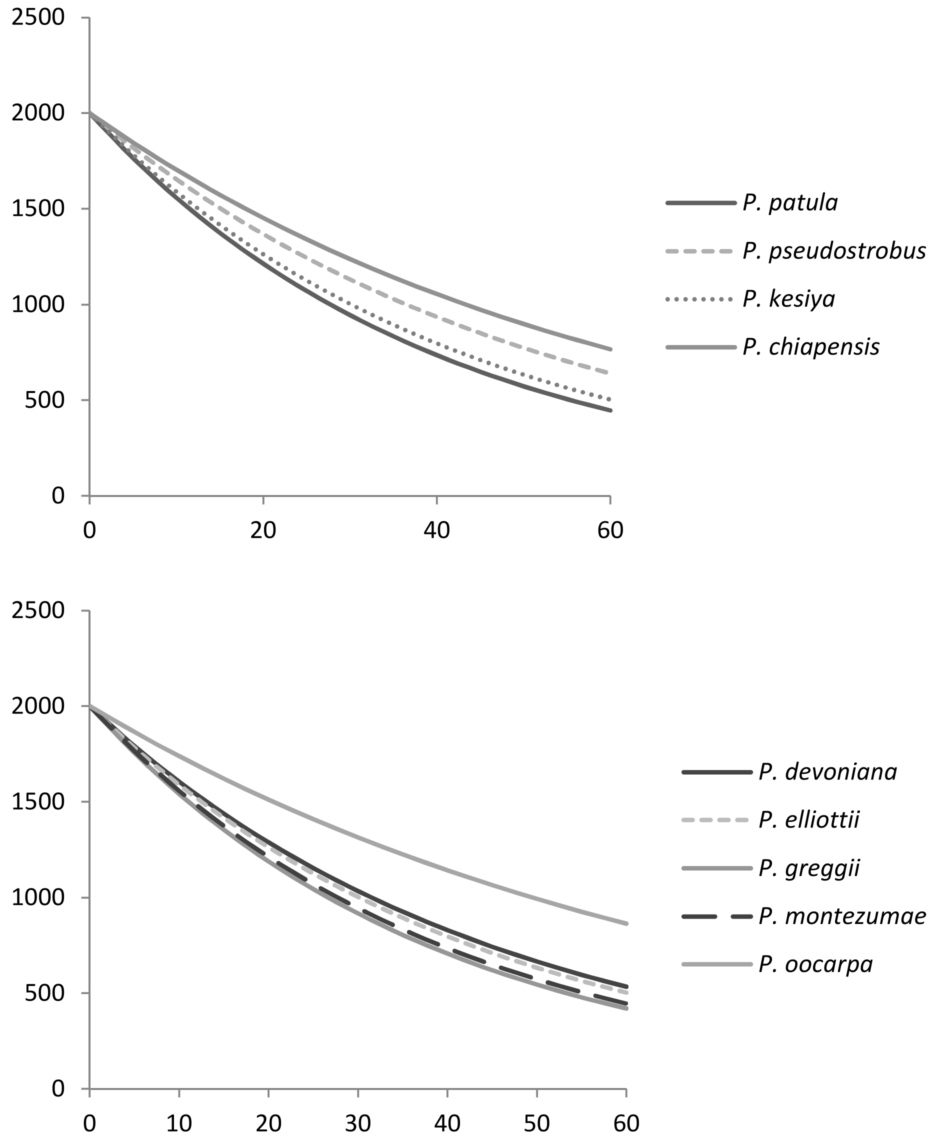


Figure 10. Number of living trees per hectare as a function of stand age in pine plantations of Central Angola.

Survival of eucalypts

The mean annual mortality rate of the 6 studied eucalypt species ranged from 0.015 (1.5% mortality per year) to 0.039. The number of survivors at 50 years ranged from 18% to 50% of the number of trees planted. Survival rate was highest for *E. siderophloia* and lowest for *E. camaldulensis* and *E. macarthurii*, with the other species being in the intermediate-to-low range. The measured plantations grew most of the time under high competition, and mortality most probably mainly affected the suppressed trees. However, sporadic clearings may have slightly increased the observed "mortality rate", i.e. the true mortality rate of the species without any human intervention would be somewhat lower (Fig. 11).

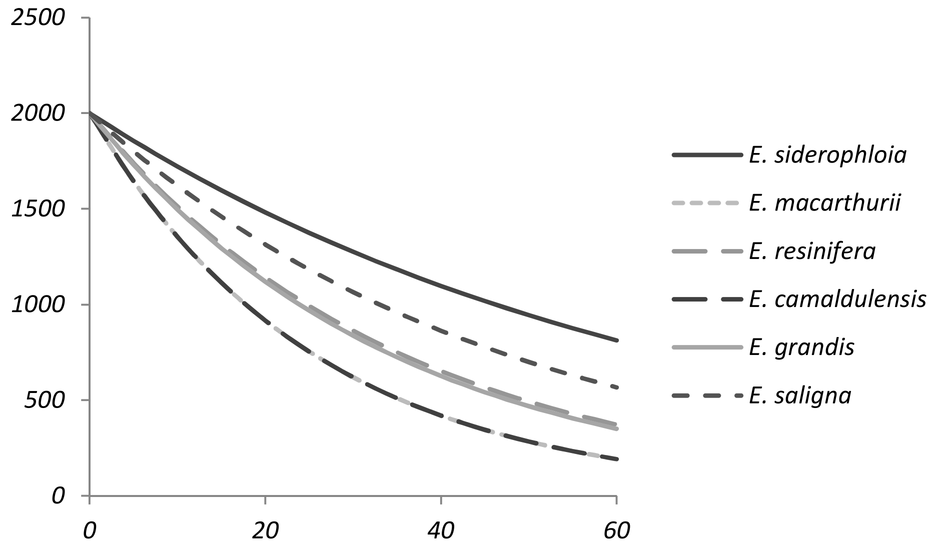


Figure 11. Development of the number of living trees in eucalypts species according to the survival models.

Optimal land use

The results from Studies I to IV were used as a source of information in land-use optimization (Study V). Based on growth simulations, as well as cost and timber price information, it was possible to calculate the wood production, net income, and net present value of tree plantations managed with different rotation lengths. This information was combined with the cost and income data for agricultural products, so as to calculate the land expectation value (LEV) of different production systems.

