TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Forst-, Geo- und Hydrowissenschaften

Management of Natural Stands of *Acacia seyal* Del. variety *seyal* (Brenan) for Production of Gum *Talha*, South Kordofan, Sudan

Dissertation for awarding the academic degree
Doctor rerum silvaticarum (Dr. rer. silv.)

Submitted by
Mohammed Hamed Mohammed
MSc. Forestry, University of Khartoum, Sudan

Evaluators:

Prof. Dr. rer. silv. habil. Heinz Röhle
Technical University of Dresden, Institute of Forest Growth and Computer Sciences

Prof. Dr. Mohamed El Mukhtar Ballal
Forestry Research Centre, Soba, Khartoum

Tharandt, May 4, 2011

Explanation of the doctoral candidate

This is to certify that this copy is fully congruent with the original copy of the dissertation with the topic:

„Management of Natural Stands of *Acacia seyal* Del. Variety *seyal* (Brenan) for Production of Gum *Talha*, South Kordofan, Sudan“

Tharandt, May 4, 2011

Mohammed

Declaration

I hereby certify that this thesis entitled “**Management of Natural Stands of *Acacia seyal* Del. Variety *seyal* (Brenan) for Production of Gum *Talha*, South Kordofan, Sudan**” is my own work and that it has not been submitted anywhere for the award of any other academic degree. Where other sources of information have been used, they have been duly acknowledged in the text.

Tharandt, May 4, 2011

Mohammed

To m*y parents, my wife Hawa, my lovely kids Abdalla, Elharith and Hiba, I dedicate this work*

Tharandt, May 4, 2011

Mohammed

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ACRONYMS AND ABBREVIATIONS

A.	Acacia
a.s.l.	Above sea level
AGB	Above ground biomass
AIC	Akaike´s information Criterion
ANOVA	Analysis of variance
ARC	Agricultural Research Corporation, Sudan
BA	Stand basal area (m^2) per unit area
BAL	Basal area of the largest tree
CART	Classification and Regression Tree
CD	Crown diameter (m)
CI	Competition index
cm	Centimeter
CPA	Comprehensive Peace Agreement
CPF	Crown permeability factor
CR	Crown radius (m)
CrPA	Crown projection area (m^2)
DBH	Diameter at breast height (cm)
FAO	Food and Agricultural Organization of the United Nations
FNC	Forests National Corporation
FRA	Global Forest Resources Assessment
GAC	Gum Arabic Company Ltd.
GLM	General linear model
IES	Institute of Environmental Studies, University of Khartoum, Sudan
IIED	International Institute of Environment and Development
JECFA	Joint Expert Committee on Food Additives
LPG	Liquefied petroleum gas
m	Meter
MAI	Mean annual increment
MCR	Mean crown radius for overstory trees
mm	Millimeter
MSE	Mean square error
NAS	National Academy of Science
NCP	National Congress Party, Sudan
NFTA	Nitrogen Fixing Tree Association
NTFPs	Non-timber forest products
OWL	Other wood land
PI	Periodic increment
QMD	Quadratic mean diameter
RIZ	Radius of influence zone
ROI	Radius of influence
SPLA	Sudanese People Liberation Army
UNDP	United Nations Development Program
WHO	World Health Organization

ACKNOWLEDGEMENTS

During the development of this thesis, there are many people from whom I have received advice and encouragement I am greatly indebted to them.

I would like to express my deep gratitude and thanks to Prof. Dr. Heinz Röhle for his continuous supervision and guidance during my PhD studies.

Thanks to Dr. Dorothea Gerold, Dr. Klaus Römisch and Prof. Dr. Uta Berger for their comments and assistance in statistical analysis. Thanks also due to Juliane Vogt for her effort to teach me R program and Janine Murphy, from Canada, for editing the manuscript.

Without the support of many people the field work would not be possible. Among them I would like especially to thank Mr. Mohamed Ahmed Ageed, Director, El Abbassia forest Division, Mr. Hamed Elmanzoul, Inspector, Umfakarin forest and Yahia Abutaba for their help and assistance.

I am also indebted to University of Kordofan for giving me this opportunity to study in Germany and to the Ministry of Higher Education and Scientific Research, Sudan for the scholarship.

Last but not least, I would like to thank all my colleagues at Institute of Forest Growth and Forest Computer Sciences, TU-Dresden for their valuable comments and help. Special thanks to Ms. Skibbe for translating the summary and theses to German language. I would like also to thanks the Sudanese group in Dresden for their lovely companion. Grateful thanks are also due to my colleagues (Mr. Elsheikh A/Kareem, Dr. Awad Abdalla and Mr. Ismael Ahmed) for following up some issues in Sudan relevant to my study. Special thanks are due to my wife and my kids for their patient and encouraging me during their stay in Germany.

1 INTRODUCTION

1.1 Background

Acacia seyal Del. is a typical tree in the African semi zones. It is a small to medium-sized tree that reaches a height of 12-17 m (Hall and McAllan, 1993; McAllan, 1993; von Maydell, 1990; National Academy of Sciences, NAS, 1980), has a stem diameter of 30 cm (Mustafa, 1997), or 60 cm under favourable conditions, and develops a characteristic umbrella-shaped crown (von Maydell, 1990). *Acacia seyal* usually reaches 9-10 m in height at maturity (Nitrogen Fixing Tree Association, NFTA, 1994). Several authors provide a valuable description of *Acacia seyal* (see for example; Elamin, 1990; Hall and McAllan, 1993; McAllan, 1993; Mustafa, 1997; von Maydell, 1990; NAS, 1980).

Like other acacias, *A. seyal* is widely distributed in the African savannas (Booth and Wickens, 1988; McAllan, 1993), often dominates the vegetation community and in some areas forms pure stands (McAllan, 1993; Wickens *et al*., 1995). It is considered one of the most common trees on clay plains that flood during the rainy season (McAllan, 1993).

The species is an important source of fuel wood, building poles, forage, commercial gums, and tannins (ELamin, 1990; Mustafa, 1997; von Maydell, 1990; NAS, 1979, 1980; Wickens *et al*., 1995) and is a source of nectar for honeybees (Booth and Wickens, 1988). *A. seyal* produces gum which though of inferior quality in comparison to that of *Acacia senegal*, is traded in Sudan under the name ´´gum *talha*´´ and makes up to 10 percent of the annual exported gum Arabic (Barbier *et al.*, 1990; McAllan, 1993; NFTA, 1994). Unlike gum from *A. senegal*, gum *talha* is not recognized as an acceptable food additive (Hall and McAllan, 1993).

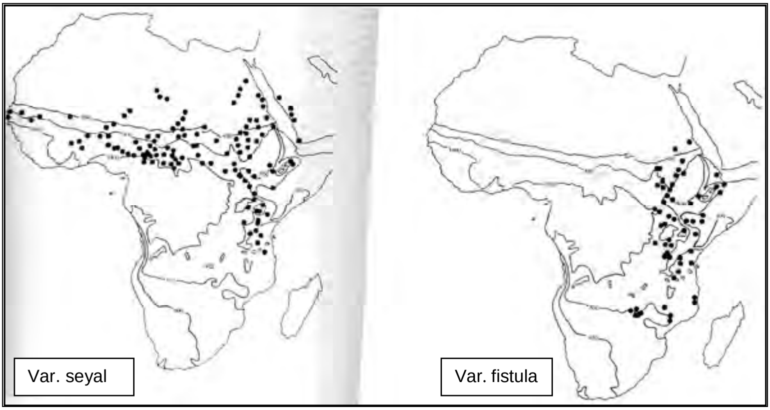
Additionally, *A. seyal* serves valuable ecological functions such as reducing soil erosion and acting as a defence line for desert encroachment in many parts of the Sudan, as is the case for the selected location for the present study, the Umfakarin forest reserve. Like other Leguminous, *A. seyal* is a nitrogen fixing tree which can be integrated into an agro-forestry system to enhance the growth of agricultural crops.

The species requires annual rainfalls of 250-1000 mm and it can withstand inundation better than other acacias (von Maydell, 1990; NAS, 1980). The species thrives in most soil types, even in heavy clay and stony soils found on the plains (McAllan, 1993; NAS, 1980). It prefers temperatures between 15-35 ºC (Vogt, 1995). It often grows with other tree species, such as *Acacia sieberana*, *Anogeissus leiocarpus*, *Balanites aegyptiaca*, *Faidherbia albida* and *Ziziphus mauritiana* (McAllan, 1993).

In general, there are two main varieties of *A. seyal*; variety *seyal* and variety *fistula*. Variety *seyal* is found in both western and eastern Africa and also on the Arabian Peninsula, while variety *fistula* is found in the eastern parts of Africa (McAllan, 1993). NAS (1980) and NFTA (1994) indicate that variety *seyal* is native to northern-tropical Africa and Egypt. The two varieties can be easily distinguished; variety *seyal* has a greenish-yellow to reddish-brown bark, while variety *fistula* has white to greenish-yellow bark (McAllan, 1993). Figure **1**.**1** shows the distribution of *A. seyal* varieties, with respect to rainfall.

In Sudan, the two varieties occur naturally in the low rainfall savannah zone and extend from Gadarif, Blue Nile, and White Nile to clay plains around Nuba Mountains and the Darfur Region (El Amin, 1990; Mustafa, 1997; Sahni, 1968). The species is distributed throughout its natural range, and is usually associated with *Balanites aegyptiaca* in the *Acacia seyal*-*Balanites* woodland area. In such formation, *A. seyal* is the dominant species, forming pure dense stands in many areas. According to Mustafa (1997), this formation begins to emerge with an increase in the annual rainfall to accumulations of more than 500 mm.

In the savanna region of Sudan, *A. seyal* has been subjected to large-scale clearing for mechanized agriculture (Mustafa, 1997; Vink, 1990; Wickens *et al*., 1995) associated with firewood and charcoal production to meet energy requirements. Besides clearance for mechanized farming and wood fuel, other factors such as grazing, deliberate and undeliberate fires also have a significant negative impact, not only on natural stands of *A. seyal* but also on natural forests in Sudan.



(Source: Hall and McAllan, 1993; McAllan, 1993)

Figure 1.1 Distribution of *Acacia seyal* varieties in Africa, with respect to rainfall

1.2 ***Problem statement***

Much of the pressure on Sudan's forests is caused by the exploitation of wood resources for mechanized farming and fuel-wood. The dependence of more than 80 percent of Sudan’s rural population on the wood biomass for their daily energy needs has accelerated the depletion of natural forest resources, as wood biomass is the most dominant and accessible source of energy. About 200,000 hectares of natural woodlands and forests are annually replaced and claimed by the agriculture (FAO, 2005) associated with the production of firewood and charcoal. As a result of such activities, for example mechanized farming and the extraction of wood fuel, natural forest areas have been fragmented and their ecological functions have notably decreased. Additionally, wood volume extracted from natural forests has also decreased. *A. seyal* natural stands provide a typical example to this practice, where vast areas are annually replaced for the above mentioned purposes.

A. seyal grows naturally in the clay plains of central and eastern Sudan and has extensively managed for firewood and charcoal production in order to meet energy requirements. The species forms either pure stands of different densities (dense, medium to poor) or mixed stands associated with other tree species.

Forest management in Sudan mainly focuses on wood production, for either fuel wood or sawn timber, in plantations and/or natural forests. However, non-timber forest products (NTFPs) extracted from natural forests and/or plantations, such as gum, are also very important and often have significant contribution to rural and national economies of many African countries (Ballal, 2002; Chikamai *et al*., 2009; Seif el Din and Zarroug, 1998). For example, in the Liban district of Ethiopia, Lemenih *et al*. (2003) indicated that gum production activities contribute to about 33 percent of the annual household subsistence, ranking second after livestock in the overall household livelihood. Included in these NTFPs is gum *talha,* the natural product of *A. seyal*.

The natural gum exudate (gum *talha*) is obtained from stems and branches of *A. seyal* trees. In some areas, such as Kordofan and Darfur regions, gum *talha* is collected by local people and sold in the market; separate from gum *hashab* (gum from *A. senegal*). In some regions of Ethiopia, gums obtained from *A. senegal* and *A.*

seyal, are also traded separately (Lemenih *et al*., 2003). Although, the species is reported to produce a significant amount of gum *talha*, little information is known about the potential of the species to produce gum.

Studies on the potentiality of *A. seyal* to produce gum under different stand densities and its response to tapping techniques, giving consideration to the amount of gum yielded by tree per season, are limited. Trees of *A. seyal* usually grow under different stand densities. Thinning practices often take place to reduce competition among trees, mainly to enhance tree growth for wood production. Such practices are rarely conducted for the promotion of gum *talha* production. Information regarding the effect of tree competition on gum *talha* production is limited.

1.3 *Objectives of the study*

Based on the problems outlined above, the general objective of this study is to manage the natural stands of *A. seyal* for production of gum *talha*.

Specific objectives

In order to realize the general goal of the current study, the following specific objectives are formulated:

- to determine the standing volume of natural *A. seyal* growing in different stand densities;
- to study the competition among trees of *A. seyal* in natural stands;
- to examine the effect of tapping techniques (tools) and time of tapping on gum *talha* productivity; and
- to develop models to be used for the prediction of gum *talha* yields.

1.4 Hypotheses of the study

The following hypotheses are proposed:

- There are high differences in gum *talha* yield due to tree competition.
- Yield of gum *talha* is affected by tapping techniques and time of tapping.
- Tree dimensions, such as the diameter at breast height (DBH), has an impact on gum *talha* yield.

1.5 Organization of the study

The study consists of five main chapters. The first chapter provides the general background on the natural stands of *A. seyal*, including its distribution and uses. Here, the problem statement, objectives and hypotheses of the study are also highlighted. A literature review is highlighted in the second chapter. This chapter also describes in general natural forest resources in Sudan, with special reference to the management of natural *A. seyal* stands. Furthermore, gum producing trees and the production of gum *talha* from natural stands of *A. seyal* and the factors that affect its production are also presented in this chapter. Chapter two also focuses on the competition among *A. seyal* trees of different stand densities. Physical attributes of the study area, beside its population, land use patterns and forest activities, are addressed in the third chapter. The methods used for data collection and analysis are explained in the same chapter. Results and discussion are highlighted in chapter four and five, respectively. A summary of the thesis, zusammenfassung (summary in German), references and appendices are provided at end of the thesis. Part of the results of this thesis was presented in international conferences[1] and published in scientific journals.

[1] Publications:

Mohammed, M. H. and Röhle, H. (2009). Effect of tree density and tapping techniques on the productivity of gum *talha* from *Acacia seyal* in South Kordofan, Sudan. International Conference on Research on Food Security, Natural Resource Management and Rural Development, Oct. 6-8, 2009, Hamburg. ISBN: 978-3-9801686-7-0 (Book of abstracts p 402). URL: http://www.tropentag.de/2009/abstracts/full/93.pdf.

Mohammed, M. H. and Röhle, H. (2010). Gum *talha* from *Acacia seyal* Del. variety *seyal* in South Kordofan, Sudan. *Research Journal of Forestry*, accepted on December 8, 2010.

Mohammed, M. H. and Röhle, H. (2010). Studying the competition in natural stands of *Acacia seyal* Del. variety *seyal*. International Conference Forestry: Bridge to the Future. University of Forestry, Sofia, May 13-15, 2010, Bulgaria. Book of abstracts p 93; ISBN: 978-954-332-072-1. Paper submitted on May 13, 2010 to journal “*Forest Ideas*” issued by the University of Forestry in Sofia.

2 SCIENTIFIC BACKGROUND

2.1 Natural forest resources in Sudan

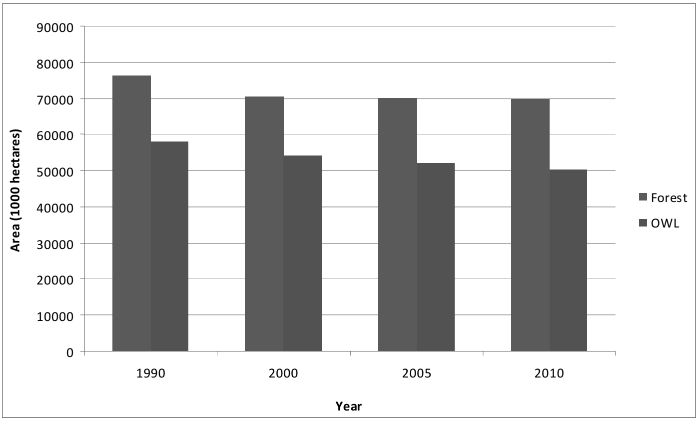
Various forest inventories were created in order to study the extent and the composition of forest resources in Sudan (Dawelbait *et al*., 2006). However, the majority of previous forest inventories were either partially conducted (not covering the whole country) or are incomplete (Dawelbait *et al*., 2006; Forests National Corporation, FNC, 2007). Based on these inventories, the total area of forest in Sudan is estimated to cover about 28 percent of the country's total land (250.6 million hectares), of which only 4.8 per cent was reserved[2] in 2007 (Forest Resources Assessment, FRA, 2010). Nevertheless, the Comprehensive National Strategy (CNS 1992-2002), a government formulated and enacted policy, called for the allocation of 25% (59.4 million hectares) of the country's total area for forest reserves (FNC, 2007). This estimate does not include other wooded lands[3] (OWL), areas which are estimated, according to the recent estimates of Global Forest Resources Assessment in 2010, to cover about 20 percent of the country's total area. Estimates of forest and other wooded land areas over time are provided in Figure **2.1**. According to these numbers, forest area is seemingly constant after 2000, but the changes in OWL areas may be attributed to the conversion of OWL into forests (FRA, 2010).

The World Bank (1986, cited in Mustafa, 1997) approximated that the average growing stock for natural forests in the Sudanese dry lands was about 24 m^3/ha. However, recently the total growing stock of forest and OWL was estimated to be 5.5 m^3/ha and the above ground biomass (AGB) is believed to be about 13 metric tons oven-dry weight (FRA, 2010). The share of biomass in total energy consumption was projected to account for from 71 to more than 82 percent of the total energy consumed in the country (FNC, 2007; Salih, 1994). After the commencement of oil production, the use of biomass energy alternatives, for example liquefied petroleum

[2] According to FRA's (2010) definition, forest reserves are all forest areas registered in the government gazette as Forest National Corporation assets. In these reserves, cutting trees is concentrated and replanting is made immediately after removal.

[3] Other wooded land is defined, according to FRA (2010), as land not classified as a "Forest", which spans more than 0.5 hectares, has trees higher than 5 meters, and a canopy cover of 5-10 percent, or trees able to reach these thresholds *in situ*. OWL may also be a combination of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly used for agricultural or urban land.

gas LPG, kerosene, etc, will have a positive impact on reducing pressure on natural forests (FNC, 2007).



Source: (FRA, 2010)

Figure 2.1 Sudan forest and other wooded land (OWL) areas 1990-2010

2.2 Production of acacia gum

2.2.1 Gum producing acacia tree species

The genus acacia, family *mimosaceae*, is widely distributed in the tropical and subtropical regions of the world, most commonly in Africa and Australia in addition to the Asia-Pacific region and the Americas (Orchard and Wilson, 2001). Gum acacia is a natural gum derived from acacia trees. Various acacia tree species, in several semi-arid African countries, are known to produce gum (Chikamai, 1999).

2.2.1.1 Gum from acacia natural stands

Natural acacia woodlands occupy large areas of the African savannah. According to Chikamai (1999) most acacia species produce gum based on natural exudation in natural stands and only four of them produce gum based on tapping, including *A. senegal* in nine African countries including Sudan, *A. laeta* in Chad and Mali, *A. ehrenbergiana* in Senegal and *A. Karroo* in Zimbabwe. Table **2.1** provides a summary of some acacia species (gum-producing trees), and the source and method of gum production in selected African countries.