The profitability of the different land-uses of Umbundu system is summarized in Table 3. Production is the most profitable in the Ombanda site class while good Epia and Otchiumbo alternate as the second in profitability depending on the cash crops. Traditional cereals, including maize and millet, have negative LEV values.

Under grass fallow (10 years) the most profitable land uses are potato and garlic cash-crop systems. With forest fallow the most profitable uses are potato and garlic cash-crops with eucalypt fallow. Long-rotation forestry fallows (30 years of pines, 10 years for eucalypts in Ombanda, and 12 years for eucalypts in Good and Poor Epia) have lower LEVs than grass and short-rotation forest fallows (10 years of pines, 7 years for eucalypts in Ombanda, and 8 years for eucalypts in Good and Poor Epia). In permanent forestry the LEV values are the highest for long rotation eucalypt (table 4).

The following sections present production frontiers, shadow prices and relationship between different variables as indicators to describe system. Figure 12a shows the production possibility boundary of the Umbundu land use system in the Angolan Highlands. The number of cows affects the productivity of the system but also the land allocation for other activities. The highest LEV corresponds to the lowest possible number of cattle units. The number of cattle is a key factor affecting the production of different crops and the land expectation value. This trend is found with different discount rates, although the curve shape seems sharper at lower discounts.

Table 3. Land expectation value (LEV) at 5% discount rate for different land use (AOA/ha). The crop species that gives the highest LEV is underlined.

Land use and site	Maize	Millet	Soya	Bean	Pea	Cassava	Potato	Onion	Sweet potato	Garlic	Peanut	Cauliflower	Cabbage	Tomato	Carrot
Permanent agriculture															
Onaka	-78,371	-315,000	-315,000	496,580	-315,000	-315,000	2,578,130	1 655 369	-315,000	7,335,444	469,435	560,202	3,404,925	146,540	1,228,933
Otchiumbo	-240,701	-315,000	-315,000	151,520	-315,000	199,100	5,759,660	333 513	2,588,450	7,665,350	1 542,270	621,655	1,153,225	-315,000	3,061,265
Elunda	-530,914	-658,449	-402,271	-142,381	-402,271	-150,611	4,439,599	-315 000	1,391,059	-315,000	-199,151	-315,000	-315,000	-315,000	-315,000
Agriculture with 10 years grass fallow															
Good Epia	-427,661	-453,913	109,411	-241,475	-288,808	-278,668	749,824	-315 000	123,764	-315,000	-79,026	-315,000	-315,000	-315,000	-315,000
Poor Epia	-403,998	-409,746	-204,790	-336,360	-281,441	-265,948	212,873	-315 000	-31,799	-315,000	-186,125	-315,000	-315,000	-315,000	-315,000
Ombanda	-200,490	-426,497	304,965	178,350	-59,988	-129,898	2,731,296	954 823	427,937	2,892,232	457,177	110,492	2,363,647	630,291	405,598
Agriculture with short 10 year) rotation pine fallow															
Good Epia	-59,293	-88,918	546,803	150,821	97,405	108,849	1,269,521	67 847	563,000	67,847	334,148	67,847	67,847	67,847	67,847
Poor Epia	38,559	31,889	269,713	117,044	180,770	198,747	754,353	141 829	470,445	141,829	291,371	141,829	141,829	141,829	141,829
Ombanda	134,307	-116,033	694,180	553,934	289,935	212,498	3,381,733	1 414 003	830,391	3,559,997	862,779	478,769	2,974,503	1,054,530	805,647
Agriculture with short 7 or 8 years rotation eucalypt fallow															
Good Epia	189,081	159,456	795,177	399,196	345,779	357,224	1,517,895	316 222	811,375	316,222	582,522	316,222	316,222	316,222	316,222
Poor Epia	135,123	126,751	425,228	233,624	313,601	336,163	1,033,466	264 730	677,152	264,730	452,409	264,730	264,730	264,730	264,730
Ombanda	396,317	131,512	988,541	840,190	560,937	479,026	3,831,386	1 749 956	1 132,622	4,019,951	1,166,881	760,683	3,400,625	1,369,713	1,106,448
Agriculture with long 30 years rotation pine fallow															
Good Epia	21,361	7,848	297,809	117,197	92,833	98,053	627,451	79 351	305,197	79,351	200,815	79,351	79,351	79,351	79,351
Poor Epia	23,837	21,156	116,749	55,384	80,998	88,224	311,548	65 346	197,432	65,346	125,454	65,346	65,346	65,346	65,346
Ombanda	124,968	-270	405,056	334,895	202,824	164,085	1,749,559	765 162	473,198	1,838,739	489,401	297,292	1,545,834	585,329	460,820
Agriculture with long 10 or 12 years rotation eucalypt fallow															
Good epia	208,434	198,261	416,551	280,581	262,240	266,169	664,713	252 090	422,112	252,090	343,531	252,090	252,090	252,090	252,090
Poor epia	178,331	176,253	250,343	202,782	222,634	228,235	401,324	210 503	312,877	210,503	257,090	210,503	210,503	210,503	210,503
Ombanda	371,168	274,962	586,329	532,432	430,977	401,218	1,619,165	862 960	638,676	1,687,673	651,123	503,546	1,462,665	724,813	629,167

Table 4. Land expectation value (LEV) at 5% discount rate for pure forestry or grazing land use.

Site type	LEV, AOA/ha	Site type	LEV, AOA/ha
Grazing		**Long rotation pine (30 years)**	
Good Epia	-315,000	Good Epia	135,610
Poor Epia	-315,000	Poor Epia	110 288
Ombanda	-315,000	Ombanda	119,848
Short rotation pine (10 years)		**Long rotation eucalypt (10 or 12 years)**	
Good Epia	467,225	Good Epia	1,334,431
Poor Epia	435,809	Poor Epia	1,000,787
Ombanda	471,153	Ombanda	1,943,299
Short rotation eucalypt (7, or 8 years)			
Good Epia	938,128		
Poor Epia	665,851		
Ombanda	1,173,486		

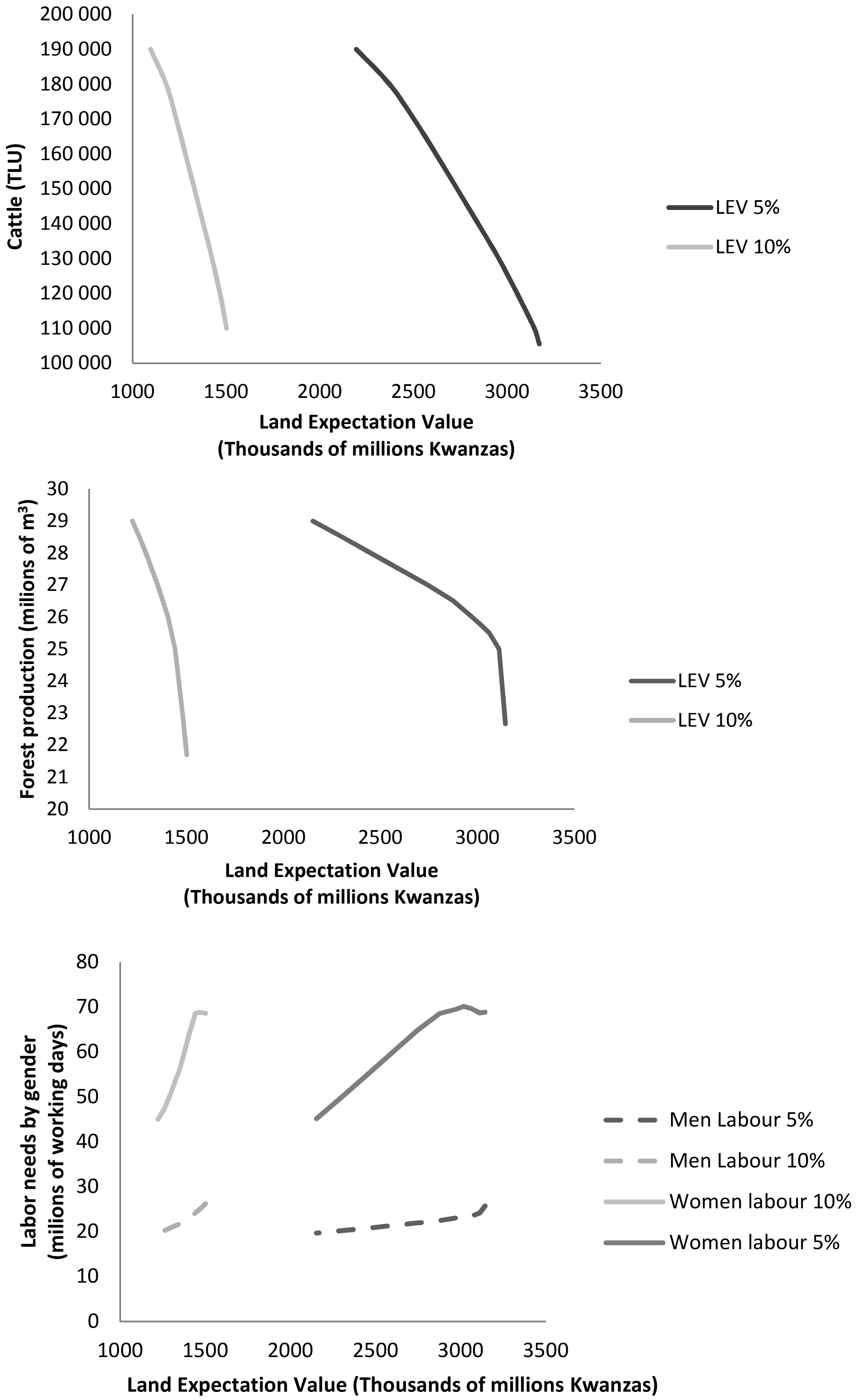


Figure 12. Production frontiers with land expectation value, number of cattle units and wood production (top and middle). The lowest diagram shows the relationship between labour consumption and land expectation value (expressed in Angolan Kwanzas) with 5% and 10% discount rates on food security constraints.

Figure 12b shows the production frontier between LEV and wood production. With a wood production lower than 26 million m³, increments in wood production slightly decrease LEV, and further increments accelerate the drop. LEV variation was also analysed considering labour needs. Figure 12c summarizes the relationship of LEV and women and men labour under two discount rates. Men labour is lower that women labour but increase rapidly when LEV increases. Women labour needs show a constant increase up to higher LEVs, but reach a plateau at maximal LEV levels.

Shadow prices reflect the cost or output value of an additional unit in the system. The number of cows has a high negative shadow price (Fig. 13) meaning that an additional cow under current management costs several million AOA. Therefore cattle are a highly limiting factor on the system. Clearly, improving animal traction productivity or even introducing mechanization would have a significant impact in the system. Ombanda is the most valuable plot type at low discount rates (5%). At 10% discount rate, Onaka and Otchiumbo become more valuable (Fig. 13).

Regarding self-subsistence production, beans and maize have the most negative shadow prices, lower than in alternative protein and carbohydrate sources. Therefore, a more diverse diet seems to improve the LEV of the system. The results suggest that replacing maize and beans by other sources of carbohydrates and proteins may improve profitability.