2.2.1.2 Gum from acacia plantations

Brown (2000) stated that “acacias are planted mainly in Africa, Indonesia and on the Indian subcontinent”. In some African countries, Burkina Faso, Ethiopia, Mali, Mauritania, Niger, Senegal and Sudan, acacia plantations are established for the production of gum Arabic mainly from the *A. senegal* species (Brown, 2000; Chikamai, 1999). Indonesian acacia plantations, i.e. *A. mangium,* are mainly established to supply wood material for pulp and paper industries (Aruan, 2004). Other countries establish acacia plantations for different purposes such as soil and water protection, recreational purposes, as fuel-wood, and for sawn timber (Brown, 2000; Elsiddig, 2003a; Orchard and Wilson, 2001).

Recent studies carried out by Ballal *et al*. (2005b) in Sudan investigated the gum yield variations in natural stands and plantations of *A. senegal* under different management regimes. In general, the average gum yield from *A. senegal* in Sudan is about 250 g/tree/season (IIED and IES, 1990). Previous estimates of gum Arabic yield from the same species were found to range from 100-200 g/tree (FAO, 1978). According to Ballal (2002), the type of stand was factored into the above estimates. In this context, he estimated the yield of gum hashab (gum derived from *A. senegal*) in plantations and natural stands. His estimates ranged from 40.5-87 and 33.0-47.7 kg/ha in plantations and natural stands, respectively.

2.2.2 Gum belt

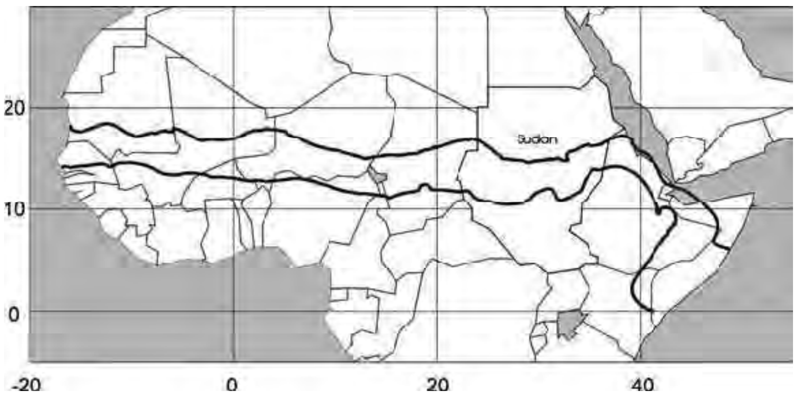
Geographically (Figure **2.2**), the gum belt occurs as a broad band that ranges from Mauritania, Senegal and Mali in the west, through Burkina Faso, northern Benin, Niger, and northern parts of Nigeria, Cameroon and Chad and from the northern Central African Republic to Sudan, Eritrea, Ethiopia and Somalia in the Horn of Africa (Ahmed, 2006). According to the International Institute for Environment and Development IIED and the Institute of Environmental Studies IES (IIED and IES, 1990), the Sudanese gum Arabic belt marks the area of Central Sudan, extending between 10 and 14°N and accounts for around one fifth of Sudan’s total area, covering an area where low rainfall interacts with sandy and clay soils. The belt acts as an important area as it provides vital economic activities for rural communities. Rural people within the Sudanese gum belt derive their income from several land-use activities, including agriculture, grazing, and forest exploitation such as the collection of forest products including gum Arabic (Sulieman, 2008). Within this region, *A.*

senegal is the only tree species which is planted and protected by farmers (Mohamed, 2006).

Table 2.1 Gum producing trees, source and method of production in some African countries

		Production source		Production method	
	Botanical source	Plantations	Natural stands	Tapping	Natural exudate
Burkina Faso	*A. senegal*	**	**		**
	A. laeta		**		**
	A. seyal		**		**
	A. gourmaensis		**		**
	A. duggeoni		**		**
	A. raddiana		**		**
Chad	*A. senegal* var. *senegal*		**	**	**
	A. laeta		**	**	**
	A. seyal		**		**
	A. polycantha		**		**
Ethiopia	*A. senegal* var. *senegal*	**	**	**	**
	A. senegal var. *kerensis*		**		**
	A. seyal var. *seyal*		**		**
	A. seyal var. *fistula*		**		**
	A. polyacanthat		**		**
	A. drepanolobium		**		**
Ghana	*A. sieberana*		**		**
	A. polyacantha		**		**
Kenya	*A. senegal* var. *kerensis*		**		**
	A. paoli		**		**
Mali	*A. senegal*	**	**	**	**
	A. laeta	**	**	**	**
	A. seyal		**		**
	A. polycantha		**		**
	A. raddiana		**		**
Mauritania	*A. senegal*	**	**	**	**
	A. laeta		**		**
	A. seyal		**		**
	A. macrostachya		**		**
Niger	*A. senegal*	**	**	**	**
	A. seyal		**		**
	A. raddiana		**		
	A. tortilis		**		**
	A. polyacanthat		**		**
Nigeria	*A. senegal* var. *senegal*		**	**	**
	A. seyal var. *seyal*		**		**
	A. nilotica		**		**
Senegal	*A. senegal*	**	**	**	**
	A. ehrenbergiana		**	**	**
	A. laeta		**		**
	A. macrostachya		**		**
	A. macrothyrsa		**		**
	A. nilitica		**		**
	A. polycanthat		**		**
	A. sieberana		**		**
	A. tortilis		**		**
Sudan	*A. senegal* var. *senegal*	**	**	**	*
	A. seyal var. *seyal*		**		**
Zimbabwe	*A. karroo*		**	**	**

**: indicates gum production source and method of production.
Source: (Chikamai, 1999)



Source: (Elmqvist *et al*., 2005)

Figure 2.2 Gum belt in Africa including Sudan

2.2.3 Gum Arabic production in Sudan

Gum Arabic[4] producing trees grow in most African countries, especially in Sub-Saharan Africa; nevertheless, most of the world's gum Arabic supply comes from Sudan (Ahmed, 2006; Wickens *et al*., 1995). In Sudan, several acacia species produce gum of different quantities and qualities. However, only gum *Hashab* (gum from *Acacia senegal*) is permitted for the food trade and the remaining types are used for industrial purposes (Wickens *et al*., 1995).

Gum Arabic is an important natural product of *Acacia senegal* (L.) Willd. and *Acacia seyal* Del. trees (IIED and IES, 1990). In Sudan, gum Arabic is obtained by tapping *A. senegal* trees in natural stands and/or plantations (Abdelnour 1999; Ballal *et al*. 2005a). However, gum from *A. seyal* (*talha*) is mostly obtained from natural stands and through natural exudation (Abdelnour, 1999; Seif el Din and Zarroug, 1998). Sudan leads the world in the production and exportation of gum Arabic and accounts

[4] According to the Joint Expert Committee on Food Additives (Joint FAO/WHO Expert Committee on Food Additives, JECFA, 1997), gum Arabic is defined as the dried exudate obtained from the stems and branches of *Acacia senegal* (L) or closely related species like *A. seyal*.

for about 80 percent of the world's gum Arabic production (Abdelnour, 1999; Abdelnour and Osman, 1999; FNC, 2007; Tadesse *et al*., 2007). At the end of the 1990s, it contributed 70–90% of the world's production (Elmqvist *et al*., 2005). However, recently gum production in Sudan has declined and yields also vary increasingly from year to year due to several factors, such as deforestation (Rahim, 2006) and price policies (Elmqvist *et al*., 2005). The product is one of the main agricultural export commodities produced in traditional rain-fed agriculture (Abdelnour, 1999; IIED and IES, 1990).

2.2.3.1 Gum Arabic production methods in Sudan

Gum Arabic, particularly gum from *A. senegal* trees, is collected by tapping *A. senegal* trees (local name: *hashab*), whereas natural exudation is collected from other acacia species. Gum Arabic production in Sudan is practiced using two main production systems, *hashab* owners and *hashab* renters. Many studies describe the two production systems of gum Arabic in Sudan (Ahmed, 2006; IIED and IES, 1990). Most of the gum is produced by smallholders on individual farms where the trees grow naturally (Elmqvist *et al*., 2005). Tapping, by making small incisions into the tree bark, begins in the hot and dry season when trees start to shed their leaves (Abdelnour, 1999; Ahmed, 2006). Trees that exceed 4 years in age are usually ready for tapping (IIED and IES, 1990). Traditional axes have been used for tapping *A. senegal* trees. Recently, a recommended tool (locally: *sonki*) that was designed and released by the Agricultural Research Centre (ARC), Sudan, has also been used for tree tapping. First gum exudatation is collected in 4-6 weeks after tapping and the subsequent collections (up to seven) are done every 15 days (Abdelnour, 1999; IIED and IES, 1990).

Several scholars have assessed the variations in gum arabic production in Sudan (see for example: Ballal *et al*., 2005b; IIED and IES, 1990). Studies by the IIED and IES (1990), indicated that there are pronounced variations in *A. senegal* stands both in clay and sandy areas, in terms of stand area, condition, stand density, production age, method of tapping, accessibility to producers, and the supply of inputs.

In other countries, such as Nigeria and Ethiopa, gum arabic production per unit area also varies according to stand type. In the Zamfara State, Nigeria, Unanaonwi (2009) studied the gum Arabic yield in plantations and natural stands. He showed that the average gum yield per tree was estimated to be 85.0 and 87.7g, corresponding to 53.1 and 18.6kg/ha, respectively, for plantations where stand density is 625 trees per hectare and natural forests where there are 212 stems per hectare. In Liban, Ethiopia, annual production per hectare ranged between 66.6 to 202.6 kg (Lemenih *et al*., 2003). Lemenih *et al*. used results based on households interviews to estimate gum production per unit area from different acacia woodlands.

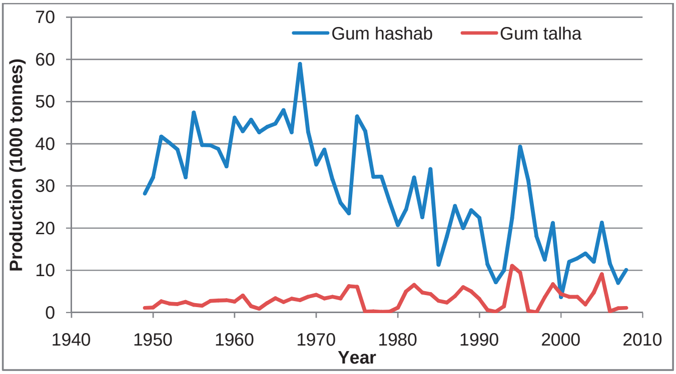
2.2.3.2 Gum *talha* the natural exudate from *Acacia seyal*

Gum *talha* is a natural exudate obtained from both the stem and branches of *A. seyal*. According to the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 1997) specification, gum *talha* is included in the term “gum Arabic” defined as the dried exudation obtained from the stems and branches of *A. senegal* (L.) or closely related species such as *A. seyal*. However, in Sudan, the gum from *A. senegal* and *A. seyal* are separated in both national statistics and trade (FAO, 1995). Unlike *A. senegal*, *A. seyal* in Sudan has not been cultivated for gum production. Nevertheless, the species is reported to produce significant amount of gum and has many traditional and industrial uses, which are generally friable and inferior to that of *A. senegal* (Anderson *et al*., 1984; FAO 1995; Hall and McAllan 1993; McAllan 1993).

2.2.3.2.1 Production of gum *talha* in Sudan

Despite the extensive use of *A. seyal* for firewood and charcoal, the species produces gum *talha* and constitutes to about 10 percent of Sudan’s total gum production, of which more than 50 percent comes from Kordofan region (Gum Arabic Company, GAC, 2008). This amount of gum production is collected only from natural exudates by local people in western Sudan (Fadl and Gebauer, 2004). Macrae and Merlin (2000) indicated that “the potential production of *talha* gum in Sudan is very large–estimated at least twice the amount of *hashab* hard gum”. Furthermore, they noted that this type of gum is not promoted by the Sudanese government, and thus remains attached to its reputation and market dominance in the *hashab* sector of the market.

Figure **2**.**3** depicts the general trend of gum Arabic in Sudan. Generally, the annual production of *hashab* gum fluctuates due to climatic variations (IIED and IES, 1990). In the case of gum *talha*, production potential estimates indicate that the mean annual production is about 4000 tons and between 3000 to 5000 tons are exported annually (Iqbal, 1993).



Source: (GAC, 2008)

Figure 2.3 Production trend of gum *hashab* and gum *talha* in Sudan

2.2.3.2.2 Factors affecting gum *talha* production

Many authors have deeply investigated factors that affect the production of gum Arabic (Ahmed, 2006; Ballal *et al*., 2005b; IIED and IES, 1990). However, most of the studies have focused on factors that affect gum *hashab* production, i.e. gum from *A. senegal* trees. Physical (soils, topography, climate), biotic, socio-economic, and institutional factors are the main influences that affect production of gum *hashab*. However, little information is available about factors that affect gum *talha* production, outside of Ali (2006) and Fadl and Gebauer (2004), who studied the affect of some factors on gum *talha* production, such as time, tool, and position of tapping.

2.3 Management of *Acacia seyal* natural stands in Sudan

In Sudan, both varieties of *A. seyal* are extensively managed for firewood and charcoal production. Historically people used *A. seyal* for generations for different purposes but mainly for the supply of firewood and charcoal (McAllan, 1993). A considerable proportion of fuel-wood derived from natural forests comes from *A. seyal* natural stands. Hence, the sustainable management of these natural stands is mainly undertaken for these purposes (Elsiddig, 2003a).

Generally, in semi-arid savannas the growth rate of *A. seyal* is low; however, early growth rates can be quite fast, trees can reach up to 1 meter in 3 months on favorable sites (McAllan, 1993). As indicated by Mustafa (1997), *A. seyal* trees can reach its reproductive stage rapidly, within 5 years in a natural stand, unless the growth is retarded by local events such as intensive browsing or fire. The periodic increment (PI) of the diameter at breast height and volume, respectively, does not exceed 1.3 cm and 5 m³/ha in 3 years (Vink, 1990a). In Sudan, the growth and yield of *A. seyal* vary according to region. For example, the mean annual increment (MAI), of *A. seyal*, in Garri forest, Blue Nile, ranged between 1.6-2.4 m³/ha/year during 1963-1966, where recorded annual rainfall was 657 to 718 mm. However, the MAI ranged between 1-1.5 m³/ha in the Rawashda forest in eastern Sudan (Vink, 1990a), where annual rainfall ranges between 450-500 mm. Trees managed on a 10-15 year rotation yield 10-35 m³/ha of fuel-wood per year (Orwa *et al*., 2009).

2.3.1 Volume and height functions for *Acacia seyal*

To estimate volume in forest stands, adequate and reliable allometric functions are needed to be established (Bjarnadottir *et al*., 2007). These functions (formulas 1 and 2) mathematically describe the relationship between the tree volume and diameter at breast height (DBH) and/or the height of the tree (Bjarnadottir *et al*., 2007; Pretzsch, 2009; West, 2004).

As the management of *A. seyal* in Sudan is mainly undertaken for fuelwood, most of the studies were conducted as part of the project “fuelwood development for energy in Sudan”. Volume and height functions have been developed, respectively, for predicting volume and the height of *A. seyal* in natural stands (Elsiddig, 2003b).

$$v = f(d) \qquad (1)$$

$$v = f(d, h) \qquad (2)$$

This means, volume (v) is a function (f) of diameter (d) when using only (d) such as in formula (1) or a function of d and height (h) when using both d and h as predictors (formula 2).

The height function (3) is another allometric function that describes the relationship between tree height and DBH (Kramer und Akça, 2008; West, 2004). It is also used to predict tree height using DBH as a predictor.

$$h = f(d) \qquad (3)$$

The stand height curve can be used to provide information about the development and growth stages of the stand; for example it can help determine whether it is a young or old stand. It also provides information about the competitive situation of the trees in the stand.

2.3.2 Silvicultural characteristics of *Acacia seyal*

The silvicultural system is a set of rules applied to a forest stand in order to ensure its renewal (Bollefontaine *et al*., 2000). There are three basic silvicultural systems that may be identified for natural forests in dry tropical zones; the coppice system, the high forest system, and the coppice with standards system. The coppice system is made up of stump and/or root sprouts, originating from “rejuvenation” cuttings, which constitute a vegetative reproduction system. The “high forest” is a stand made up of trees directly grown from seed on site. The “coppice with standards” is a mixed system designed to perpetuate stands with trees of which some have originated from seeds and others are derived from vegetative regeneration (Bollefontaine *et al*., 2000).

2.3.2.1 Direct seeding

Many direct seeding trials have been carried out in the dry tropical zones, and their success depends on several factors, such as seed quality, weed competition and anthropogenic disturbance (Bollefontaine *et al*., 2000). In general, propagation of *A. seyal* occurs via self-seeding and root suckers (Orwa *et al*., 2009). Nevertheless, seedlings can be raised in the tree nursery from seed or cuttings (McAllan, 1993). *A. seyal* can be established by direct seeding if there is reliable rainfall and adequate protection for the seedlings (Hall and McAllan, 1993; McAllan, 1993; Mustafa, 1997). Seed pretreatment, for example scarification, sulphuric acid treatment (Orwa *et al*., 2009), or soaking in hot water for 30 minutes (Hall and McAllan, 1993; McAllan, 1993), is important to accelerate seed germination but not essential. Management through coppicing is also possible and may help regenerate and manage species with good coppicing ability (Mustafa, 1997).

2.3.2.2 Natural regeneration of *Acacia seyal*

Regeneration is an important aspect for the development and management of forest stands. Therefore, the success of natural forest management depends on the success of natural regeneration which is influenced by many factors. The most important of which are soil seed bank (Du *et al*., 2007), gap size (Myers *et al*., 2000) and biophysical and soil factors, in addition to other disturbance factors such as the presence of herbivores and fires. Mustafa (1997) investigated some of these factors in his study on *A. seyal* regeneration in the dryland region of the Sudan clay plain. In order to maintain the ecological and other functions of the forest, it is necessary to gather information about regeneration. Natural regeneration starts when gaps occur. However, Mustafa (1997) illustrated that *A. seyal* seedlings were recruited from naturally dispersed seed regardless of the available gap size between the individual tree crowns.

2.3.2.3 Thinning

Savannah acacias' natural mortality is normally caused either due to competition or other disturbing factors such as fires, browsing, and droughts (Bukhari, 1998; Smith and Goodman, 1986). Like other savanna acacias, *A. seyal* responds to spacing and thinning regimes. According to NFTA (1994) *A. seyal*, for the production of poles and firewood in Sudan, has an assumed initial stock of 1000 stems per hectare, however regular thinning after 10 and 14 years can reduce stocking to 675 and 450 stems/ha, respectively. Employing a 4 m grid for spacing is suitable for sorghum and sesame intercropping (McAllan, 1993; NFTA, 1994).

Forest authorities in Sudan direct the commercial logging of mostly *A. nilotica* in the reserved riverine forests and *A. seyal* for firewood and charcoal to supply the cities, mostly via clearing *A. seyal* and other acacias from areas allocated for agriculture (Gorashi, 2001).

2.3.2.4 Pruning

Evaluations of the response to pruning all branches of *A. seyal* trees, for example pollarding and lopping, indicates a limited recovery capacity in mature trees and may lead to mortality (Bollefontaine *et al*., 2000; Orwa *et al*., 2009). In the dry season in western Sudan, the cattle owners formerly lopped the branches or the entire crown for their cattle in times of fodder scarcity (McAllan, 1993; Orwa *et al*., 2009).