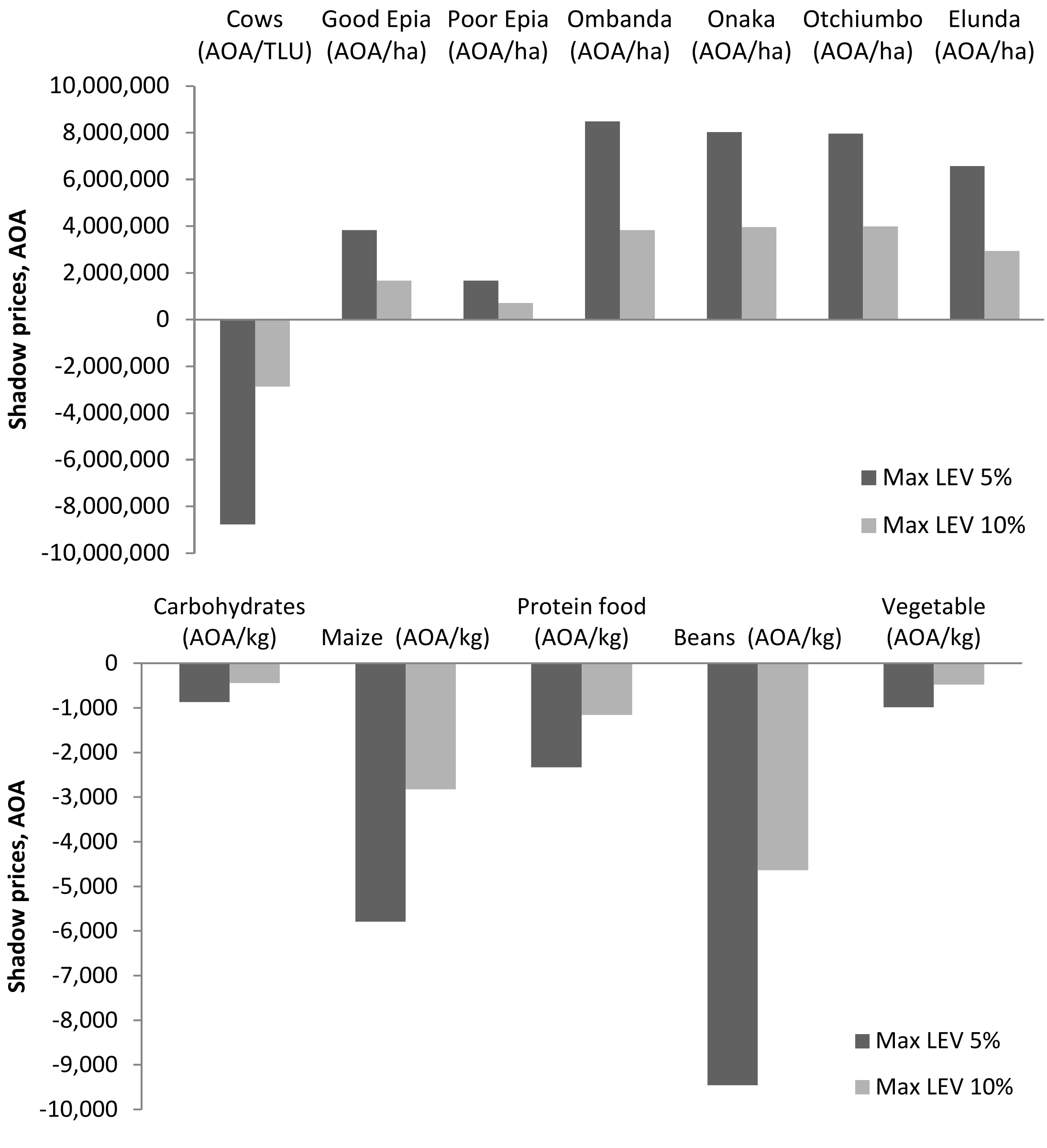


Figure13. Shadow prices for different production constraints of the Umbundu system.

Table 5. Constraints (production ≥) under the subsistence system in Angolan Highlands

	Baseline	**Diet**	**Timber**
Cattle (TLU)	110,000	110,000	110,000
Carbohydrates (Tn)	213,005	213,005	213,005
Maize (Tn)	149,104	106,503	149,104
Protein food (Tn)	142,173	142,173	142,173
Beans (Tn)	99,521	71,087	99,521
Vegetables (Tn)	203,833	203,833	203,833

Three alternatives were tested to get the optimal land-use plans using LEV with discounting rates of 5% and 10%. The alternatives summarized different possibilities with the current situation (the 'Baseline' alternative), with specific changes in traditional diet (the 'Diet' alternative), and with a clear regional specialization in forest production (the 'Timber' alternative). The diet alternative presents the highest land expectation value while timber production shows the lowest. The production constraints of the three optimization cases are summarized in Table 5.

Once the constraints for subsistence are accomplished, the system also produces cash crops and forests products as revenue commodities (Fig. 14). A part of these products is linked to fallow management and cattle pasture needs, while cash crops are in competition with subsistence production. The Diet alternative promotes the highest production of cash crops, while timber production remains the same as in the current Baseline alternative. In the Timber alternative there is a slight decrease in firewood production, an increase in pole production, and some decrease in cash crop production.

Figure 15 summarizes land allocation by main land uses under the different alternatives and discount rates during the agriculture phases. The Baseline alternative shows that protein-source crops need more of the cultivated area, with all the Good Epia sites and most of the Poor Epia and Elunda sites used specifically for protein-rich crops (Fig. 15a). Carbohydrate-rich crops and cash crops used large areas of both Poor Epia and Otchiumbo sites. Under a 10% discount rate, some areas of Poor Epia are used for pure forestry without an agriculture period. The Diet alternative uses more of the available fertile area for cash crops. Some Poor Epia and Elunda is used, in addition to the Otchiumbo sites, for more profitable cash crops such as garlic and potatoes. Under a 10% discount rate, a significant area of Poor Epia also gets allocated to pure forestry (Fig. 15b). The Timber alternative (Fig. 15c) allocated all Poor Epia plots to pure forestry, while cash crops remained limited to a handful of Otchiumbo areas. Good Epia is allocated to proteins and vegetable crops to assure the minimal subsistence requirements. Carbohydrates and some minimal cash crops are produced in Otchiumbo and Onaka areas. Under a 10% discount rate, there is no area allocated to cash crops but some Ombanda area is allocated to pure pastures to meet the needs of the cattle herds.