2.4 Competition among trees in forest stands

Competition, as defined by Allaby (2006), is the "interaction between individuals of the same species, or between different species populations at the same trophic level, in which the growth and survival of one or all species or individuals is affected adversely". In ecology, competition is a biological process that occurs among individuals using the same limited resource (Begon *et al*., 2006; Berg, 2008; Kimmins, 2004). The resources for which plants commonly compete include water, light, soil minerals, and growing space (Berg, 2008). According to Allaby (2006) "competition leads either to the replacement of one species by another that has a competitive advantage, or to the modification of interacting species by selective adaptation (whereby competition is minimized by small behavioral differences, e.g. in feeding patterns)".

2.4.1 Types of competition

Competition can be grouped into two types, according to the mode of competition (mechanism) and the competing species. According to the mechanism, competition can be either interference or exploitative. Allaby (2006) defines the two types as follows: 1) interference competition occurs when two organisms demand the same resource and that resource is in short supply, and one of the organisms denies its competitors[5] access to the resource; 2) exploitation competition (exploitative competition) occurs when two species require the same limited resource and where the more efficient species is most likely to succeed. Competition according to competing species is either intra-specific or inter-specific competition (Kimmins, 2004). The first one occurs when individuals of the same species compete for a resource while the second occurs when individuals of different species compete for a resource.

In forest stands, trees grow close together and compete for resources. Individual trees interact spatially; hence the growth of some individuals is affected (Gadow and Hui, 1999). Trees that receive few resources usually perform and produce less than those receive sufficient resources. According to Wenger (1984), in a multi-layered stand competition among trees in the first layer results in gradual replacement of the

[5] A competitor according to Allaby (2006) is a plant species that exploits conditions of low stress and low disturbance.

intolerant trees and that leads to succession. Schwinning and Weiner (1998) in their study about the mechanisms of competition among plants stated that “when plants are competing, larger individuals often obtain a disproportionate share of the contested resources and suppress the growth of their smaller neighbors”. They further defined the mode of competition among plants according to their sizes into five categories. These include:

- complete size symmetric competition where resource uptake among competitors is independent of their relative sizes;
- partial size symmetry competition when the uptake of contested resources increases with plant size, but less than proportionally;
- perfect size symmetry where the uptake of the contested resources is proportional to size (equal uptake per unit size);
- partial size asymmetry where the uptake of contested resources increases with plant size, and larger plants receive a disproportionate share; and
- completely size-asymmetric competition, where the largest plants obtain all the contested resources.

Schwinning and Weiner (1998) also identified other types of competition such as “one-sided competition” or “dominance and suppression”, referring to the mode of competition that exists when larger plants obtain all the contested resource. In this case, the available resources assigned for the smaller plants decrease and, under severe competition, this leads to natural mortality.

2.4.2 Spatial and non-spatial competition

As noted by Hasenauer (2006), “the basic principle for most of the competition processes assumes a certain minimum distance between neighboring trees before competition occurs”. Based on this principle, competition can be distance-dependent or distance-independent (Alder, 1995; Hasenauer, 2006; Vanclay, 1994; Wimberly and Bare, 1996). The distance-dependent or spatial competition is based on the measurements of tree coordinates or locations (Biging and Dobbertin, 1992; Hegyi, 1974; Münder and Schröder, 2001; Pretzsch 1995; Pretzsch, 2009) in addition to stem and crown size (Pretzsch, 2009). Distance-independent or non-spatial competition is based on the measurements of stand density (Nagel, 1999; Pretzsch, 2009; Wykoff *et al*., 1982). Position-dependent and position-independent are also termed by Pretzsch (2009) referring to distance-dependent and distance-independent, respectively. Furthermore, he provides a valuable description of different approaches for measuring distance-dependent and distance-independent competition indices.

2.4.3 Measuring the degree of competition

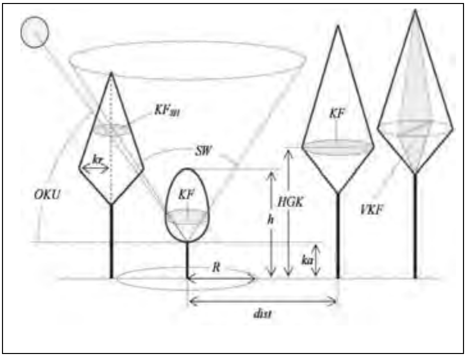
Measuring the degree of competition is an important element for forest growth and silviculture, as it affects the growth and yield of trees in forest stands. A competition index (CI) characterizes the degree to which the growing space of an individual plant is shared by other plants (De Luis *et al*., 1998). A CI describes the degree of competition caused by the adjacent trees to the growth and production capability of a subject tree. The term “competition index” has been intensively used in forest growth and yield research as a measure of individual trees’ resource availability (Pretzsch, 2009; Wichmann, 2002) and dominance or suppression of a tree in comparison to its neighbors (Wichmann, 2002). It is also used in silviculture as a tool to assess silvicultural management options, such as planting density (De Luis *et al*., 1998).

Recently, there has been considerable literature published about the methods of estimating the competition index (Alder, 1995; Biging and Dobbertin, 1992; Hegyi, 1974; Münder and Schröder, 2001; Nagel, 1999; Pretzsch, 1995; Pretzsch, 2009; Wykoff *et al*., 1982). These methods are based on different approaches for identifying the neighboring trees, for example using bases such as competitors that compete with the subject tree and evaluating the competition strength. A more detailed description of these methods is provided by several authors; (see for example, Alder, 1995; Gadow and Hui, 1999; Pretzsch, 2009; Vanclay, 1994).

Competitors’ selection and quantification for a CI can be completed by various methods, but generally there are two steps to measure the competition value for each subject tree that these methods were based on; first, the selection of the competitor trees; and second the quantification of the competition effect. The quantification of the competition indices using CroCom program will be described later in this chapter (see section 3.5). Figure **2**.**4** explains the different methods for the identification of the competitors. The figure describes some common approaches for competitors’ selection, as identified in scholarly works (Münder, 2005; Pretzsch, 2009; Schröder, 2003):

- Search cone method. The approach is based on the assumption that the competition for light is uniform in all directions and that the effect of neighboring trees increases by decreasing the distance from the target tree (Münder, 2005). In this method, an inverted cone with a 60° opening angle is placed on the target tree. The cone should be placed at 60% of the height of target tree. All trees whose their crowns fall within this search cone are considered competitors (Pretzsch, 2009).
- Fixed influence radius. This method employs a fixed radius called the “radius of influence” around the focal tree. All trees falling within this radius are considered competitors for the focal tree. A modified fixed radius method was applied in this study to identify the competitor trees of the *A*. *seyal* trees assigned for gum yield.
- South-oriented zone of influence. According to Münder (2005) and Schröder (2003) the method based on the assumption that the focal tree is shaded by the crown of competitors, mainly from the south, for example via sunlight interception where it is assumed that the sun is at its highest geographical position. All trees that intersected with the immaginary line of sunlight with reference to the subject tree were selected as competitors.
- Crowns overlap method. In this method, all trees whose crowns overlap with the crown of central tree are considered to be competitors (Bella, 1971).

Previous methods are based on distance-dependent approaches for the identification of competitors. Some approaches are based on distance-independent for selecting the competitors as described by Pretzsch (2009).



Source: (Röhle *et al*., 2003)

Figure 2.4 Methods of selection the competitor trees
Where: R = radius; dist = distance; ka = height to the beginning of the crown; h = height; HGK = height to the greatest crown width; VKF = vertical crown area; KF = horizontal crown area; SW = angle of the inverse cone; SH = height to the intersection point; kr = crown radius; OKU = the angle of incidence of sunlight to crown base of the subject tree.

3 MATERIALS AND METHODS

3.1 Background

This chapter provides an overview of the study area, highlighting the location, physical attributes, population and land-use patterns. Methods for data collection and analysis are also described in this chapter.

The current boundaries of South Kordofan state were established by the Comprehensive Peace Agreement (CPA), which took place in Kenya in 2005 between the Sudanese People Liberation Army (SPLA) and the National Congress Party (NCP) of the Sudan. South Kordofan is comprised of four main physiographic regions. These regions are the Nuba Mountains, the eastern plains, the southern plains, and the western sandy plains. The state (Lat. 9° 50´- 12° 46´ N and Long. 29° 15´- 32° 28´ E), which occupies the south part of Greater Kordofan, has an area of about 79470 km^2. Administratively the state is divided into eight localities; Rashad, Abu Gibeiha, Talodi, Kadugli, Lagawa, Assalam, Abyei and El Dilling, where Kadugli is the capital of the state.

3.2 Study area

This study was conducted in the Umfakarin Natural Forest Reserve (about 540 m a.s.l, Lat. 12° 29´- 12° 35´ N and Long. 31° 17´ 33 ´´- 31° 20´ E) (**Figure 3.1**). This forest has an area of about 2689 ha and lies 44 km north El Abbassiya town, belonging to the Rashad locality (7872 km^2), South Kordofan state. The forest was gazetted in 1993 under gazette number (8) and is surrounded by four villages (Umfakarin, Elhafirah, Elhafirah Dardig and Awlad Rahal). The inhabitants of these villages mainly depend on the reserved forest for firewood, charcoal, building materials, grazing, and hunting.

Sudan's forest legislation recognizes forest ownership as institutional, private and community forests, in addition to governmental forests, which are either state or central[6] forests. Regional (or state) forests are located in the specified state and are

[6] According to the FRA (2010) definition, central forests are forests owned by the central government (federal) institution (Forests National Corporation). Community forests (social forests) are forests owned by groups of rural population (villagers). Regional (state forests) are forests owned and administrated by the forest authority in that state. Individual private forests (community) are those which are owned by individuals (one or many). Institutions' forests are forests owned by agricultural schemes, farmer unions, and companies (private or public).

supervised by that state, while central forests can be elsewhere in Sudan, yet the central forest authority monitors and controls forests practices within them. South Kordofan state forests consist of eight administrative circles, each of which has a number of divisions in which the central and/or state forests are located and administered. For instance, Umfakarin forest is a central forest located in the El Abbassia division, in the Rashad circle, South Kordofan state but is under the direct supervision of the central forest authority. Figure **3.2** illustrates the status of the Umfakarin forest reserve in South Kordofan state forests.

The criteria for selecting this forest for the present study rests on the fact that the Umfakarin natural forest reserve is situated in the northeastern part of South Kordofan and is considered as the first defense line for desert encroachment in this part. Additionally, the forest consists of almost pure natural stands of *A. seyal* and is accessible during different seasons throughout the year, while most natural forests are not accessible to forest officers during rainy seasons.

■ Location of the study site; Umfakarin Natural Forest Reserve

Figure 3.1 Location of Umfakarin Natural Forest, South Kordofan, Sudan.
Available at: http://www.sd.undp.org/UNDP_protocol_areas.htm

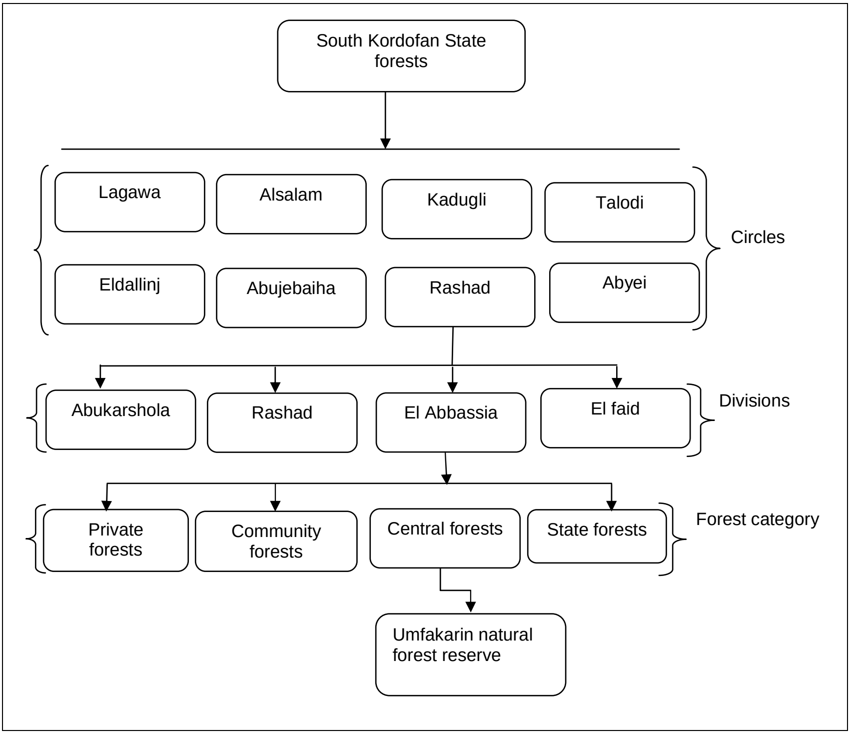


Figure 3.2 Status of the Umfakarin Natural Forest in South Kordofan state forests

3.2.1 Physical attributes

3.2.1.1 Climate

The northern part of South Kordofan is situated in a low-rainfall woodland savannah while the southern part is in a high-rainfall savannah. The annual rainfall ranges from 350-900 mm and increasing from north to south. Rainfall commences in May and lasts up to September or October, in southern parts of the state, with a peak in August. Temperatures range from 30-35℃. The types and densities of vegetation covers are distributed according to rainfall, soil and topography. Figure **3.3** depicts the climatic diagram (1997-2006) for the Rashad locality, the nearest meteorological station to the Umfakarin Natural Forest Reserve. This climatic diagram shows the curves for average monthly temperatures in ℃ versus the average monthly rainfall in mm with a ratio of 1:4. This means, for instance, that the distance along the ordinates is the same for 20 mm precipitation and 5℃ air temperature (Schultz, 1995). As described by FAO (2001) and Schultz (1995, 2005) at this ratio, times during which the precipitation curve is above the temperature curve are considered humid, while the remaining periods are classified as arid.

Seasonal flooding is the most conspicuous feature in the forest. Every year most parts of the forest, especially the dense vegetation patches, are inundated for almost two to four months. Figure **3.4** shows the conditions in the Umfakarin Reserve Forest during the rainy season 2007/2008.

3.2.1.2 Soil and topography

There are three different main soil types that prevail in South Kordofan; clay plains, sandy clay (non-cracking soils) locally known *Gardud,* and sandy soils. The clay plains comprise about 32 percent while the *Gardud* and sandy soils comprise about 27 and 21 percent of the total state area, respectively. The rest are rocky soils in hilly areas and other soils. Clay soils, and to some extent sandy clay and sandy soils, are suitable for the cultivation of cash crops and basic food staples. Sandy-clay loam, sandy-loam and *Mayaat* (soil under water bodies) are the major soil types that prevail in the Umfakarin Forest Reserve.

In general, the forest reserve can be described as a slightly undulating land surface with the exception to a few seasonal streams that penetrate some parts of the forest. No physical features seem to be clearly bounded by the forest reserve or inside the forest.

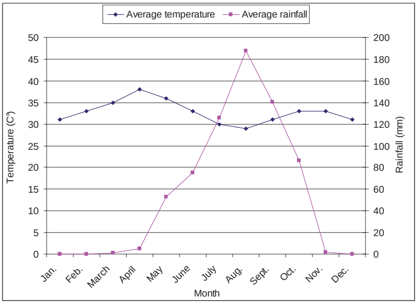


Figure 3.3 Climatic diagram (1997-2006) for the Rashad Locality, South Kordofan

Figure 3.4 Conditions of Umfakarin Natural Forest during rainy season, 2007/2008

3.2.1.3 Vegetation cover

Climatic factors, soil types and topography determine not only the distribution of vegetation cover but also the type of vegetation that grows in a certain area. Badi *et al*. (1989) stated that various types of woodland savannah are produced as a result of the influence of both rainfall and soil quality. Accordingly, vegetation type is gradually or drastically changed and distributed. Vegetation cover in the northern parts of the state is relatively poor and consists of scattered acacia trees followed by medium and dense stands of different tree species and shrubs, as rainfall increases to south.

According to Harrison and Jackson (1958), the area is classified as *A. seyal-Balanites* woodland, a low-rainfall woodland savannah, located on clay, where *A. seyal* trees dominates this type of vegetation associated with *Balanites aegyptiaca*. Other thorny and broad-leaf non-thorny woody species are also present, such as *A. mellifera*, *A. senegal* (in abandoned cultivated areas), *Terminalia spp* and *Dalbergia melanoxylon*. In the hilly areas, where the elevation reaches to 1000 m a.s.l, *Combretum hartmannianum* and *Anogeissus leiocarpus* are found together with *Sterculia setigera* and *Boswellia papyrifera*. Along seasonal streams and light seasonal drained sites, *Borassus aethiopum* is found, while *Hyphaene thebaica* is confined to wetter areas and along streams. Species such as *A. nilotica* are found in flooded areas. In limited areas introduced tree species are present, such as *Azadrachta indica, Ailanthus excelsa*, *Eculyptus spp*. and *Khaya senegalensis,* which are found in some plantations. Other shrub species, such as *Adenum obesum* (toxic) and *Feretia apodanthera* (used for tea), also occur in the region. Figure **3.5** illustrates forest cover[7] in Sudan and Kordofan based on the global forest resources assessment, FRA 2005.

Natural regeneration is the driving force of forest renewal. Figure **3.6** illustrates the density of *A. seyal* regeneration in open areas in the Umfakarin Forest.

The availability of herbs and grasses, such as *Asparagus sp*., *Triumpheta flavescens*, *Cympopogon nervatus*, *Tribulus teristeris*, *Acanthospermum hespideum, Hibiscus canabinus* etc, makes the area favourable for grazing by both domestic and wild animals. The diverse nature of vegetation cover attracts pastoralists to move from north Kordofan to south Kordofan during the dry seasons, in order to provide proper resources for their animals to graze.

[7] According to the definition set out by the FRA 2000 and 2005, the term forest includes natural forests and forest plantations and refers to land with a tree canopy cover of more than 10 percent and an area of more than 0.5 ha. Trees in forest should be able to reach a minimum height of 5 meters.

In the Umfakarin Forest, vegetation cover is about 75 percent[8], *A. seyal* represents 90 percent. Other woody plants are also found, such as *A. mellifera* at the forest's edge, *Balanites aegyptiaca*, *A. polycantha*, *A. senegal*, *A. nilotica* in water bodies, *A. sieberana*, *Cordia Africana*, *Boscia senegalensis* and *Dichrostachys cinerea*. The general structure of the Umfakarin Forest can be characterized by either type and/or the density of its prevailing vegetation. *A. seyal* of different densities dominates the forest. In this investigation, these densities can be categorized based on the number of trees per unit area, or into three strata-dense, medium, and slight, strata. The existence and diversity of the ground vegetation or understory are determined by the low density of the tree canopy that allows light to penetrate beneath the canopy.

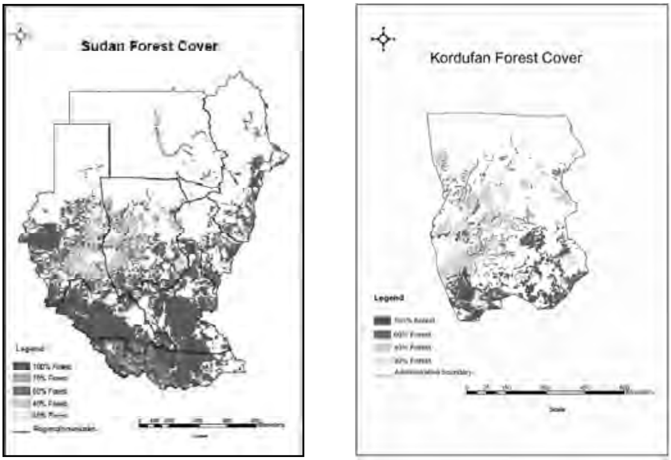
3.2.2 Population

According to the Sudan population census in 2008, South Kordofan has a population of 2.3 million persons, representing about 6 percent of the country's total population. The state is inhabited by a variety of ethnic groups practicing different livelihoods. Agriculture, livestock breeding, and the collection of timber and non-timber forest products are the residents' main livelihoods.