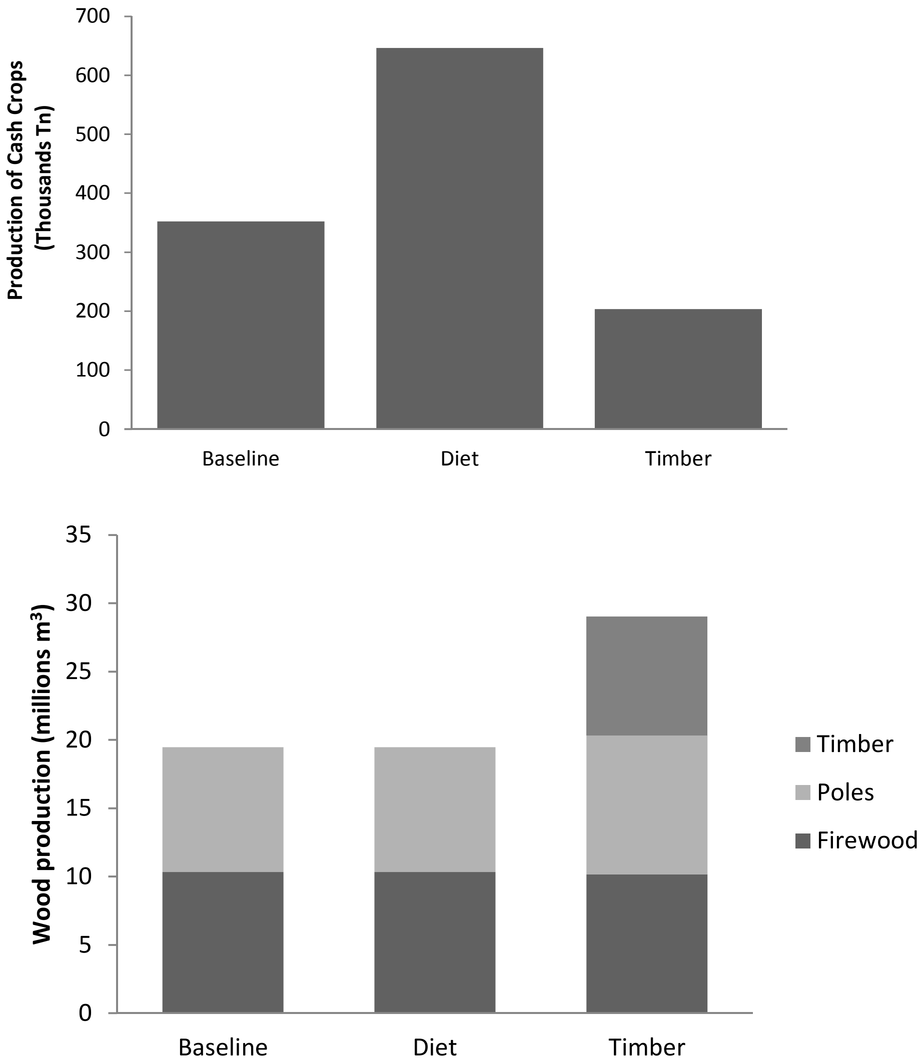


Figure 14: Production of cash crops (top) and forest production (bottom) in different alternatives.

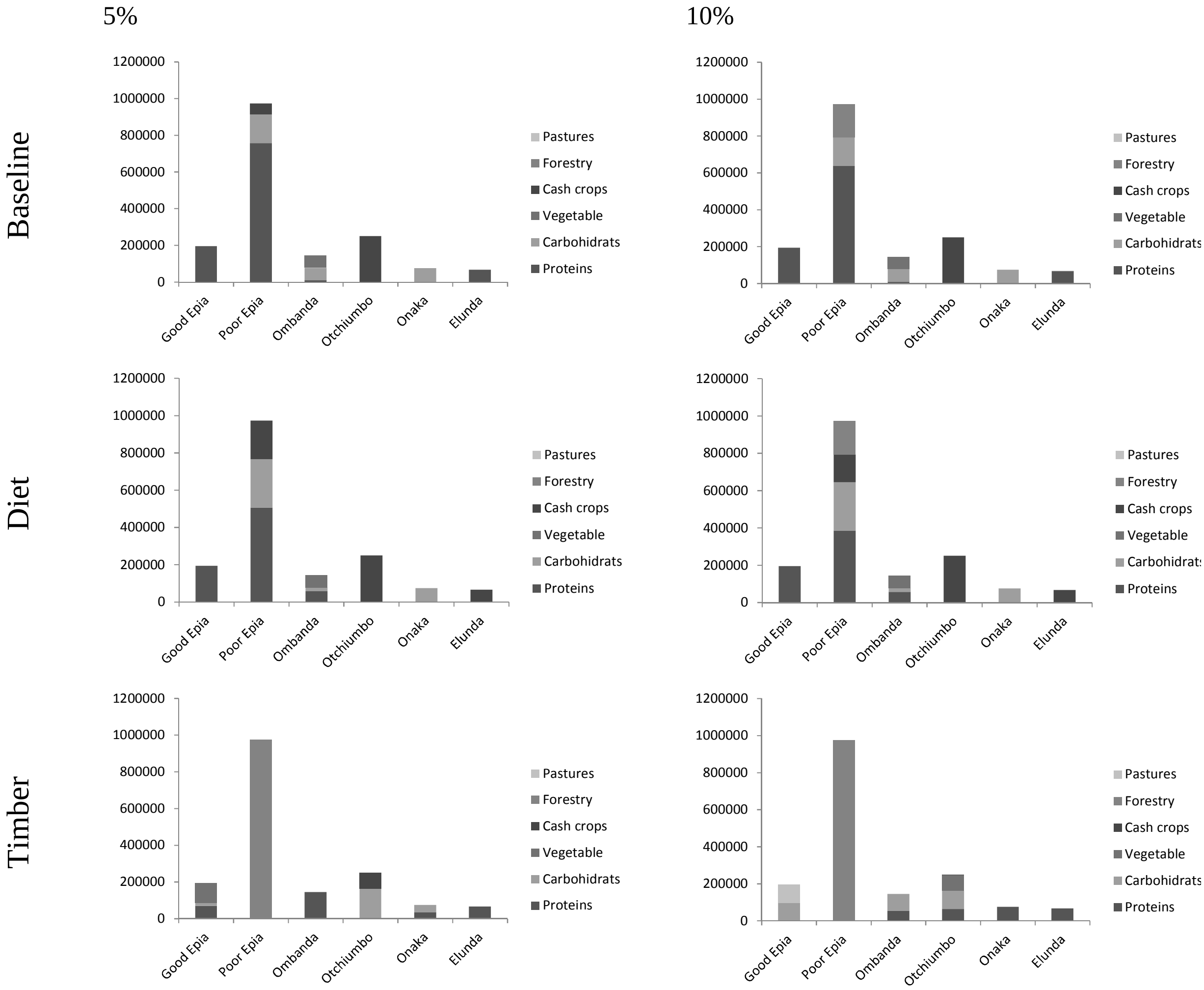


Figure 15. Optimal land use under different alternatives and 5% and 10% discount rates, including a) maximizing LEV under baseline conditions, b) with a more diversified sources of carbohydrates and protein-rich diet; c) maximizing timber production under the current food diet patterns

Regarding fallows (Fig. 16) under the Baseline alternative, Good Epia, Ombanda and most of the Poor Epia fallows are under short rotation eucalypts, while about 500,000 ha of Poor Epia is under long-rotation eucalypt fallow. When discount rate is increased up to 10%, the Poor Epia under long rotation eucalypt fallow decreases to less than 200,000 ha. The same pattern is found under the Diet alternative (Fig. 16). Figure 16 shows the situation under the Timber alternative. Both 5% and 10% discount rates show all Poor Epia planted with eucalypts under a long-rotation fallow. Ombanda and Good Epia remain under permanent pastures, with a share of Ombanda under permanent grassland.