3.2.3 Land use patterns

The state has a comparative advantage in agricultural and horticultural crops, gum Arabic and livestock production. Although the state produces a surplus of food and cash crops, large numbers of inhabitants face food insecure, especially during rainfall, due to poor infrastructure and limited access to markets. The most important crops are sorghum, maize, cotton, sesame, millet, fruits, and vegetables. A near-majority of the population engages in agriculture. Rain-fed cultivation comprises both smallholder subsistence farming and large-scale mechanized farming. Small irrigated gardens exist where water is available from seasonal water sources or shallow aquifers. The total area of land that is suitable for agriculture in South Kordofan is in the range of 15 million *Feddans* (1 *Feddan* = 0.42 ha), of which seven million *Feddans* are demarcated and allocated for mechanized farming.

[8] Personal communication (September 10, 2007) with H. Elmanzoul (Umfakarin Forest Inspector)



Source: (Dawelbait *et al*. 2006)

Figure 3.5 Forest cover in Sudan and Kordofan

Figure 3.6 Regeneration of *A. seyal* in open areas in the Umfakarin Forest, 2007

3.2.4 Forest activities in the Umfakarin Natural Reserve Forest

Protection against illegal felling, fires, and planting (filling gaps) programmes are the only currently running forestry activities in the forest reserve (Figure **3.7**). Although there is a forest camp inside the reserve that exist to control illegal felling, more than 5 illegal felling cases was reported by the forest camp from October 2007 to February 2008. Cutting *A. seyal* for firewood and charcoal production is a common activity practiced by the inhabitants for income generation. To maintain the biodiversity of the forest reserve, the forest department in El Abbassia has started to fill gaps with different tree species, such as *A. seyal*, *A. senegal*, *A. nilotica*, *Balanites aegyptiaca* and *Hyphaene thebaica*. The population around the forest reserve engages in forest activities such as planting and weeding programmes.

Figure 3.7 Forest activities in the Umfakarin Natural Forest Reserve, 2007/2008
Line weeding (top left and right), fire damage assessment (bottom left) and fire line around the forest camp (bottom right).

3.3 Data collection

Data for this study were collected between September 2007 and February 2008 at the Umfakarin Natural Forest Reserve, South Kordofan, Sudan.

3.3.1 Reconnaissance survey

The purpose of the reconnaissance survey was to provide a general background about the area, through observations about the forest under investigation, in terms of geographical aspects, forest cover, composition, and structure. This survey was completed in September 2007 by both automobile and foot.

3.3.2 Pre-test samples

Pre-test samples were taken in September 2007 to:

1. Check all the diameter classes. Since *A. seyal* is a multi-stem species (McAllan, 1993), usually forking below diameter at breast height (DBH), it was decided to measure the diameter at a height of 0.25 m to quickly set the diameter classes. Four classes of diameter were determined; 9-11.5, 13.5-16, 18-20.5 and above 21 cm, based on diameter of 0.25 m height ($d_{0.25}$). This criterion was used to determine which trees (subject trees) would be selected and used in actual field survey of gum *talha* production.
2. Check the stand densities of natural *A. seyal*. In this investigation, three stand density categories, dense, medium and slight, were determined. The dense stratum, 396 stem/ha on average, is usually inundated for at least two months during rainy season. However, medium and slight strata, with an average 271 and 209 stem/ha, respectively, are not inundated.
3. Fix the so-called ‘radius of influence’ (ROI) within which neighboring trees could be identified as competitors for the focal tree.

The term focal, target or subject tree is used in this study to refer to the *A. seyal* tree, either tapped by local tools or untapped, selected for gum exudate collection. The results of pre-test were not incorporated into the results of this study. Two types of field data were gathered, namely mensurational and gum tapping and collection data.

3.3.3 Mensurational data

The objective was to determine the stocking (yield characteristics) per unit area through the measurement of tree dimensions. According to observations obtained via the reconnaissance survey and pre-test sampling, three categories of stand density were determined based on the number of trees per unit area. These categories, as described in section 3.3.2, are dense, medium and slight strata (Figure **3.8**). In each stratum, single focal trees were selected based on diameter at 0.25 m height ($d_{0.25}$). A total of 482 target trees were selected of which 158, 160, and 164 individual trees were classified in dense, medium and slight strata, respectively.

3.3.3.1 Single tree measurement

To achieve the objective of this study the following parameters were measured for all subject trees and neighbouring trees within the radius of influence for each target tree:

- Tree species by number and diameter over bark (in, cm) at heights of 0.25 ($d_{0.25}$), 0.50 ($d_{0.50}$) meter and diameter at breast height (hereinafter referred to as DBH, in cm) using diameter tape. To facilitate measuring a measuring pole was used to fix the positions of different diameters (Figure **3.9**). Target trees were identified based on diameter at 0.25 m height (or $d_{0.25}$). This procedure was completed to facilitate a quick selection of target trees, as the species is a multi-stemmed and usually forks below the DBH.
- Tree height (h, in m) using Blume Leiss.
- Estimation of the beginning of the crown (m).
- Crown radius (CR, in m) which, as defined by Van Laar and Akça, (2007), is the distance between the centre of the tree bole and the outer edge of the crown. The measurements were taken in up to 4 cardinal directions, using a measuring tape and compass, starting from the north by an interval of 90 degrees. The projection of the crown was determined according to Grote (2003) and Röhle (1986) by vertically looking up to the crown extension.
- Angles and distances of neighboring trees from the focal tree using both a compass and measuring tape.
- Qualitative indication of the target tree, such as healthy or infected.
- Number and species of natural regeneration lower and higher than 1.3 m height.

Figure 3.8 Different densities of *A. seyal* trees in the Umfakarin Forest, South Kordofan, 2007
Top left: dense stratum; top right: medium stratum; bottom left: slight stratum; and bottom right: *A. seyal* associated with other species.

Figure 3.9 Measuring pole used for marking the position of tree diameters

3.3.3.2 Identifying the competitors

Normally when measuring trees in a stand, sample plots of a specific radius are distributed systematically or randomly within the forest stand. In this study, each sample has a different radius referred to as the radius of influence (ROI) or the radius of influence zone (RIZ). These terms are frequently used in forest growth and measurement for the calculation of competition indices (CIs) as a measure of the competition between trees in forest stands. In previous studies, the criteria for determining RIZ, and thus the competitors, was based on different methods. For example, Arney (1973) used the radius of influence equivalent to open-grown crown radius of Douglas-fir trees on the Pacific coast. While Hegyi (1974), includes all competitors within a radius of ten feet (3.05 m). In the present study, a different approach was adopted to select competitor trees, as trees have different forms, especially the tropical dry ones such as *A. seyal* in Sudan. The criterion for identifying competitors was based on the height of the subject tree. The radius of influence was determined after several attempts in pre-test sampling. This radius of the circle is a function of tree size (Gadow and Hui, 1999). The suitable influence zone used to identify competitors was defined as the radius of a circle equal to the height of subject tree multiplied by a factor (1.25), $r = h*1.25$, where r is the radius of influence (in, m) and h is tree height (in, m). All trees falling within this radius were considered to be competitors of the focal tree. Several characteristics such as DBH, tree height, height to the crown base, and crown radii of target tree and its competitors beside competitors coordinates were measured and incorporated into the computation of the competition indices.

3.3.3.3 Tree mapping

Polar coordinates were used to describe the position of individual trees in each sample plot. Within the radius of influence, trees were mapped using the subject tree as a focal point. Figure **3.10** shows the distribution of neighbourhood trees, whereby the distance from the target tree fell within an area of 380.13 m^2 (radius or r = 11 m). Mapping the locations of neighbourhood trees was carried out according to Dimov (2004), by measuring the angle from the north using a compass and the horizontal distance (m) to each tree from the subject tree. Appendix **1** shows the form used for tree measurements and tree mapping.

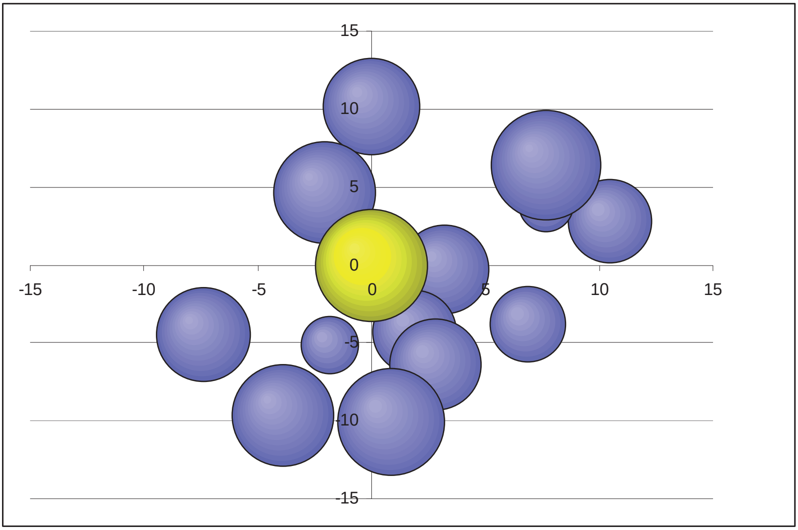


Figure 3.10 Positions of neighborhood trees relative to the subject *A. seyal* tree within a radius of 11 m (380.13 m²) in a dense stratum in the Umfakarin Forest, South Kordofan, Sudan. The size of each bubble refers to the circular crown projection area (CCPA, in m²). Subject tree (yellow) and competitor trees (blue).

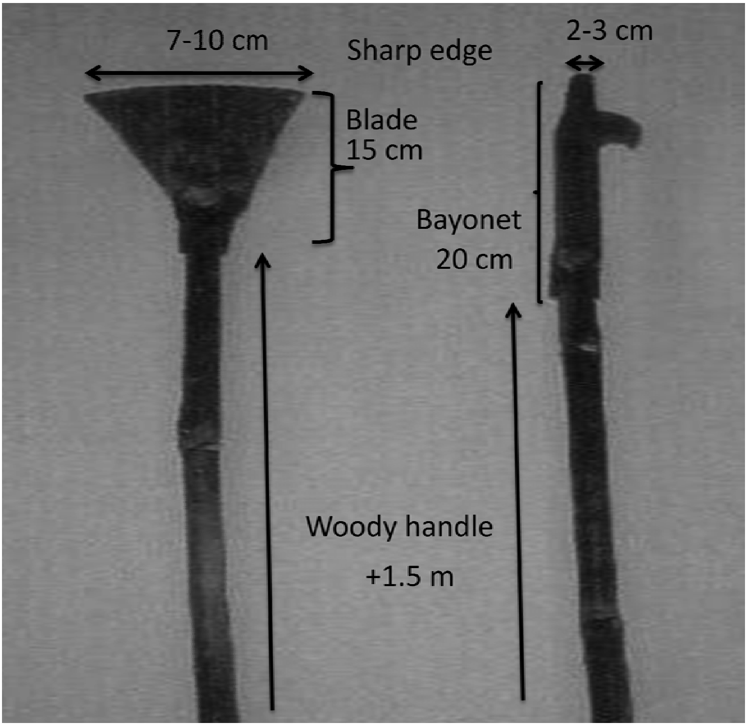
3.3.4 Gum tapping and collection techniques

3.3.4.1 Background

Tapping refers to scratching the bark of the stem and/or branches of the tree, while avoiding damaging the cambium layer, in order to accelerate gum exudation. Like other acacias, *A. seyal* produces exudates (gum) either naturally or following scratching of the bark. Traditionally, the natural exudates from *A. seyal* are often collected by local people in both the Kordofan and Darfur regions, Sudan. Different local tools are used by gum tappers in Sudan for tapping *A. senegal* trees for gum production. For example, axes are traditionally used for tapping the stems and/or branches of *A. senegal*. However, the tool is not recommended, as it is difficult to control the depth of the incisions made in the stem and/or the branch of the tree. Another tool that is used is called a m*akmak* (Figure **3.11**, left), which is also used for tapping other gum producing trees. A *Makmak,* weighing 0.50-0.75 kg with a 15 cm blade with a 7-10 cm sharp edge, is designed for tapping gum trees, for example *A. seyal*, by pushing the blade upward into the bark. The tapping tool "s*onki*" (Figure **3.11**, right) or "bayonet" (IIED and IES, 1990), 20 cm in length and 0.25-0.50 kg, is used for tapping *A. senegal* tree (Ballal *et al*., 2005b; Mohamed, 2005) in Sudan, is the only tool recommended tapping this tree species*.* The s*onki* has to be pushed under the bark and pulled back (IIED and IES, 1990). No tapping tool is recommended for tapping *A. seyal* trees. But for the purpose of this study, both the, m*akmak* and *sonki* were used for tapping trees of *A. seyal*. Both tools were also used by Ali (2006) and Fadl and Gebauer (2004) for tapping this species in the Umfakarin Forest, South Kordofan, Sudan.

3.3.4.2 Selection and marking trees for tapping

A total of 482 target trees, covering the diameter ranges ($d_{0.25}$ = 9-11.5, 13.5-16, 18-20.5 and above 21 cm) were selected, based on diameter at 0.25 m height ($d_{0.25}$), from three stand density-dense, medium and slight- strata. Stems of the selected trees were numbered and marked by three bands of different colors to facilitate gum tapping and collection for gum tappers (Figure **3.12**). The tapping dates, October 1st, 15th and November 1st were chosen for tapping *A. seyal* trees using both the s*onki* and m*akmak* in combination with the use of untapped trees for control. Tapping was completed by local people living adjacent to the Umfakarin Forest. Figure **3.13** illustrates the gum tapping and collection techniques in addition to gum exudation from tapped and untapped trees.



Source: Adapted from Ali, 2006

Figure 3.11 Local tools used for tapping *Acacia seyal* for gum production (*Makmak* and *sonki*, from left to right)

Figure 3.12 Techniques for marking *Acacia seyal* trees for gum tapping
Top right: (yellow band) for *sonki*; bottom left: (red band) for *makmak;* and bottom right: blue band for untapped trees.

Figure 3.13 *Acacia seyal*: gum tapping and collection techniques
Top left: tapping techniques; top right: gum collection; bottom left: natural gum exudation; and bottom right: gum exudation after tapping.

3.3.4.3 Gum collection

Gum samples were collected after two weeks from the date of tapping at an interval of 15 days. The total number of pickings ranged from 7 to 9 (Table **3.1**). Collection was done manually, either directly by hand or with the assistance of tapping tool. Gum samples collected from each target tree were kept in a container and dried at room temperature for 72 hours and then weighed. Total gum produced by each target tree per season was obtained by summing up the gum samples collected from all pickings. Tapping and collection form is illustrated in Appendix **2**.

Table 3.1 Gum tapping and collection schedule

Stratum	Dates of gum tapping and collection									
	1st Oct.	15th Oct.	30th Oct.	15th Nov.	30th Nov.	15th Dec.	30th Dec.	15th Jan.	30th Jan.	15th Feb.
Dense	T	C	C	C	C	C	C	C	C	C
		T	C	C	C	C	C	C	C	C
			T	C	C	C	C	C	C	C
Medium	T	C	C	C	C	C	C	C	C	C
		T	C	C	C	C	C	C	C	C
			T	C	C	C	C	C	C	C
Slight	T	C	C	C	C	C	C	C	C	C
		T	C	C	C	C	C	C	C	C
			T	C	C	C	C	C	C	C

Key: T = tapping; and C = collection (which was done for each tree at each time).

3.4 Computational statistics of tree and stand values

Quadratic mean diameter (QMD, in cm), mean height, basal area per hectare, number of trees/ha, standing volume per hectare, and crown parameters were computed for trees in each stratum, as follows:

- Quadratic mean diameter

The quadratic mean diameter, i.e. diameter at breast height (DBH) corresponding to the average basal area of trees in the stand was obtained (Formula 4) according to Kramer and Akça (2008), Vink (1990b) and West (2004).

$$D = \sqrt{\sum_{i=1}^{n} \frac{d_i^2}{n}} \quad \text{......} \quad (4)$$

Where D is the quadratic mean diameter (QMD, in cm); n is the number of observations; and d_i is the diameter at breast height (DBH, in cm) of i, tree.

- Stand basal area

Basal area per hectare was calculated by multiplying the mean diameter with number of trees per hectare (Formula 5).

$$BA = \pi * N * D^2/40000 \quad \text{......} \quad (5)$$

Where BA is the basal area per hectare (m²); D is the QMD; and N represents the number of trees per hectare and π represents 3.14159265.

- Stand mean height

The mean height of the stand was calculated following Kramer and Akça (2008) and Van Laar and Akça (2007) by regressing the Michailow stand height curve on the mean DBH (Formula 6).

$$H = 1.3 + a_0 * e^{(a_1/D)} \quad \text{......} \quad (6)$$

Where *H* is the mean height (m); *D* is the QMD; *e* is the base of natural logarithm; and a_0 and a_1 represent coefficients.

- Single tree volume was obtained using Formula 7, as illustrate below:

$$v = ba * h * ff \quad \text{......} \quad (7)$$

Where *ba* represents the tree's basal area (in m^2, $ba = d^2 * \pi / 40000$); *d* represents tree diameter (DBH); *h* represents the observed tree height (m); *ff* is the form factor (ff = 0.5 according to El Dool, 1988); and π = 3.14159265.

- Standing volume

The Stand-level volume equation (Gadow and Hui 1999) was used to derive the standing volume in m³/ha:

$$V = BA * H * ff \quad \text{......} \quad (8)$$

Where V is volume in m³/ha; BA, H and ff represent Basal Area, height and form factor, respectively.

- Crown parameters

The measured four crown radii were used to calculate the average crown radius (CR, in m) and the crown projection area (CrPA, m²). The CR, which is equal to ½ the crown diameter (CD, in m) was obtained by calculating the arithmetic mean of the four radii. Two crown shapes, i.e. circle and ellipse, were assumed for *A. seyal* for the calculation of CrPA. CrPA of either a circle or ellipse for the individual trees was calculated according to the equations (9) and (10).

Circular crown area:

$$CrPA = \left(\frac{r_1 + r_2 + r_3 + r_4}{4}\right)^2 * \pi \qquad (9)$$

Elliptic crown area:

$$CrPA = \left((r_1 * r_2) + (r_2 * r_3) + (r_3 * r_4) + (r_4 * r_1)\right) * \pi / 4 \qquad (10)$$

Where: *CrPA*= crown projection area (m²); $r_1 \ldots r_4$ = crown radii (m); and π represents 3.14159265.

3.4.1 Stand height curve

Height-diameter relationship was evaluated using several height functions (Table **3**.**2**) based on data from medium stand density (Kramer and Akça, 2008). The criteria for selecting the best model to be used for the *A. seyal* height curve were based on R², Akaike's Information Criterion (AIC) and plausibility of the curve. Stand height curves were produced for dense, medium, and slight strata using the selected allometric height function.

Table 3.2 Potential models used for evaluation of height-diameter relationship of *A. seyal*

Function name	Function
Parabolic	$h = a_0 + a_1 * d + a_2 * d^2$
Petterson	$h = 1.3 + \left(\frac{d}{a_0 + a_1 * d}\right)^2$
Prodan	$h = 1.3 + d^2 / (a_0 + a_1 * d + a_2 * d^2)$
Michailow	$h = 1.3 + a_0 * e^{(a_1 / d)}$
Hendrickson	$h = a_0 + a_1 * \log d$
Van Laar	$h = e^{(a_0 + a_1 / d + a_2 / d^2)}$

Source: (Kramer and Akça, 2008)

Where: h = total height (m); d = diameter at breast height (DBH, in cm); log = natural logarithm; e = base of natural logarithm (≈ 2.7183); a_0, a_1 and a_2 are coefficients. Observations (n = 1235) based on data from medium stratum.

3.4.2 Volume functions

The volume function (Formula 11) was based on a regression model. The relationship between the tree volume and the combination of DBH and height was derived in order to estimate the standing volume of *A. seyal* trees in natural stands.

$$v = a_0 + a_1 * d^2 * h \qquad (11)$$

Where, each parameter is the same as identified above. This volume function was used by Bi (1994) to estimate the volume under bark of *Eucalyptus viminalis* in New South Wales, Australia, and by Elsiddig (2003b) to estimate the standing volume of natural *A. seyal* in eastern Sudan.

3.5 Quantification of competition indices using CroCom

Eight competition indices (CIs) were quantified using the computer program CroCom (Münder *et al*., 2008). The models used for CI quantification are presented in **Table 3.3**. The necessary input variables for the program include tree code, species and number, tree location or coordinates, DBH, height, crown radii, height of crown base, canopy class (overstorey or understorey), and crown permeability factor[9], (or CPF, estimated to be 0.4 for *A. seyal*). The input data for each target tree and its neighborhood trees were prepared in an excel spreadsheet and saved as a database file.

Locations of the competitors were identified by Polar coordinates (*θ*, *d*) which were converted to Cartesian (*x*, *y*). The Polar system locates the position of each competitor by measuring the horizontal distance (*d*) and the angle (*θ*) from the focal tree to the competitor. The Cartesian system locates points on a plane by measuring the horizontal and vertical distances from an arbitrary origin to a point. To convert such readings from Polar to Cartesian, the following formulas were adopted:

$$x = d * \sin(\theta * 0.0174532925) \qquad (12)$$

$$y = d * \cos(\theta * 0.0174532925) \qquad (13)$$

Where: x and y are defined as the positions of the perpendicular projections of the point onto two axes (x and y), expressed as signed distances from the focal point.

[9] CPF is the possibility of sunlight to transmit beneath the tree canopy. The value of CPF ranges between 0 and 1; the crown is totally opaque when CPF = 1. CPF was estimated to be 0.4 for *A. seyal*. The estimate was made by Dr. Gerold (Institute of Forest Growth, TU-Dresden, Germany) for comparing *A. seyal* photos with Scots pine and European larch (CPF = 0.4; see Schröder, 2003 and Münder, 2005) .

The constant (0.0174532925) was used to transform the compass readings from “degrees” to “radians” (1 degree = 0.0174532925 radian); *d* and θ represent horizontal distance and angle (compass reading) of the competitor from the focal tree, respectively.

The results of the data analyzed by CroCom create intra- and inter-specific competition indices. According to the CroCom definition, the intra-specific competition expresses the competition between trees sharing the same crown layer, while inter-specific competition exists between trees growing at different layers. However, in ecology, inter-specific competition refers to the competition that occurs whenever two different species attempt to utilize the same limited resources, while intra-specific is the competition between individuals of the same species (Kimmins, 2004; Begon *et al*., 2006). To avoid confusion between these two concepts, in CroCom and ecology, intra- and inter-layer competitions will be used to refer to the competition between trees sharing the same layer and the competition between trees growing in different layers, respectively. The final competition index induced by the competitors is the sum of inter- and intra-layer competition.

Table 3.3 Models used for CIs quantification in CROCOM Programme

Index formula	Variables used in the model	Author (s)
Distance-dependent competition indices		
$CI\_HEGYI = \sum_{j=1}^{nj} (d_j / d_i)/(dist_{ij})$	DBH, distance	Hegyi 1974
$CI\_HEGYI\_2 = \sum_{j=1}^{nj} (g_j / g_i)/(dist_{ij} + 1)$	Basal area, distance	Hegyi 1974
$CI\_KF = \sum_{j=1}^{nj} \frac{KF_j(SH)}{KF_i}$	Crown dimensions	Biging and Dobbertin 1992
$CI\_KV = \sum_{j=1}^{nj} \frac{KV_j(SH)}{KV_i}$	Crown dimensions	Biging and Dobbertin 1992
$CI\_PRETZSCH = \sum_{j=1}^{nj} Beta_{ij} * KQF_i / KQF_j$	Angle of inverse cone and crown dimensions	Pretzsch 1995
$CI\_VKF = \sum_{j=1}^{nj} \frac{VKF_j / VKF_i}{dist_{ij} + 1}$	Crown dimensions and distance	Münder und Schröder 2001
Distance-independent indices		
$CI\_C66 = \sum_{j=1}^{nj} KF_{j(HGK_i)}$	Crown dimensions	Nagel 1999
$CI\_BAL = G_{cum} = \sum_{j=1}^{n_{max}} g_j$	Basal area	Wykoff *et al*. 1982; Schütz 2001; Schütz und Röhnisch 2003

Source: (Scütz 2001; Schütz and Röhnisch 2003; Schröder 2003; Münder 2005; Rivas *et al*. 2005)
Where: *i* = focal tree; *j* = competitor; d = diameter at breast height (DBH); $d_{j\ max}$ = DBH of trees larger than the subject tree (in cm); BAL = basal area of trees larger than the subject tree (m^2/ha); g_i = basal area (BA, in m²); G_{cum} = cumulative BA of trees larger than the subject; n_{max}= number of trees of basal areas larger than the subject tree; *nj*= number of competitors; $dist_{ij}$= distance $tree_i$- $tree_j$; *Beta* =

gradient of straight line connecting base of search cone and top of competitor tree; *KF* = horizontal crown area; *KQF*= *KF* at height of search-cone base; *HGK* = height of greatest crown width; *SH* = height of intersection of search cone and tree axis; *KV*= crown volume; *VKF* = vertical crown area; and *h* = height.

Definition of indices used in CroCom:

Distance-dependent competition indices

1. CI_HEGYI (Hegyi, 1974): also known as the "Jack-Pine-index" was discovered in 1974 by Hegyi and is considered to be the most famous and easiest index (Münder, 2005; Schröder, 2003) to use to quantify competition indices in forest stands. The index is only based on DBH of both the target tree and its competitors and the horizontal distance between each competitor and the target tree.
2. CI_HEGYI_2 (Hegyi 1974): similar to first index but employs basal area instead of diameter.
3. CI_KF (Biging and Dobbertin, 1992): based on the horizontal crown area and the height of intersection of the search cone and tree axis.
4. CI_KV (Biging and Dobbertin, 1992): the index uses crown volume based on the height of intersection of the search cone and tree axis.
5. CI_PRETZSCH (Pretzsch, 1995): this index is a component of the forest growth simulator, SILVA, developed at the Chair of Forest Yield Science at the Technical University of Munich, Germany. It is used to quantify the competition index based on the identification of competitors by means of the search cone method.
6. CI_VKF (Münder and Schröder, 2001): this index is based on the vertical crown area and horizontal distance between the competitor and subject tree.

Distance-independent competition indices

1. CI_C66 (Nagel 1999): based on the horizontal crown area at the height of greatest crown width. The C66 of a subject tree is calculated by summing up the horizontal crown areas of all trees cut at the height of its greatest crown width, which is fixed at 66.6% of crown length from the top (Nagel 1999 in Schröder *et al*., 2007). The C66 index identifies competitors either as all trees belonging to the same stand (distance-independent mode) or by checking a

fixed critical radius (distance-dependent mode) (Schröder *et al*., 2007). The latter was used in this study to identify competitors.

2. CI_BAL (Wykoff *et al*., 1982): this index is also termed the “G_{cum}” or shading index (Schütz, 2001; Schütz and Röhnisch, 2003) and can be calculated by summing up the basal areas of the trees larger (BAL) than the subject tree.

3.6 Statistical analysis

3.6.1 Test for normality

The test for normality is an important procedure for testing the null hypothesis that the data sample came from a normally distributed population. Many statistical procedures are used for testing departures from normality. In this study, normality plots with tests (Kolmogorov-Smirnov or Shapiro-Wilk) were used to test whether the data have come from a normally distributed population. In this investigation the goodness of fit, for example Shapiro-Wilk test (Zar, 2009), was selected. If a test of significance gives a p-value greater than the chosen alpha level (in this case α = 0.05), then one can conclude that the data came from a normally distributed population. The Shapiro-Wilk test statistic (*W*) is calculated as follows (Sachs and Hedderich, 2006):

$$W = \frac{(\sum_{i=1}^{n} a_i x_{(i)})^2}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad \ldots\ldots (14)$$

Where:

$x_{(i)} = (x_1 \ldots x_n)$ is the i^{th} ordered sample values ($x_{(1)}$ is the smallest value); $a_i = (a_1 \ldots a_n)$ are constants obtained from the measures of order statistics of a normally distributed random variables; $\overline{x}$ is the sample mean; and n is the sample size.

3.6.2 Simple linear correlation

The simple linear correlation considers the linear relationship between two variables (x and y), but neither is assumed to be functionally dependent upon the other (Van Laar and Akça, 2007; Zar, 2009). The correlation coefficient (*r*) is the most important parameter to be determined in simple linear correlation. There are several different correlation methods, but the most common type is the Pearson, or product moment, correlation. The relationship between two variables when removing the influence of other variables is referred to as a partial correlation. The value of *r* ranges between 1 and -1, or -1<*r*<+1. As indicated by Zar (2009), a positive correlation implies that if one variable increases in value then the other variable also increases in value; a negative correlation indicates that an increase in value of one of the variables will be accompanied by a decrease in value of the other variable. If r = 0, there is no linear association between the two variables. The mathematical formula for computing the correlation coefficient (*r*) is provided by Zar (2009), as depicted in Formula (15):

$$r = \frac{\sum xy - \frac{\sum x \sum y}{n}}{\sqrt{\left(\sum x^2 - \frac{(\sum x)^2}{n}\right)\left(\sum y^2 - \frac{(\sum y)^2}{n}\right)}} \quad \text{.. (15)}$$

Where: r = correlation coefficient; x and y = are dependent and independent variables, respectively; and n = number of observations.

3.6.3 Regression analysis

Regression analysis is useful for evaluating the association between two or more variables and expressing the nature of such relationships (Husch *et al*., 2003). Regression is either simple, if only two variables are considered, or multiple, if more than two variables are considered. The simplest relationship between one dependent and one independent variable, for example a simple linear regression, is illustrated below in Equation 16. However, when a number of predictors (independent variables) influence the dependent variable (Zar, 2009) the situation is best expressed by Equation 17.

$$\hat{y}_i = a_0 + a_1 x_i + \varepsilon_i \quad \text{.. (16)}$$

$$\hat{y}_i = a_0 + a_1 x_1 + a_2 x_2 + ... + a_n x_n + \varepsilon_i \quad \text{.. (17)}$$

Where: $\hat{y}_i$ is the dependent or response variable (predicted value); $x_1, x_2 ... x_n$ are independent or explanatory variables; a_0 is the intercept and also denotes the expected value of dependent variable when the independent(s) variable(s) is zero; $a_1, a_2 ... a_n$ are parameters to be estimated by linear regression: and ε_i represents the error or residual which is the difference between the predicted value and the observed value of the response variable.

Generally, a nonlinear regression represents any regression in which the relationship between the dependent and independent variable(s) is not linear. Regression models such as logarithmic, exponential or any forms in which the estimated parameters do not appear in an additive manner are examples of nonlinear regression. The normal nonlinear regression model (Equation 18) can be written as:

$$y_i = f(\beta, x'_i) + \varepsilon_i \quad \text{.. (18)}$$

Where: y_i = ($y_1...y_n$) is a vector of predictors for the i^{th} of *n* observations; $x_i^{'}$ = $(x_1...x_n)$ is a vector of explanatory variable; β= $(a_1...a_n)$ is a vector of parameters to be estimated by non-linear regression; and ε_i = random error, ε_i ~ *N (0, σ²)*.

Some examples of non-linear regression models (Equations 19-21) used in this study are depicted below.

$$y = a_0 + a_1 * \ln(x) \quad (19)$$

$$y = a_0 * a_1^{\,x} \quad (20)$$

$$y = a_0 * e^{(a_1/x)} \quad (21)$$

Where: y represents the outcome variable; x illustrates the explanatory variable; ln represents a natural logarithm; e is the base of natural logarithm and is approximately equal to 2.7183; a_0 *and* a_1 denote parameters to be estimated by regression model; and ε refers to error.

The most important parameter to be determined by regression analysis is the coefficient of determination (or R^2). The coefficient of determination ($0 \leq R^2 \leq +1$) quantifies the regression's goodness of fit which indicates how suitable the model is for the data presented. R^2 is sometimes referred to as expressing the goodness of fit of the line for the data or as the precision of the regression (Zar, 2009). R^2 also measures the proportion (or percentage) of the total variation in response variables as explained by the regression model. When new explanatory variables are added to a regression equation, R^2 may increase even if the new variables have no predictive capability. Unlike R^2, adjusted R^2 (R^2_{adj}) may not increase unless the new variables have a real predictive capability. R^2 and R^2_{adj} can be calculated using the Equations depicted in 22 and 23.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (22)$$

$$R^2{}_{adj} = R^2 - \frac{k*(1-R^2)}{n-k-1} \quad (23)$$

Where: R^2 is the coefficient of determination; R^2_{adj} represents the adjusted R^2; y_i depicts the observed values from $i = 1...n$; $\hat{y}_i$ denotes predicted values; $\bar{y}_i$ is the average value of y_i; k is the number of parameters; and *n* represents the number of observations.

The standard error of the estimate (SE) is another parameter used to measure the accuracy of predictions originating from a regression analysis. SE is indicated as the root of the mean square error (MSE) and can be calculated using the following formula:

$$SE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n-k}} \ or \ \sqrt{MSE} \quad (24)$$

Where: SE is the standard error of the estimate; MSE is the mean square error; and k, y_i, $\hat{y}_i$ and n represent the variable depicted in the equation above.

Akaike's Information Criterion (AIC)

AIC is an index proposed by Akaike (1974) to measure the fit of the model (Burnham and Anderson, 2002). The AIC is recently used for judging the performance of several candidate models. The minimum value of the index, the adequate model fit to the data. The mathematical formula for calculating AIC is as follows:

$$AIC = 2k + n[\ln(RSS)] \quad (25)$$

Where: AIC is Akaike's Information Criterion; k is the number of parameters in the model; n is number of observations; ln is the natural logarithm; RSS is the residual sum of squares.

Transformation of non-linear into linear regression models

Some non-linear models can be transformed into linear versions. In this study, and for the sake of testing the significance of the regression lines, non-linear regression models such as equations 26 and 27 were transformed into a linear form, using a logarithmic transformation. The two models were transformed as follows:

$$\log(y_i) = \log a_0 + x_i * \log a_1 \quad (26)$$

$$\log(y_i) = \log a_0 + a_1 / x_i \quad (27)$$

Where: log is the logarithm to the base 10; and y_i, x_i, a_0 and a_1 are as previously explained.

Test of significance between regression lines

There are three possible comparisons for testing the significance between linear regression lines (Glantz, 2005):

- test for a difference in slope (regardless of the intercepts)
- test for a difference in intercept (regardless of the slopes)
- overall test of coincidence, in which if the lines are different.

This study deals only with the first option, the test of differences in slope regardless of the intercepts. A simple method for testing the hypothesis whether the slopes of two regression lines are different or not (H_0: $b_1=b_2$) has been identified by many authors (see e.g. Glantz, 2005; Husch, 1963; Zar, 1999). The procedure for comparing the two slopes is analogous to the *t* test for differences between two means. The mathematical term or the test statistic is:

$$t=\frac{b_1-b_2}{S_{b_1-b_2}} \qquad (28)$$

Where the standard error of the difference between regression coefficients is:

$$S_{b_1-b_2}=\sqrt{\frac{(S^2{}_{y.x})_p}{(\sum x^2)_1}+\frac{(S^2{}_{y.x})_p}{(\sum x^2)_2}} \qquad (29)$$

The pooled residual mean square is calculated as:

$$(S^2{}_{Y.X})_p=\frac{(residual\,SS)_1+(residual\,SS)_2}{(residual\,DF)_1+(residual\,DF)_2} \qquad (30)$$

The critical value of the *t* for this test has (n_1+n_2-4) degrees of freedom (where n_1 and n_2 are the number of observations for lines 1 and 2 respectively). To compare several regression lines (H_0: $ß_1 = ß_2 = \ldots = ß_k$, where *k* is the number of lines needed to be tested), an analysis of covariance has to be used (Zar, 1999). *F* statistic can be calculated using the following formula:

$$F=\left(\frac{SS_c-SS_p}{k-1}\right)/\left(\frac{SS_p}{DF_p}\right) \qquad (31)$$

Where:

SS_c is the common residual sum of squares; SS_p is the pooled residual sum of squares; and DF_p is the residual degrees of freedom.

The steps taken to calculate SS_c, SS_p and DF_p are shown in the following table (Table 3.4).

Table 3.4 Calculations for testing significant differences between slopes of *k* regression lines

	∑x²	∑xy	∑y²	RSS	RDF
Regression 1	A_1	B_1	C_1	$SS_1 = C_1 - B_1^2 / A_1$	$DF_1 = n_1 - 2$
Regression 2	A_2	B_2	C_2	$SS_2 = C_2 - B_2^2 / A_2$	$DF_2 = n_2 - 2$
.	.	.	.	.	.
.	.	.	.	.	.
Regression *k*	A_k	B_k	C_k	$SS_k = C_k - B_k^2 / A_k$	$DF_k = n_k - 2$
Pooled regression				$SS_p = \sum_{i=1}^{k} SS_i$	$DF_p = \sum_{i=1}^{k} (n_i - 2)$
Common regression	$A_c = \sum_{i=1}^{k} A_i$	$B_c = \sum_{i=1}^{k} B_i$	$C_c = \sum_{i=1}^{k} C_i$	$SS_c = C_c - B_c^2 / A_c$	$DF_c = \sum_{i=1}^{k} n_i - k - 1$

Source: (Zar, 1999)

Logistic regression

Logistic regression, or sometimes the logistic model, is used for the prediction of the probability of occurrence of an event. The difference between the logistic model and the linear regression model is that the outcome variable in a logistic regression is binary or dichotomous (Hosmer and Lemeshow, 2000; Zar, 1999). The dependent variable has two possible values, for example yield or no yield, male or female, or more, for example low, medium, and high. The independent variable(s) can be measurable and/or categorical. In this study, a binary logistic regression was used to describe the relationship between the dependent variable (gum yield) and the independent variables (stand density, tapping tool, tapping date, DBH and competition index value). The dependent variable (dichotomous) was set as 1 and 0 referring to yield and no gum yield. In this case, the mathematical expression of logistic model can be written as follows:

$$y = 1/(1 + \frac{1}{e^{a_0 + a_1 x_1 + a_2 x_2 ... + a_n x_n)}}) \qquad (32)$$

Where: *y* is the probability of gum yield; other variables are defined as explained previously.

The Wald χ^2 statistic is used to test the significance of each variable´s coefficient in the model and can be calculated by squaring the quotient of the coefficient divided by its standard error, compared with a tabulated χ^2 with 1 degree of freedom under a certain level of significance (α = 0.05).