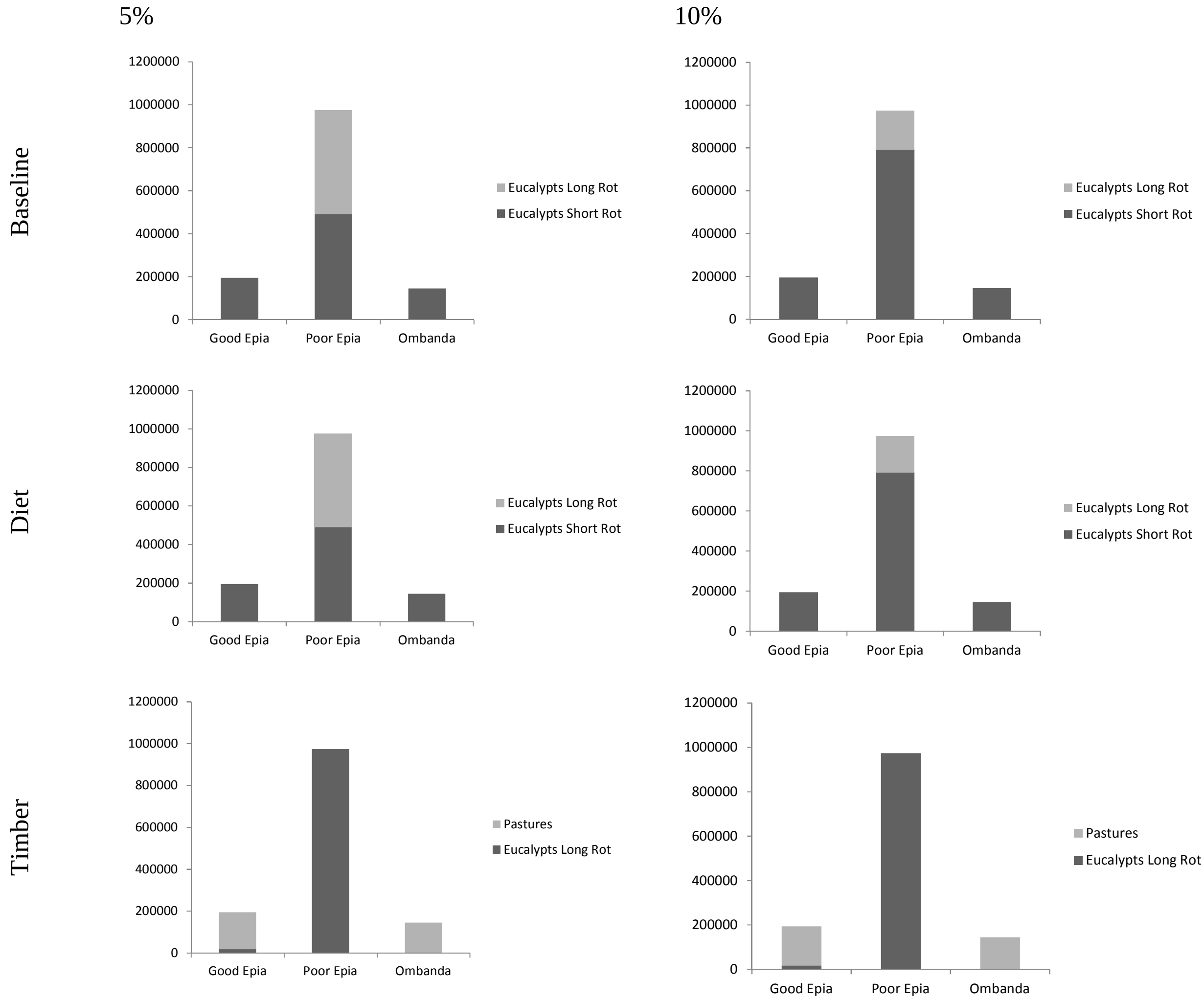


Figure 16. Optimal areas under fallow in different alternatives (Baseline, Diet, Timber) under 5% and 10% discount rates. Other production systems are not selected.

4. DISCUSSION

4.1. Analysis of methodology

The characterization and description of the Umbundu land use system included subjective elements in the methodological approach. While clergies and ethnographers have searched a more cultural heritage, Marxist technicians looked for the collectivist side of the system. There is also some subjectivity in this thesis, but systematic analysis, the applied qualitative and quantitative methods, the peer reviews, and self-criticism approaches should have diminished most of these limitations.

These studies of the thesis are relevant not only for the development of growth and optimization models but also for preserving the growth information accumulated on trees in the few remaining plots in the Angolan highlands. At the time of writing, most of the measured plots have already disappeared due to illegal logging or land-use changes. It will take another 40 years to obtain similar data for the Angolan Highlands. The used datasets represent a vast area of the Miombo forests that cover 2.5 to 4 million km² of the southern African highlands (Abdallah and Monela 2007). The developed models provide useful tools for forest management in this ecosystem. Publishing this growth information pays tribute to the technicians that planned these research experiments in early 1960s and to southern African silviculture in general. The modelling data used in Studies II to IV had some restrictions. The dataset for species other than *P. patula* and *E. saligna* were collected in only one location, Tchianga Research Station, where most of the species have two to three plots. Furthermore, the dominant height data came from a limited number of stand ages, i.e. just one age class for most species except *P. patula* and *E. saligna*. This weakness was reduced by using the additional data of *P. patula* and *E. saligna* to develop the dominant height models. In addition, guide curves were compared to earlier dominant height models for the same or similar species around the world. These comparisons show that the models developed in Studies II to IV give a similar growth curve shape as most of the previous models developed for pines and eucalypts in southern Africa and other intertropical countries. In the case of eucalypts, most of the existing international scientific literature refers to younger plantations. Therefore, these previous curves are not always logical for older ages, and few other studies have included tropical eucalypt plantations older than 20 years. This is an added asset of the models of this thesis.

The studied plots were never subjected to systematic silvicultural treatments. Before independence, during the early years of the Tchianga plantation, trees were quickly replanted to replace dead trees, whereas after independence, the stands were neither thinned nor pruned, but were sometimes treated with non-systematic thinnings. Therefore, the results for mortality should be interpreted with caution.

Pine and eucalypt species had false rings in some growth years. Also, at older stages, suppressed trees had very thin annual rings, making it hard to differentiate the annual increment. These thin rings are due to very slow growth, sometimes just a few cells, under high competition. These limitations reduce the precision of the models. The use of a high-precision visible-spectrum camera in Studies II and III and x-ray imaging in Study IV improved the quality of the dataset. Furthermore, the measurement of all annual growth rings in a high number of trees generated a large dataset of 29,817 observations, which partly compensates for the above-mentioned limitations.

The used data collection methodology shows promise for developing growth and yield models in areas that lack repeated measurements in permanent plots. Increment cores were collected from old plantations, and experimental analyses using x-ray and high-resolution imaging were introduced to generate the dataset. A constraint in the modelling studies (Studies II to IV) was the lack of independent dataset to validate the models. The priority was to use all height and radial increment data for modelling instead of saving part of them for the model validation process.

Due to a restricted dataset, the mortality models, strictly speaking, only apply to non-thinned stands planting at a density of 1100 – 1600 trees per ha. However, this is a typical planted density for pines and eucalypts in the Angolan Highlands. The mortality models do not show how mortality is distributed among diameter classes. Field observations suggest that suppressed trees die first and, therefore, the limitation can be solved by removing small trees in simulations until the number of survivors is the same as that predicted by the model.

The growth models reported in Studies II to IV are the first for tropical pine and eucalypt species in Angola, and among the very few individual-tree growth models for these species in Southern Africa. Some of the studied species showed high growth rates, and some species have not been previously considered able to reach so high growth rates under Angolan conditions. A key outcome of the research is the proof that the Angolan Highlands hold high potential for a forestry-driven economy.

The thesis developed models for predicting forest product yields but no modelling was done for agricultural crop yields, carrying capacity of pastures, labour needs, and costs. These parameters were calculated based on fieldwork, colonial agriculture statistics and averages borrowed from the international literature. Although the LP models that accommodate these production data describe the production potential of the analysed land use system, they fail to reflect the actual decision-making situation, which needs to consider also uncertainty and risks. Study V minimized these weaknesses by including several system constraints, including diet needs and minimal bean and maize production, among others. Under subsistence farming local farmers use crops with more predictable harvests and plant areas larger than necessary in order to ensure a sufficient amount of food and reduce uncertainty (Hildebrand et al. 2003). An illustrative example is the maize and millet farming system which shows a negative NPV. Farmers do not consider some inputs such as women or child labour as a cost, and growing cereals provide a high degree of certainty of harvests in the subsistence system.

Study V used LP to optimize the traditional land use system. LP is well adapted for optimizing traditional land use systems where subsistence farming plays a fundamental role. Therefore, most of the system characteristics can be simulated as a closed system, and those with interconnections can be limited by constraints (Just 2002; Hildebrand et al. 2003). LP is limited to situations where the objective function and constraints are linear (Dykstra 1984), but this is not always the case under traditional land use allocation schemes. Incomes are not always linearly related to cultivation area because the unit price may depend on the amounts produced and the prevailing demand. Prices change differently depending on whether the production is for subsistence or cash crops. Surplus of subsistence products may not be absorbed by the local market, resulting in a decrease in their market prices. Cash crop prices may also change in a non-linear way with increasing production. Study V diminished the limitations caused by linearity assumption through sensitivity analyses and constraints fixed for various products (Bertomeu and Gimenez 2006). The methodology used to build the LP equations has the bonus of making it possible to understand system trade-offs (Santé and Crescente 2007) and possible conflicts.

4.2. Analysis of main findings on this research

Study I confirms the hypothesis how the Umbundu system has had a structural function in the highland economy (Morais 1976). The system provided self-sufficiency to rural communities while also produced fresh and staple food for the urban centres in the highlands and the Benguela coastal region. The Umbundu system has evolved through conflicts, increasing its diversity, accumulating technical know-how by incorporating new crops and varieties, and improving forested fallows. The system has also adapted to labour availability, food security under military conflict, and changing land tenure and ownership (Pössinger 1973).

Colonial pioneer foresters felt that the Angolan Highlands had promising conditions for fast-growing plantations. Studies II to IV confirm these expectations and bring insight into the technical knowledge guiding forest plantation management. Despite the limitations in the data, a full set of models was developed for 9 pine species and 6 eucalypt species under Angolan conditions. These models allow foresters to improve forest management and planning, and make it possible to predict the future development of pure pine and eucalypt stands growing in conditions that match the highlands of Angola, i.e., the whole Miombo forest ecoregion of southern Africa. The models indicate high growth rates for several species, some of which were analysed for the first time in Angolan conditions. While the traditionally-used *E. saligna* and *E. grandis* show the best performances, with rates similar to other highly productive areas in the intertropic zone (Poyton 1979; von Gadow and Bredenkamp 1992), *P. patula*, which is the mostly widely used species in Angola, was not the fastest-growing pine species. High altitude and low probability at frost occurrences benefit more sensitive of the studied pine species like *P. pseudostrobus* and *P. kesiya* over *P. patula* or *P. elliottii*. *P. kesiya* and *P. pseudostrobus* showed higher growth rates than the same species in other intertropical plantations. Therefore, these species should be considered for future plantation programs in the Angolan Highlands. The studies also provided potential rotation lengths for pines and eucalypts that partially confirm those traditionally employed by the colonial technicians (Silva 1971). Eucalypt rotation lengths for maximal wood production varied from 8 to 12 years, while pine rotations should be longer, from 20 up to 35 years. New eucalypt hybrids and clones should also be tested, in line with recent developments in other intertropical regions, e.g., Bahia, Brazil (Delgado-Matas and Pukkala 2012).