3.6.4 Post-Hoc tests in the analysis of variance (ANOVA)

Post-hoc tests are generally performed only after obtaining a significant difference between the means of several treatments and where additional exploration is needed to provide specific information about the reason why the means are significantly different from each other. In this study, an ANOVA test was applied in order to test whether the means of gum yield obtained from different gum tapping treatments are equal or not. In addition to that, Post-hoc in ANOVA, based on the Scheffé test, was applied to make simple comparisons of all possible pair-wise gum yield means. The Scheffé test (*S* test) can be used to test the null hypothesis of the form $H_0 : \mu_B - \mu_A = 0$ (Zar, 1999), where μ_B and μ_A are the values of the two means. The important parameters to be quantified when conducting Scheffé test (*S* test), are the test statistics (*S*), and the critical value of *S*. The mathematical breakdown of S statistic is:

$$S = \frac{|\bar{X}_B - \bar{X}_A|}{SE} \quad \text{……………………………………………………………………….} \quad (33)$$

Where:

$$SE = \sqrt{S^2\left(\frac{1}{n_A} + \frac{1}{n_B}\right)} \quad \text{…………………………………………………………………….} \quad (34)$$

And the critical value is:

$$S_\alpha = \sqrt{(k-1)F_{\alpha,k-1,N-k.}} \quad \text{………………………………………………………………….} \quad (35)$$

Where: S is the Scheffé test statistics; $\bar{X}_A$ *and* $\bar{X}_B$ represent the mean values of treatments A and B respectively; SE denotes the Standard error; S_α is the critical value of *S;* n_A *and* n_B are the number of observations in treatments A and B, respectively; k is equal to the number of treatments; N represents the number of observations in all treatments; and F_α represents the tabulated Fisher value (in this case α = 0.05) under $k-1$, and $N-k$ degrees of freedom.

To accept or reject the null hypothesis depends on the S_α value. If S_α< *S* statistics the null hypothesis should be rejected and if it is not then the hypothesis is acceptable.

3.6.5 Regression tree

Classification and Regression Trees (CART) is a package available in R software via the user-contributed packages rpart and tree (R Development Core Team, 2008; Venables *et al*., 2009). The classification tree is mainly used for predicting categorical dependent variables, while the regression tree is used to predict continuous dependent variables (Cappelli and D'Elia, 2006). In this study, the regression tree was applied to predict gum *talha* productivity based on a set of explanatory variables.

Tree-based models are computationally intensive methods that are used in situations where there are many explanatory variables and the aim is to identify which of them can be included in a regression model (Crawley, 2007), and to find interaction variables (Faraway, 2006). Tree-based methods are non-parametric tools that allow modelling the relationship between a response variable and a set of predictors by means of a recursive binary partitioning approach (Cappelli and D'Elia, 2006). The advantages of tree-based methods which can be summarized by the following (Crawley, 2007):

- They are very simple.
- They are excellent for initial data inspection.
- They provide a very clear picture of the structure of the data.
- They provide a highly intuitive insight into the types of interactions that exist between variables.

In a regression tree, the response variable is a continuous measurement, whereas explanatory variables can be any mix of continuous and categorical variables (Crawley, 2007). In this study, the model is fitted using a regression tree by stating that gum yield (response variable) is a function of several explanatory variables, including stand density, tapping tool, date of tapping, tree competition and DBH.

The data frame containing all variables, for example response and predictors, were prepared in an excel worksheet and saved in a pure text format, for example comma-separated value (CSV). The prepared file can be loaded directly into R as a data frame, using the "read.table" function. To run the program, the user must type some commands, such as the command "print" which shows the summary statistics for the model, contains the node number, the split, the number of observations per node, deviance, and the mean value of the response variable at each terminal node. As explained by Crawley (2007), in the command "print" of the regression tree model, the terminal nodes (leaves) are denoted by the symbol (*). The node number is on the left, labelled by the variable on which the split at that node was made, following which the ´split criterion´ which shows the threshold value of the variable that was used to create the split. The number of cases involved in the split (or into the terminal node) follows. This is followed by the deviance at that node. The last value on the right is the mean value of the response variable within that node or at that leaf (for illustration see Figure **3.14**). The figure consists of four terminal nodes; each node expresses the mean value ($x_1 \ldots x_4$) of the dependent variable. In this figure, factor 1 with a threshold is the most important explanatory variable that has a prominent influence on the dependent variable. The right branch, greater than the threshold, produces a mean value equal to x_4, while for the left branch, less than the threshold, factor 2 is the most important.

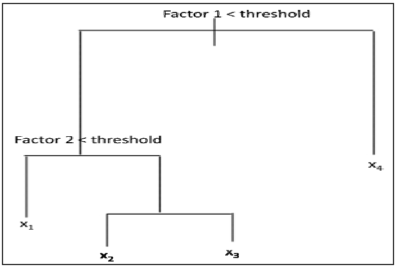


Figure 3.14 Mean values of the dependant variable above and below the threshold of the explanatory variable.
$x_1 \ldots x_4$ are mean values of the dependent variable for the specific classification.

3.7 Software

The manuscript is written and prepared in the word processor, Microsoft Office Word (2003). However, data entry and mathematical processes were conducted using an Excel spreadsheet in Microsoft Office Excel (2003). Data analysis was performed using SPSS Statistics 17.0 Release 17.0.0 (Aug 23, 2008). Other software such as *CroCom 3.0* and R were also used.

The software CroCom 3.0 (German version) was developed by Münder *et al*. (2008) specifically for the calculation of crown competition indices. The software was obtained from the Institute of Forest Growth and Forest Computer Sciences, Technical University of Dresden, Germany.

R is an integrated suite of software facilities for data manipulation, calculation, and graphic displays, including (Venables *et al*., 2009):

- an effective data handling and storage facility,
- a suite of operators for calculations on arrays, in particular matrices,
- a large, coherent, integrated collection of intermediate tools for data analysis,
- graphical facilities for data analysis and display either directly with a computer or using a hardcopy, and
- a well-developed, simple and effective programming language

The R programme is available for download from the R Project, at http://www.r-project.org/.

4 RESULTS

4.1 Stand values

The most common measurements made in stands, as mentioned by Husch *et al*. (2003), Van Laar and Akça (2007), West (2004) are age, basal area, number of tree stems per unit area, mean diameter, mean height, standing volume and stand biomass. This section deals with the aspects of stand values such as mean diameter, mean height, basal area, stand volume and the number of stems per unit area.

In this investigation, three stand categories, or strata, were distinguished based on stand density in the Umfakarin Forest, namely dense, medium and slight strata. Stand values, such as basal area (BA, in m² per hectare) and the number of trees per hectare, besides mean diameter at breast height (DBH, in cm), mean height (h, in m) and volume (V, in m^3 per hectare) were obtained, a summary of which can be found in Table **4.1**. Stand BA ranged from 3.09 m²/ha in slight stratum to 5.93 m²/ha in dense stratum. The three stand categories vary in terms of the number of trees per unit area, ranging from 209 to 396 stems per hectare, with standing volume ranging from 10.86 to 22.10 m^3/ha. Stands of dense, medium and slight density have mean DBH 12.2, 13.4 and 12.2 cm with mean height 7.2, 7.6 and 6.7 m, respectively.

Table 4.1 Stand values of natural *A. seyal* in different stand densities

Stratum	DBH(cm)	h (m)	BA/ha (m^2)	V/ha (m^3)	N/ha
Dense	12.2	7.2	5.93	22.10	396
Medium	13.4	7.6	4.87	19.45	271
Slight	12.2	6.7	3.09	10.86	209

Where: DBH is the quadratic mean diameter at breast height (over bark, cm); h is the mean tree height (m); BA is the basal area (m^2); V is the stand volume (m^3); N is the number of trees per hectare

Table **4**.**2** illustrates the number of natural regeneration (greater or less than 1.3 m in height) per hectare by stratum of *A. seyal* and other associated species. In general, all stands had a very limited number of seedlings. *A. seyal* occurs at all strata; however, only 9-50 seedlings per hectare, ≥ 1.3 m in height, were recorded. Seedlings from other species of ≤ 1.3 m height occur in dense and slight strata with a density of 8 and 15 seedlings per hectare, respectively.

Table 4.2 Number per hectare of natural regeneration greater and less than 1.3 m height

Stratum	*Acacia seyal*		Associated species	
	≥ 1.3 m	≤ 1.3 m	≥ 1.3 m	≤ 1.3 m
	Number of seedlings per hectare			
Dense	50	-	-	8
Medium	9	-	-	-
Slight	11	-	-	15

Diameter at breast height and height frequency distribution for the three strata was identified. Figure **4.1** illustrates the DBH and the height frequency distribution of natural *A. seyal* stands in the Umfakarin Forest. As illustrated by this figure, the frequency distribution of DBH classes (at 5 cm intervals) and the height classes at 1.5 m intervals, of the three strata, shows an irregularly distributed form, especially height in medium and slight strata. Normality test was conducted and revealed that tree dimensions, i.e. DBH and height of *A. seyal* are not normally distributed ($P < 0.000$; Appendix **3**).

4.1.1 Modelling height curves

The results of the evaluated models were based on data from medium stand density. Lines of the best fit of the evaluated height functions in combination with observed data were illustrated in

Figure **4**.**2**. Additionally, Table **4**.**3** provides details about the evaluated models, their estimated parameters, the coefficient of determination values (R^2) and Akaike´s information Criterion (AIC). A model with the greater R^2 value and smaller AIC is the best. The statistical analysis resulted in a very similar values of R^2 (0.237-0.242) and AIC (479.00-486.36) as well. Based on the results of the evaluated models, a Michailow height function ($R^2 = 0.237$) was selected as it also produces a line of the best fit acceptable from a biological point of view. A scatter plot was created with DBH representing the independent variable on the horizontal axis and height, the dependent variable, plotted on the vertical axis. The distribution of data points on the scatter plot expresses the trend of the height-diameter relationship.

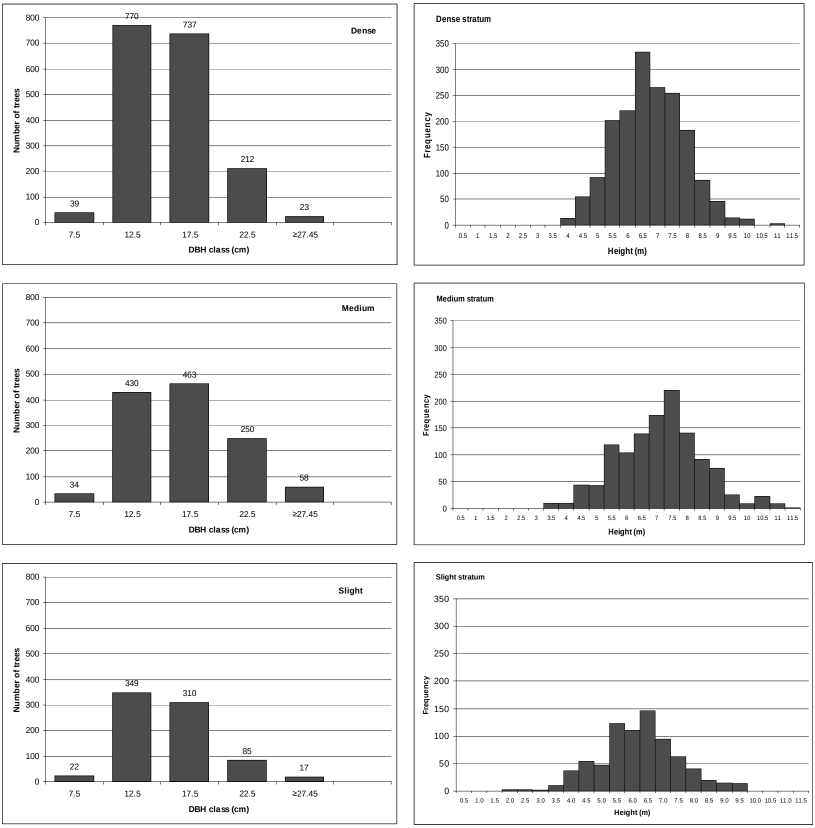


Figure 4.1 DBH and height frequency distribution for *A. seyal* in the Umfakarin Forest
Number of observations: dense = 1781, medium = 1235, and slight = 783.

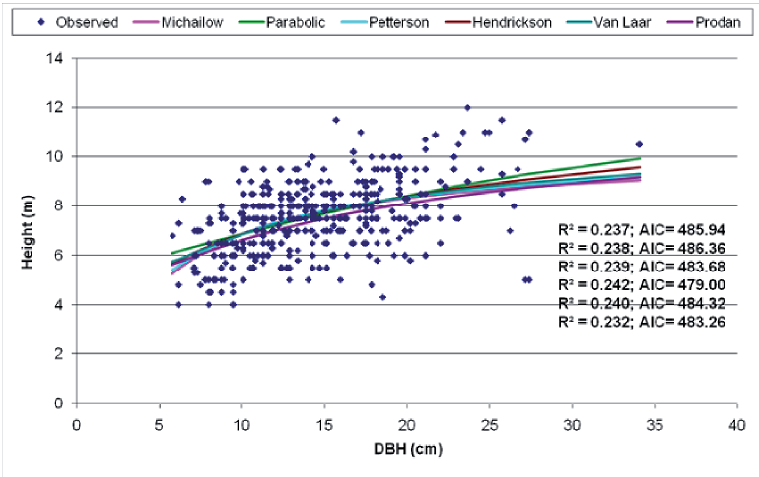


Figure 4.2 Observed data and the lines of best fit (evaluated height functions) for *A. seyal*

Table 4.3 Models evaluated for the height curve of *A. seyal* natural stands in the Umfakarin Forest, South Kordofan, Sudan.

Function	Function	a_0	a_1	a_2	R^2	AIC
Parabolic	$h = a_0 + a_1 * d + a_2 * d^2$	4.908	0.216	-0.002	0.238	486.36
Petterson	$h = 1.3 + \left(\frac{d}{a_0 + a_1 * d}\right)^2$	0.961	0.328		0.239	483.68
Prodan	$h = 1.3 + d^2 / (a_0 + a_1 * d + a_2 * d^2)$	-1.267	0.977	0.095	0.240	483.26
Michailow	$h = 1.3 + a_0 * e^{(a_1 / d)}$	8.917	-4.714		0.237	485.94
Hendrickson	$h = a_0 + a_1 * \log d$	1.762	5.096		0.242	479.00
Van Laar	$h = e^{(a_0 + a_1 / d + a_2 / d^2)}$	2.399	-6.125	13.654	0.240	484.32

Where*:* *h* = total height (m); *d* = diameter at breast height (DBH, in cm); log = natural logarithm; *e* = base of natural logarithm (≈ 2.7183); a_0, a_1 and a_2 are parameters to be estimated by nonlinear regression; and R² = coefficient of determination. Observations (n = 1235) based on data from medium stratum.

Figure 4.3 illustrates the Michailow height curves for each different stratum in combination with other observed data. For each stratum, the data points appear to be randomly scattered, or not around the line of best fit, which indicates a low correlation between height and diameter. Parameters estimated by the Michailow height function for the three strata are presented in **Table 4.4**. R^2 values ranged from 0.193 in dense stratum to 0.240 in slight stratum. Thus, R^2 value decreases with an increase in the number of trees per unit area. Results of statistical test revealed that the slopes of the height curves in different stand densities are not significantly different (using the conventional significant level, i.e., $\alpha = 0.05$). Because the slopes for the curves in the three strata do not significantly differ, a combined height curve ($R^2 = 0.227$) was produced and included (**Figure 4.3**, bottom right). The maximum height (asymptote = 10.2 m) is reached by trees in medium stratum. Trees in dense and slight strata reach a maximum height of 9.3 and 9.4 m, respectively.

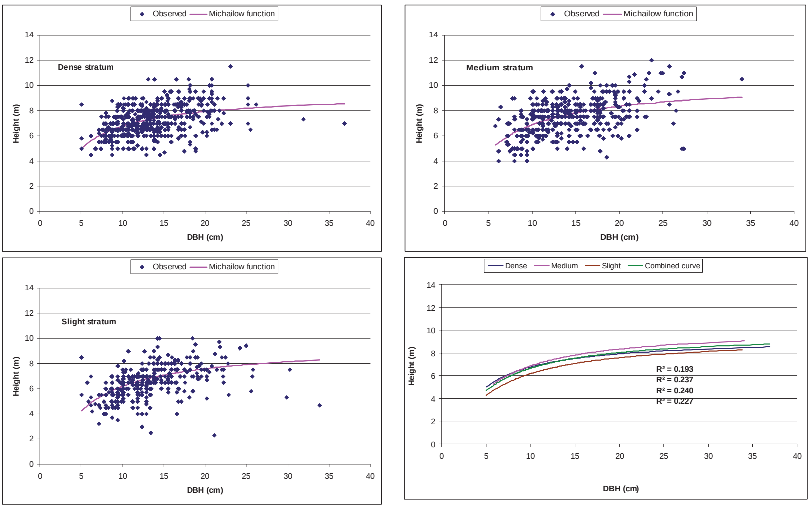


Figure 4.3 Observed data and the line of best fit (Michailow height curve) of *A. seyal*

Table 4.4 Summary of estimated parameters of the Michailow function used for A seyal height estimation in different strata, Umfakarin Forest, South Kordofan, Sudan.

Stratum	n	a_0	a_1	R^2	Asymptote
Dense	1781	8.039 (0.125)	-3.857 (0.193)	0.193	9.3
Medium	1235	8.917 (0.166)	-4.714 (0.250)	0.237	10.2
Slight	783	8.102 (0.214)	-5.072 (0.328)	0.240	9.4

a_0 and a_1 are parameters to be estimated by non-linear regression; in parenthesis is the standard error of parameter; n = number of individual trees; R^2 is coefficient of determination.

4.1.2 Volume functions

Figure 4.4 depicts the volume curves, which are applied to estimate the standing volume of *A. seyal*, together with observed data for different stand densities. The data points for all strata are scattered around the line of best fit, up to around 20 cm DBH. The resulting pattern indicates the dependence of volume on DBH and height. It is worth mentioning that the height used for the volume function is the estimated height, for example the height derived from the height curve. Table **4.5** presents the parameters uncovered by the volume function. The coefficient of determination ranged from 0.906 in slight stratum to 0.928 in medium stratum. Results of a statistical test showed that slopes of the three volume curves are not significantly (α = 0.05) different from each other. Consequently, a combined volume curved was derived.

4.1.3 Relationship between DBH and crown radius

Figure 4.5 depicts the observed data and the fitted curves resulting from the relationship between DBH and the crown radius (CR). Statistical analysis revealed no significant difference ($p < 0.000$) between the observed means of crown radius (2.65, 2.65 and 2.68 m) in dense, medium and slight stands. Table 4.6 provides a summary of nonlinear regression parameters for crown radius (CR, in m) in relation with DBH of *A. seyal* in different strata. The distribution of data points, in all strata, appears to be randomly scattered, which expresses the poor relationship between CR and DBH. The slopes of the three fitted regression lines were statistically tested and revealed to have no significant difference (α = 0.05) from each other. Therefore, a combined curve was produced. The relationship between CR and DBH at slight stratum produced R^2 = 0.547, followed by the dense and medium strata which produced R^2 count to 0.414 and 0.233, respectively.

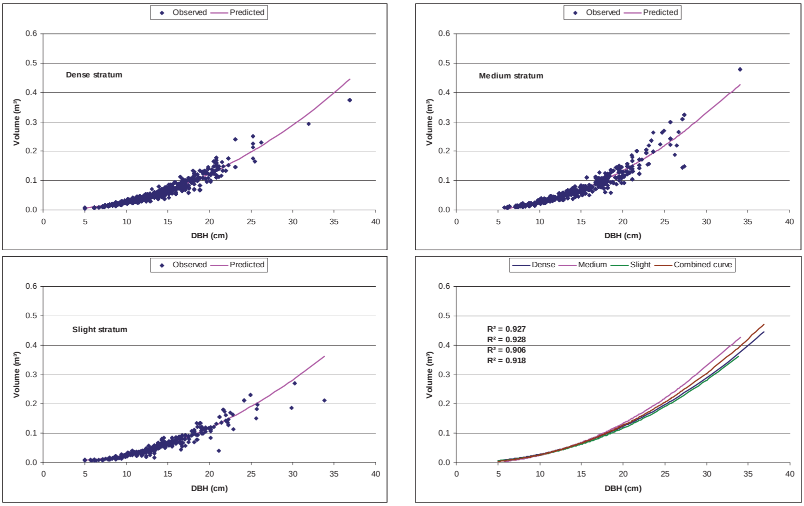


Figure 4.4 Volume function for A. seyal natural stands in different stand densities.

Table 4.5 Summary of nonlinear regression parameters for volume as a function of DBH and height for *A. seyal* in different strata, Umfakarin Forest, South Kordofan, Sudan.

Stratum	n	a_0	a_1	R^2
Dense	1781	0.002 (0.000)	3.761E-5 (0.000)	0.927
Medium	1235	-0.004 (0.001)	4.144E-5 (0.000)	0.928
Slight	783	0.002 (0.001)	3.760E-5 (0.000)	0.906

Parameters as previously explained in Table 4.4; in parenthesis is the standard error of parameter.

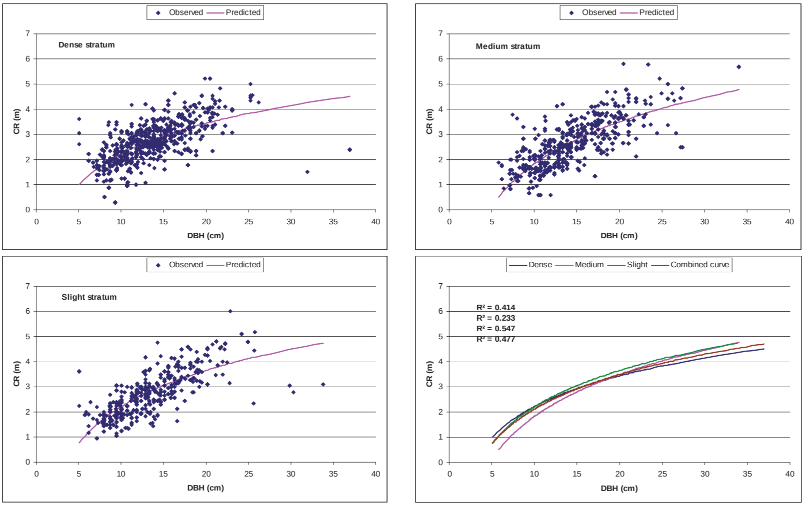


Figure 4.5 Diameter at breast height (DBH) in relation to crown radius (CR) of *A. seyal* for different stand densities, Umfakarin Forest, South Kordofan, Sudan.

Table 4.6 Summary of nonlinear regression parameters for crown radius (CR, in m) in relation to DBH of *A. seyal* in different strata, Umfakarin Forest, South Kordofan, Sudan.

Stratum	n	a_0	a_1	R^2
Dense	1781	-1.840 (0.127)	1.762 (0.050)	0.414
Medium	1189	-3.202 (0.303)	2.225 (0.115)	0.233
Slight	783	-2.588 (0.173)	2.082 (0.068)	0.547

Parameters as previously explained in Table **4.4**; in parenthesis is standard error of parameter.

4.2 Single tree values

4.2.1 Competition indices (CI) and tree dimensions

4.2.1.1 Frequency distribution of CI-values

Frequency distribution was conducted for three select indices in different stand densities, including CI_Hegyi and CI_Hegyi_2 which represent distance-dependent competition indices, and CI_C66 which represents the distance-independent index. The frequency distribution of the selected indices revealed an irregular distribution form, as illustrated in Figure **4**.**6**. The pattern of distribution for distance-dependent index values (at an interval of 0.5) appears to be similar. A normality test was used to investigate whether the values of these indices are normally distributed or not (Table **4**.**7**). The results illustrate that the values are not normally distributed.

Table 4.7 Results of normality test of selected competition indices

Stratum	Index	Mean	Median	SD	Min.	Max.	Skewness	Shapiro-Wilk	
								Statistic	P-value
Dense	Hegyi	1.56	1.42	0.92	0.11	6.93	1.55	0.91	0.000
	C66	148.31	142.33	87.47	0.00	380.68	0.57	0.96	0.000
	Hegyi_2	1.83	1.37	1.50	0.05	8.55	1.53	0.86	0.000
Medium	Hegyi	1.07	0.92	0.65	0.00	3.44	0.83	0.94	0.000
	C66	142.18	114.42	280.42	0.00	3600.0	11.93	0.17	0.000
	Hegyi_2	1.35	0.88	1.17	0.00	6.41	1.49	0.84	0.000
Slight	Hegyi	0.60	0.51	0.47	0.00	2.19	0.76	0.94	0.000
	C66	54.96	37.84	52.72	0.00	279.03	1.44	0.87	0.000
	Hegyi_2	0.66	0.47	0.64	0.00	3.26	1.27	0.87	0.000

Number of observations per stratum (dense = 158; medium = 160; slight = 164); SD = standard deviation

4.2.1.2 Partial correlations

Figure **4**.**7** illustrates the results of significant partial correlations between various competition indices (CI) and tree dimensions. Results of the partial correlation indicate that most indices, with the exception of CI_PRETZSCH, CI_BD_KV and CI_C66, show a clear and negative significant correlation with DBH in the three different strata. The maximum negative partial correlation coefficient, (-0.70), was obtained by CI_HEGYI_2 in dense stratum. The Pretzsch index revealed a negative correlation for height in dense and slight strata. Other indices, with the exception of CI_BD_KV and CI_VKF, exhibited a positive correlation with height. Crown diameter revealed a negative partial correlation with all indices except CI_BAL which showed no correlation.

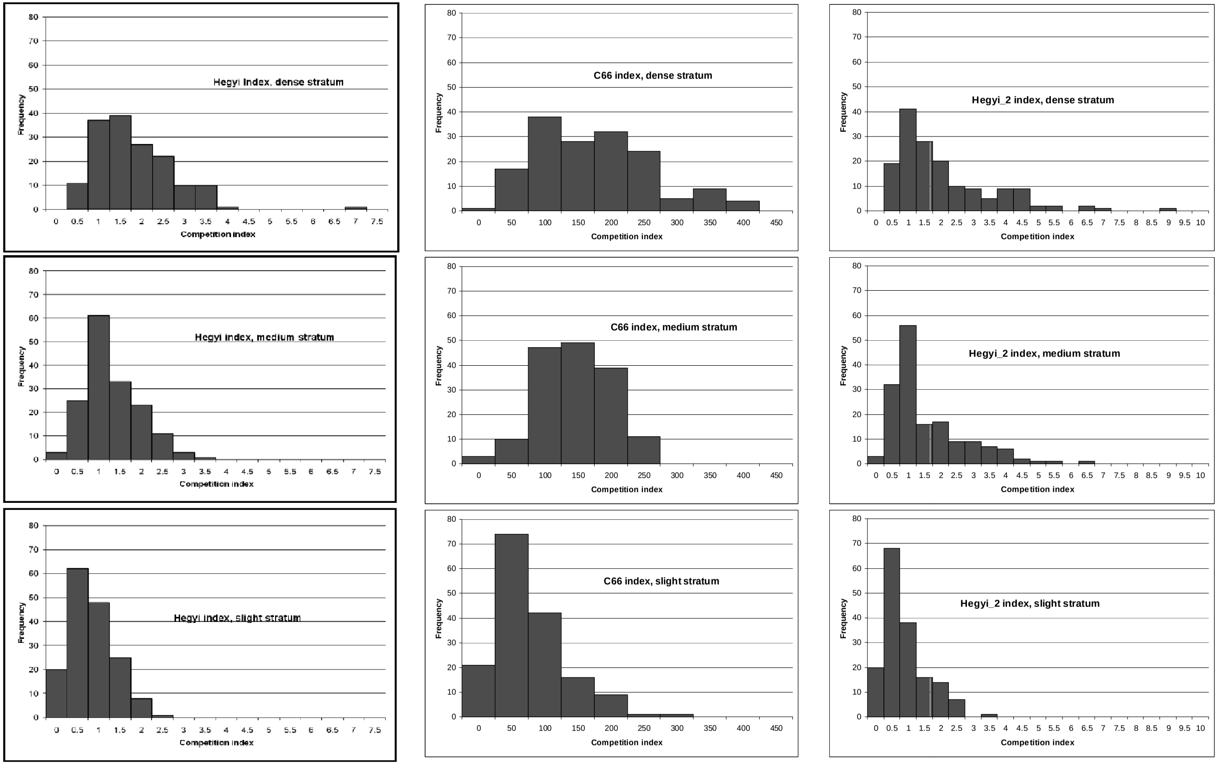


Figure 4.6 Frequency distribution of the selected competition index values for *Acacia seyal*

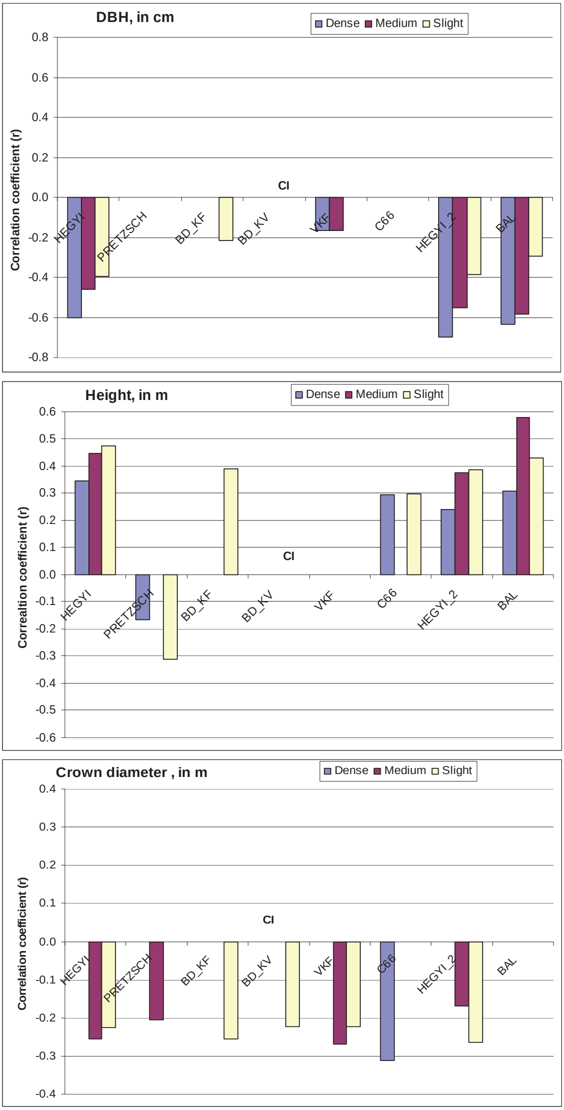


Figure 4.7 Partial correlation between competition indices and *A. seyal* dimensions
The figure shows only the significant correlation between CIs and tree dimensions

4.2.1.3 Selection of an appropriate competition index

The relationship between tree dimensions (DBH, height and crown diameter) and various competition indices was tested by a logarithmic function. The criterion for selecting the appropriate index that better relates to the tree dimension in a specific stratum was based on the coefficient of determination (R^2); the higher the value of R^2, the better the index expresses the relationship. Values of R^2 vary according to tree dimension, competition index and stand density. Table **4.8** depicts the result of the association between tree dimensions and competition index values at different stand densities. In this table, the maximum R^2 (0.690) was obtained as a result of the relationship between DBH and the HEGYI_2 index in dense stratum. Another index, such as the Hegyi index, has also produced a significant relationship (R^2 = 0.238 to 0.471) with DBH. Tree height on the other hand, revealed a negligible association with all indices, with the exception of the Pretzsch index (R^2 = 0.238) in slight stratum. After further inspection of this table, tree crown diameter revealed no relationship with all indices meaning that crown diameter is independent to stand density or competition. Based on the results of this table, Hegyi_2 is the most important index as it better relates to DBH. Thus, Hegyi_2 index can be considered an appropriate index for expressing competitive situations using DBH as an explanatory variable. The selected logarithmic model is able to explain up to 70 percent of the variation. Scatter plots with logarithmic fitted lines, as a result of the association between DBH and the Hegyi_2 index for the different stand densities, were produced and are displayed in **Figure 4.8**. The data points are randomly scattered and do not lie on the line of best fit in medium and slight strata. However in dense stratum, the data points are scattered around the line of best fit, with some scattered points which indicate the presence of outliers. In this figure, the value of the competition index decreases as the DBH increases and the line of the best fit points down to the right, indicating a negative relationship between CI and DBH. In general, CI decreases and approaches zero when DBH exceeds 22 cm in all strata.

Table 4.8 Relationship between CIs and tree dimensions in different *A. seyal* stand densities

index	Diameter at breast height (cm)			Height (m)			Crown diameter (m)		
	a_0	a_1	R^2	a_0	a_1	R^2	a_0	a_1	R^2
Dense stratum (number of target trees = 158)									
Hegyi	6.886(0.455)	-2.022(0.172)	0.471	1.099(0.926)*	0.228(0.457)*	0.002	1.915(0.284)	-0.223(0.172)*	0.011
Pretzsch	22.346(10.294)	-7.651(3.881)	0.024	44.873(15.058)	-21.135(7.433)	0.049	1.707(4.758)*	0.302(2.879)*	0.000
BD_KF	79.311(23.564)	-25.180(8.884)	0.049	93.964(35.210)	-40.099(17.380)	0.033	13.957(11.032)*	-0.611(6.676)*	0.000
BD_KV	119.575(46.616)	-39.408(17.574)	0.031	183.534(68.877)	-83.073(33.998)	0.037	15.448(21.625)*	0.197(13.086)*	0.000
VKF	7.289(1.251)	-2.217(0.472)	0.124	7.385(1.922)	-2.939(0.949)	0.058	1.531(0.610)	-0.051(0.369)*	0.000
C66	226.378(59.330)	-29.635(22.368)*	0.011	-102.361(86.089)*	124.122(42.495)	0.052	182.675(27.093)	-21.513(16.395)*	0.011
Hegyi_2	12.352(0.568)	-3.993(0.214)	0.690	3.608(1.506)	-0.879(0.743)*	0.009	2.225(0.465)	-0.246(0.281)*	0.005
BAL	13708.007(912.266)	-4281.186(343.930)	0.498	2640.901(1908.508)*	-104.294(942.058)	0.000	3051.054(585.824)	-388.634(354.503)*	0.008
Medium stratum (number of target trees = 160)									
Hegyi	4.260(0.350)	-1.200(0.131)	0.347	1.375(0.523)	-0.152(0.260)*	0.002	1.417(0.279)	-0.200(0.158)*	0.010
Pretzsch	16.083(1.942)	-5.373(0.725)	0.258	13.653(2.553)	-5.911(1.267)	0.121	6.015(1.417)	-2.435(0.804)	0.055
BD_KF	73.589(28.997)	-22.718(10.829)	0.027	43.854(35.434)*	-15.286(17.579)*	0.005	29.924(18.961)*	-9.662(10.762)*	0.005
BD_KV	90.160(30.632)	-28.457(11.440)	0.038	64.843(37.513)*	-25.095(18.610)*	0.011	36.589(20.112)*	-12.753(11.415)*	0.008
VKF	6.021(0.673)	-1.800(0.251)	0.245	3.962(0.910)	-1.359(0.451)	0.054	2.530(0.490)	-0.748(0.278)	0.044
C66	262.989(185.971)*	-45.441(69.452)*	0.003	195.567(224.953)*	-26.614(111.600)*	0.000	165.760(120.399)*	-13.615(68.336)*	0.000
Hegyi_2	8.463(0.531)	-2.677(0.198)	0.535	3.688(0.923)	-1.167(0.458)	0.040	1.527(0.504)	-0.105(0.286)*	0.001
BAL	8836.195(977.141)	-2507.069(364.919)	0.230	384.370(1337.806)*	890.758(663.691)*	0.011	2427.199(719.750)	-147.911(408.515)*	0.001
Slight stratum (number of target trees = 164)									
Hegyi	2.498(0.269)	-0.723(0.102)	0.238	0.488(0.356)*	0.058(0.186)*	0.001	0.506(0.210)	0.050(0.118)*	0.001
Pretzsch	3.675(0.719)	-1.208(0.271)	0.109	5.927(0.768)	-2.860(0.402)	0.238	0.943(0.521)*	-0.255(0.293)*	0.005
BD_KF	16.347(2.666)	-4.842(1.007)	0.125	1.443(3.287)*	1.145(1.722)*	0.003	4.713(1.951)	-0.626(1.099)*	0.002
BD_KV	22.446(3.160)	-6.993(1.193)	0.175	16.641(3.893)	-6.626(2.039)	0.061	5.755(2.381)	-0.975(1.341)*	0.003
VKF	2.788(0.368)	-0.842(0.139)	0.185	2.299(0.450)	-0.908(0.236)	0.084	0.740(0.279)	-0.095(0.157)*	0.002
C66	42.815(34.268)*	4.618(12.938)*	0.001	-56.278(38.601)*	58.585(20.220)	0.049	31.423(23.389)*	13.591(13.178)*	0.007
Hegyi_2	3.679(0.338)	-1.148(0.128)	0.333	1.283(0.475)	-0.328(0.249)*	0.011	0.649(0.282)	0.004(0.159)*	0.000
BAL	3531.612(670.889)	-1027.195(253.297)	0.092	-356.486(807.714)*	625.304(423.085)*	0.013	108.639(478.292)*	410.457(269.482)*	0.014

* = parameter not significant

In parenthesis: standard error of the estimate; a_0 and a_1 = coefficients; R^2 = coefficient of determination.

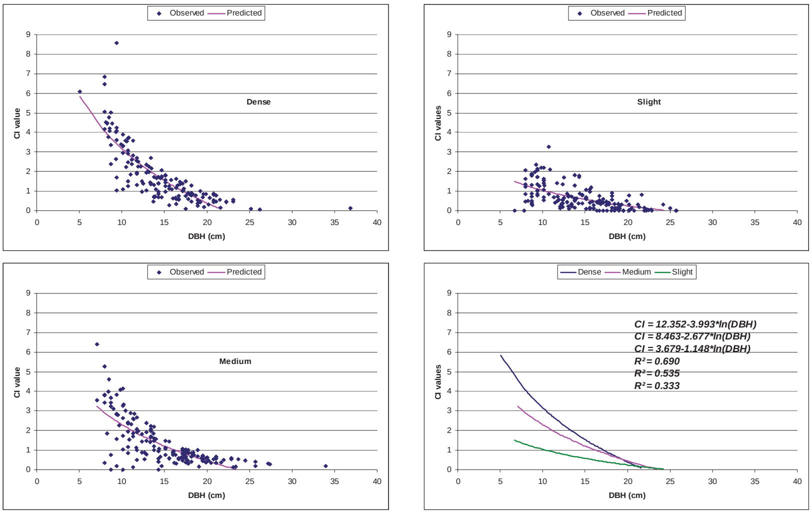


Figure 4.8 *Acacia seyal* and the relationship between DBH and competition index (CI) values (CI_Hegyi_2)

4.2.2 Production of gum *talha* from natural stands of *A. seyal*

A total of 482 individual trees of natural *A. seyal*, of three different stand densities, were selected and exposed to tapping techniques by local tapping tools on three tapping dates. Average gum yield and the number of individual trees per each tapping treatment are shown in Table **4.9**. Trees tapped by *sonki* (n= 16) on first of October at medium stratum have the highest gum yield, with a value of about 56 g/tree/season. The minimum gum yield, 2 g/tree/season, was obtained on 15 October by 18 untapped trees in slight stratum.