Good governance in rural development policies should include both soft and hard measures, including access to new irrigation technologies and mechanical traction, access routes and markets, but also changes in traditional diet, supporting mixed cereal and pulse farming, and capacitating labour, especially women. Timber, firewood and pole production should be encouraged in the poorest sites and in fallows. Study V indicates that forestry-based land uses can offer a sustainable solution for the poorest sites.

The optimization study (V), in line with this study hypotheses, reveals latent conflicts based on the system trade-offs. The optimal alternatives show that the traditional system can meet the subsistence needs while producing economic benefits for the developing Angolan economy. The amount of cattle in the system limits the possibilities to produce cash crops or timber, or increase LEV while meeting the subsistence needs in terms of daily food. One of the strategies found for the Umbundu system is to diminish the number of cows and include specialized agriculture, leaving cattle breeding to neighbouring peoples such as the Nhaneka Humbe from whom the farmers could acquire calves and oxen for animal traction. Further development by increasing plough productivity or introducing new techniques can have significant impacts on the production.

Another limiting factor and therefore a potential precursor of conflict is labour availability. The system evolved under a high surplus of women labour during slave and gum trade caravans and military conflicts, and it still depends on woman labour as a production factor. The on-going rural exodus will decrease labour availability and could spread conflicts across the system unless certain changes in productivity and labour factors are implemented (Pinstrup-Andersen 1994).

Cash crops were an important economic driver in the region under the colonial rule (Diniz 1973). The analysis shows that this started to happen again due to the increasing economic dynamism in the urban centres. Increasing prices of cash crops in the urban centres will increase the demand on sites with the highest LEV under cash crop cultivation regimes, i.e., Ombanda and Onaka sites. These site classes are not abundant in the region, which could create conflicts related to the ownership of these sites, conflicts between community and individual rights (Deininger and Castagnini 2006; Delgado-Matas and Pukkala 2012), and occupation of underutilized former European farms.

This study findings eventually can be considered for a larger geographical scope of southern Africa highlands and other inter-tropic regions. This study found strong opportunities for forestry-based land uses in the region, as growth and yield rates are high for fast-growing species. Under high timber prices, permanent forest plantations can compete with subsistence crops, grazing areas and cash crops. Under these circumstances, conflicts may emerge between foresters and farmers. This thesis showed that pure forestry should expand essentially to poor Epia sites, while more fertile sites classes should be left for pure agriculture and various fallow systems.

Seasonal labour needs affect the system and it should be taken into consideration when designing gender and social policies in the region. Gender-based policies should understand and comprehensively consider the critical issue of women labour needs during the harvest peak. The research clearly states the important role of women on addressing food security in the system. Additionally, education policies should regard the children recruitment for farm tasks during the peaks, and its effects on decreasing school attendance. In addition, women will continue to hold only a back-seat role if they are not empowered in the decision-making process. Alternatives that reduce the seasonality of labour needs represent a promising way forward for a more sustainable development (Siskos et al. 1994; Santé and Crecente 2007). Further development in the Umbundu system should focus on labour needs from gender perspective. Men do not consider women or child labour as an additional ‘cost’, and therefore intensive unpaid labour is not minimized in the system. This same trend has been reported in other traditional African systems (Pukkala and Pohjonen 1990; Thangata et al. 2007).

Future policy should promote changes in traditional diet to enhance more diverse sources of carbohydrates and proteins, increase labour productivity and animal traction, and empower the roles of women in the production system, i.e. land tenure, technical capacity, and access to loans. New technologies and crop varieties that increase yields in Ombanda and Onaka can guarantee food security for most of the local rural families. Forest plantations should be promoted in the poor Epia sites and as a way to reduce competition and potential conflicts with cash crop site needs.

4.3. Future research needs

Planning and optimization tools in traditional land uses in the Angolan Highlands are constrained by the lack of forest growth and yields models. This thesis developed models for most commonly planted species in the area. However, the region is still lacking models for native forest and models for non-timber forest products. Miombo forests provide the traditional economy with firewood, mushrooms, wild fruits, and medicines, among other products, all of which should be added to future optimization analyses. Future research should concentrate on the development of models, production functions and measures for relevant non-wood products and services provided by Miombo forests. Models should also be developed for uneven-aged pine and eucalypt forestry, as well as eucalypt coppice forestry, including different silviculture treatments such as thinnings.

The decrease in natural forests is going to increase the pressure on planted stands to respond to the multiplicity of uses and attributes that characterize native forests in the Angola Highlands as well as southern and eastern Africa in general. The conservation of remaining Miombo forests under a sustainable management is therefore a key factor, and new plantations will need to be established to reduce the pressure on the limited native forests. Any new plantations established also need to address multi-objective functions, which will thus require multi-objective forest planning on these plantations. Multi-objective forest planning need to predict stand development under alternative management options, and calculate the amounts of all products and services that are important for farmers and decision makers. To predict the development of environmental services and non-timber attributes such as erosion control or medicine production in the plantations, new models should be developed relating these attributes to stand structures.

Future research should include mapping of sites classes for further spatial analysis of the system. The use of correlations between the international classification soil system and the Umbundu nomenclature should facilitate the mapping process. New crops varieties and the introduction of new cultivation techniques should be monitored and included in the analyses. Furthermore, adding the elasticity of traditional crop prices and its effect on farmer-led planning would reinforce the realism of optimization.

The developed LP model presents an opportunity to test and follow the implementation of governance and development policies. Optimization helps to understand the trade-offs and conflicts in the system under alternative land use scenarios. Therefore, future research should aim at modelling the effects of governance decisions on traditional system management.

The research outcomes should also be validated by local farmers. The results go a long way towards confirming traditional farmer knowledge and current practices (Hildebrand et al. 2003). In order to improve the methodology and find effective planning tools that meet farmers’ and users’ problems and needs, the alternatives should be discussed with the farmers (Ellis et al. 2004). The tools should enhance endogenous cultural heritage and promote long-term ecological and economic sustainability.

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