Gum *talha* yields are classified into six yield classes (g) namely, ≤ 50, 51-100, 101-150, 151-200, 201-250 and ≥ 251 g. In each yield class, the number of trees in addition to the total and average gum *talha* yield (g) in different stand densities were obtained and summarized in Table **4.10**. The maximum total gum yield (1076.07 g) was obtained in the lowest yield class (≤ 50 g) by 84 observations in dense stratum. Upper yield classes are characterized by few or absence of trees. Irrespective of tapping date and tool of tapping, the average gum yield (g) of a tree per season and gum production (kg/hectare/season) were also obtained for the different stand densities. On average, trees in slight stratum produced a higher amount of gum (20.58 g/tree/season) than those of the other strata. Gum *talha* production ranges between 3.59 to 4.78 kg/ha. In all strata, a high number of trees (between 41-53 percent) in the lowest gum yield class (≤ 50 g) were detected. The number of trees in the second yield class upwards represents less than 5 percent of the selected trees in dense stratum. In medium and slight strata, the number of trees in the same yield classes represents about 6 and 13 percent, respectively. The high yielding trees for example classes 151-200 and upwards, constitute about only 2 percent of the total target trees (482). Non-yielding trees constitute about 43, 53 and 45 percent of the selected trees in dense, medium and slight stratum, respectively.

Table 4.9 Average yield of gum *talha* and number of trees by different tapping treatments

Stand density	Tapping tool	Tapping date	Gum yield (g)	SD	N
Dense	Makmak	Fifteenth Oct	17.36	49.95	22
		First Nov	10.94	13.43	18
		First Oct	30.14	70.64	17
	Sonki	Fifteenth Oct	3.78	5.16	18
		First Nov	13.60	23.84	19
		First Oct	11.74	12.45	15
	Untapped	Fifteenth Oct	4.36	7.49	15
		First Nov	7.70	15.93	14
		First Oct	6.89	16.86	20
Medium	Makmak	Fifteenth Oct	8.59	19.29	23
		First Nov	12.63	33.17	21
		First Oct	9.58	26.72	32
	Sonki	Fifteenth Oct	11.02	29.06	23
		First Nov	4.49	7.68	23
		First Oct	56.07	76.97	16
	Untapped	Fifteenth Oct	6.20	15.21	7
		First Nov	3.51	8.66	15
Slight	Makmak	Fifteenth Oct	16.60	28.59	24
		First Nov	25.78	66.85	27
		First Oct	32.71	50.75	21
	Sonki	Fifteenth Oct	17.09	43.23	19
		First Nov	22.55	49.99	21
		First Oct	36.63	71.27	16
	Untapped	Fifteenth Oct	2.01	3.96	18
		First Nov	14.61	43.84	9
		First Oct	4.59	7.39	9

N = number of observations per treatment; SD = standard deviation

Table 4.10 Number of trees, total and average gum *talha* yield (g) per yield class and production (kg/ha) in different stand densities

Stratum	N_0	Gum yield class (g) ≤ 50	51-100	101-150	151-200	201-250	≥ 251	Average yield (g)	Production (Kg/ha)
		Total gum yield (g)							
Dense	68	1076.07 (84)	199.64 (3)	101.46 (1)	0.00 (0)	234.38 (1)	293.42 (1)	12.06	4.78
Medium	85	809.91 (65)	292.16 (4)	560.39 (4)	0.00 (0)	202.27 (1)	254.28 (1)	13.24	3.59
Slight	74	830.57 (69)	838.18 (12)	368.62 (3)	515.93 (3)	204.53 (1)	616.86 (2)	20.58	4.30

N_0 = number of non-yielding trees; number of observations (dense = 158; medium = 160; slight = 164); number of trees/ha (dense = 396, medium = 271, slight = 209); in parenthesis: the number of trees per yield class.

4.2.3 Factors affecting gum yield

4.2.3.1 Gum yield and tree size (DBH)

Regardless of the gum tapping treatments, the relationship between gum yield and DBH for the different three stand densities was tested. Observed values and the modelled ones-smooth lines are graphically presented in Figure 4.9. The data dots are randomly distributed, indicating a high-level of variability for yields in all strata. The following linear regression model (Equation 36) based on the same figure could be used to predict the yield of gum *talha* in medium stratum; where *Y* is the predicted gum yield (g) per tree and *d* is the tree diameter (DBH, in cm). Generally, as gum yield increases, DBH also increases. Dense stratum, however, produce a curved space below the curves of medium and slight strata. The maximum R^2 value (0.146) was obtained in medium stand density. This means that the model is able to explain a small proportion (only 15%) of gum yield variation.

$$Y = 3.562 * d - 28.061 \quad (36)$$

Parameters are described in the text.

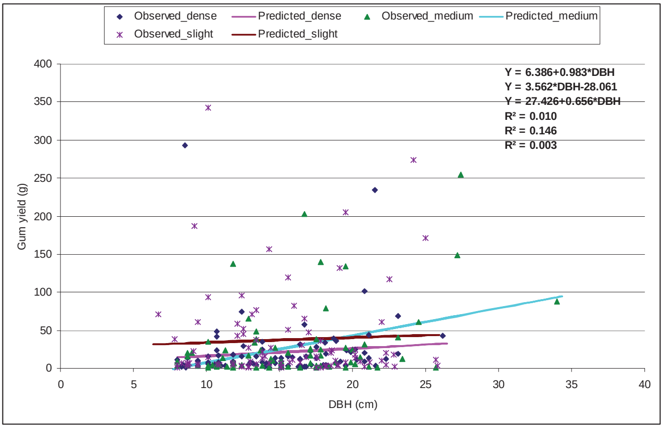


Figure 4.9 Gum *talha* yield in relation to tree diameter for different stand densities
Number of observations per stratum (dense = 90, medium = 75 and slight = 90)

4.2.3.2 Determining factors influencing gum yield using regression tree

To examine factors determining gum *talha* yield, the regression tree package was used and was applied to predict the mean value of gum yield obtained from *A. seyal* trees using different tapping treatments. Gum yield, a measurable response variable, can be expressed as a function of several explanatory-measurable and categorical-variables. These explanatory variables include: stand density (dense, medium and slight), tapping tool (makmak, sonki and untapped trees) and the date of tapping (1^{st} October, 15^{th} October and 1^{st} November) in addition to DBH and competition index (CI). The regression tree model is shown in **Figure 4.10**. This figure illustrates that the model contains of 6 terminal nodes (or leaves, i.e. 4, 6, 7, 10, 22 and 23). DBH, tapping tool, date of tapping and CI contribute to the construction of the tree. DBH is the most important explanatory variable that influences gum yield. The model splits the original data set into two partitions, below and above the DBH threshold value (23.95 cm), which are not evenly distributed. The data set below the threshold includes 97% of the total observations, whereas the set above the threshold reflects only 3% of the observations (see right-hand branch of the Figure **4**.**10**). The model starts with the root node (1) which contains the entire data set (n = 482). The model indicates that the overall mean value of gum is 15.35 g. The predicted mean values of gum yield and number of cases (n) for each terminal node are provided in the same figure. The intermediate and terminal nodes´ number is depicted in parentheses. In the left-hand branch and in the terminal node (4), the minimum gum yield value (5.87 g) is given by 105 untapped trees when DBH is less than the threshold (23.95 cm). In node 7, located in the right-hand branch, the maximum gum yield (124.70 g) is only obtained by 8 trees with DBH larger than the threshold when CI is greater than 0.125. Further details regarding the results of regression tree analysis for predicting gum *talha* yield are shown in Appendix **4**. Node number, variables used at each split and split criterion, number of observations, the deviance associated with split and mean value of gum yield (g) are obtained and summarized in the same appendix.

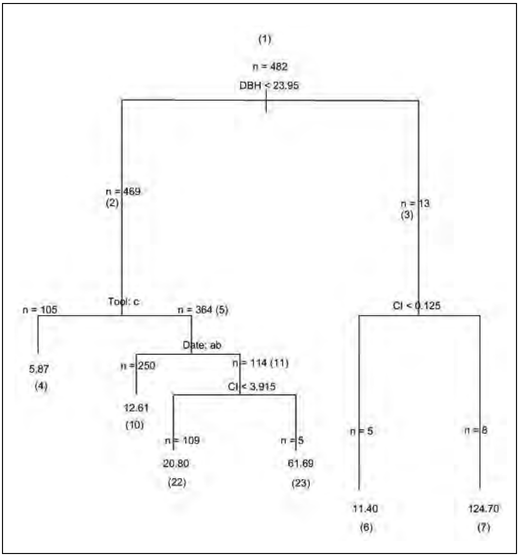


Figure 4.10 Regression tree model for predicting yield of gum *talha*
Means of gum yield are shown in the terminal nodes (4, 6, 7, 10, 22 and 23); in parentheses are node number; n is the number of observation per node; CI = Hegyi_2 competition index; tool (a: makmak, b: sonki, c: untapped trees); date (a: 15th October, b: 1st November, c: 1st October).

4.2.3.3 Determining factors that influence gum yield using GLM

The results of the regression analysis under a general linear model (GLM)/UNIVARIATE showed that at least one treatment is different. To explore the differences in gum yield among significant categorical variables in each stratum, post-hoc tests (or post-hoc comparison tests) following ANOVA and based on Scheffé test were carried out. The results of the ANOVA showed that only the date of tapping is significant for medium stratum. Tapping tool is not significant in all strata (Appendix **5**). The Tests of Between-Subject Effects table (Appendix **6**), shows the results of GLM univariate in which gum *talha* yield is estimated per each stratum by the fixed factors (tapping date and tool of tapping) in addition to DBH and CI as covariates. The results show that the only significant ($p = 0.000$) overall model is in medium stratum and the effect size is partial eta squared (analogous to $R^2 = 0.304$), meaning that the model explains 30.4% of the variance in gum *talha* yield. The overall models in dense and medium strata are not significant. Table **4.11** provides information about whether the means of gum yield for different tapping dates are significantly (α = 0.05) different from each other. In this table, the results of the post-hoc test indicate that the significance ($p < 0.021$) detected stemmed from a difference between just two groups of dates; the first of October vs. the first of November. The other comparisons were found to be insignificant. More details about the differences in gum yield are presented in the table of the homogenous subset (Table **4**.**12**). As illustrated by this table, the outputs of Scheffé test produces gum averages either in one subset or two subsets for each group. Averages within the same subset are not significantly different from each other (α = 0.05). For example, in the case of one subset in dense and slight strata, there is no significant difference in gum yield between the different tapping dates. However, for medium stratum, there are two subsets. This means that, in the first subset, there is no difference ($p = 0.943$) in gum yield between the fifteen of October and the first of November. In the second subset, there is also no difference between first and fifteen of October. However, gum yield is different ($p = 0.050$) between the first of October and the first of November.

Table 4.11 Post-hoc-test, following ANOVA, based on Scheffé test for testing the difference in gum *talha* yield

Stratum	Date (X)	Date (Y)	Gum mean difference (X-Y)	SE	Sig.	95% Confidence limit	
						Lower	Upper
Dense	First of October	Fifteen of October	6.516	6.291	0.586	-9.040	22.073
		First of November	4.848	6.410	0.752	-11.002	20.698
	Fifteen of October	First of November	-1.668	6.323	0.966	-17.303	13.966
Medium	First of October	Fifteen of October	15.748	6.535	0.058	-0.407	31.902
		First of November	17.939*	6.375	0.021	2.180	33.698
	Fifteen of October	First of November	2.191	6.207	0.940	-13.152	17.535
Slight	First of October	Fifteen of October	16.122	9.442	0.236	-7.215	39.459
		First of November	5.747	9.583	0.836	-17.939	29.433
	Fifteen of October	First of November	-10.375	8.907	0.509	-32.391	11.640

*. The mean difference is significant at the 0.05 level
X and Y are specified dates; SE is the standard error of the mean

Table 4.12 Homogenous subset for average gum yield (g) based on Scheffé test

Dense			Medium				Slight		
Date of tapping	N	Subset 1	Date of tapping	N	Subset 1	Subset 2	Date of tapping	N	Subset 1
2	55	12.811	3	59	7.136		2	61	12.449
3	51	22.825	2	53	9.328	9.328	3	57	22.825
1	52	28.571	1	48		25.075	1	46	28.571
Sig.		0.591			0.943	0.050			0.227

Means for groups in homogeneous subsets are displayed; Date of tapping: 1 = first of October, 2 = fifteenth of October and 3 = first of November

Taking into account only the yielding trees and considering all the explanatory variables, the results of GLM indicate that only DBH, date (1st of October) and the use of makmak are significant ($p < 0.05$) for medium stratum. The coefficients of the significant variables (DBH, 1st of October and makmak) were used to derive a regression model (Equation 37) for predicting the outcome of gum *talha* yield. The performance of the model was assessed by the coefficient of determination (R^2). The results of the analysis indicated that the adjusted R^2 for the final model was 0.256, explaining approximately 26% of the total variation in gum yield (Figure 4.11). The distribution of the data points indicates no clear association between the selected significant variables and the gum yield.

$$Y = 4.079 * d + 61.944 * t - 70.444 * T \quad (37)$$

Where: Y is the gum yield per tree (g); d denotes diameter at breast height (DBH, in cm); and

$$t = \begin{cases} 0 & \text{if the tapping date is not first of October} \\ 1 & \text{if the tapping date is first of October} \end{cases}$$

$$T = \begin{cases} 0 & \text{if the tapping tool is not makmak} \\ 1 & \text{if the tapping tool is makmak} \end{cases}$$

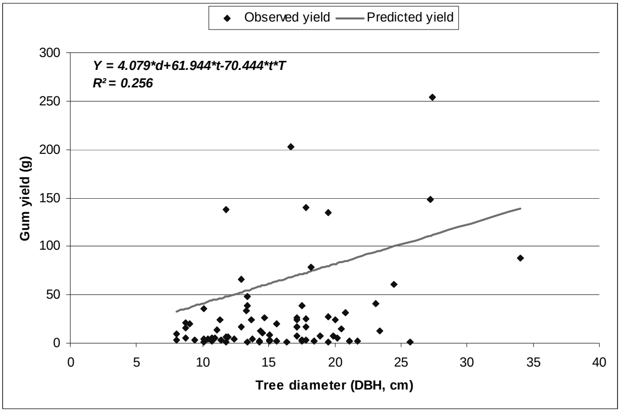


Figure 4.11 Observed and predicted gum yield (g) of *Acacia seyal* at medium stratum

Number of observations (only yielding trees) = 75; d = DBH (cm); t = time of tapping (1st of October); T = tapping tool (makmak)

4.2.3.4 Determining factors affecting gum yield using logistic regression

The classification table (Table **4**.**13**) displays the correctly (predicted), incorrectly (not predicted) and overall predictions of the binary logistic model results. The model was used to classify both yielding and non-yielding trees. For instance, the percent of correctly classified yielding trees was calculated by dividing the number of correctly-classified cases by the number of correctly and incorrectly predicted observations. However, the overall percentage correct was obtained by adding the total correctly predicted yielding trees with the correctly predicted non-yielding trees and then dividing the total of the two by the total observations for both yielding and non-yielding trees. In dense stratum, the model correctly classified 80.2% of trees as yielding trees and 46.3% of the non-yielding trees. Similarly, in the medium stratum the model correctly identified 54.7% of the yielding trees and 70.6% of the non-yielding trees, whereas 74.4% and 54.1% were correctly classified, respectively, for yielding and non-yielding trees in the slight stratum. The classification table shows that the model's overall predictions (total predictive efficiency) account for 65.8, 63.1 and 65.2% for dense, medium and slight strata, respectively.

The results of the logistic regression analysis and the variables to be used in the model are presented in Table **4**.**14**. The significance of each variable is measured using a Wald statistic. Using a cut value ($p = 0.05$) by default as a criterion for including or not including the variables in the final equation, it appears that in dense stratum the model contains only the tool (untapped; $p = 0.001$) and constant ($p = 0.001$). In medium stratum, the constant, DBH, tool (sonki) and the date (1^{st} of October) are the suggested variables to be included in the equation ($p < 0.05$). However, for slight stratum the constant, DBH, tool (untapped) and the date (1^{st} of October) should be used in the model ($p < 0.05$).

Table 4.13 Classification table* of the logistic regression analysis of gum *talha* yield

Stratum	Step	Observed yield		Predicted: Yield probability: No yield	Predicted: Yield probability: Yield	Predicted: Percentage correct
Dense	1	Yield probability	No yield	31	36	46.3
			Yield	18	73	80.2
		Overall percentage				65.8
Medium	3	Yield probability	No yield	60	25	70.6
			Yield	34	41	54.7
		Overall percentage				63.1
Slight	3	Yield probability	No yield	40	34	54.1
			Yield	23	67	74.4
		Overall percentage				65.2

*. The cut value is 0.5

Table 4.14 Results of logistic regression analysis (dependent variable: gum yield)

Stratum	Parameter	coefficient	S.E.	Wald	Sig.
Dense	Untapped	-1.251	0.360	12.096	0.001
	Constant	0.707	0.204	12.049	0.001
Medium	DBH	0.081	0.036	5.014	0.025
	Sonki	0.711	0.343	4.300	0.038
	1^{st} of October	0.999	0.373	7.186	0.007
	Constant	-1.927	0.625	9.517	0.002
Slight	DBH	0.111	0.040	7.668	0.006
	1^{st} of October	1.043	0.404	6.679	0.010
	Untapped	-1.738	0.447	15.088	0.000
	Constant	-1.316	0.616	4.564	0.033

S.E = standard error; only the significant parameters are shown.

5 DISCUSSION

The following chapter presents the discussion on the results revealed in the present study. There are three sections included in this chapter. The first one deals with stand structure, composition and modeling height and volume functions of *A. seyal*. The second section discusses the competition among individual trees of *A. seyal* in natural stands. The third section focuses on the production of gum *talha*, factors affecting the production and models for gum *talha* yield.

5.1 *Stand characteristics*

Stand characteristics, such as composition, structure, basal area, and volume, are common attributes assigned to entire stands based on plot measurements.

5.1.1 Forest composition and structure

As previously mentioned three stands densities, based on the number of trees per unit area, of *A. seyal* in the Umfakarin Natural Forest Reserve were distinguished, namely dense, medium and slight strata. Important features of these stands can be described as mono-species, single-layered, and naturally regenerated. Additionally, there have been no silvicultural treatments or felling operations in the forest, with the exception of illegal felling in some parts of the forest by local people who live adjacent to the reserve. The stands are typical for the Garri forest in Blue Nile, Sudan which was described by Vink (1990a) as "*A. seyal* formation of 10-20 years old, of natural origin, pure, no understory, no natural regeneration and the site is being grazed by villages´ livestock". *A. seyal* of different densities dominate the forest, nevertheless, other trees and/or shrubs are also found, such as *A. mellifera*, *Balanites aegyptiaca*, *A. polycantha*, *A. senegal*, *A. nilotica*, *A. sieberana*, *Cordia Africana*, *Boscia senegalensis,* and *Dichrystachst sinaria*.

Stand structure is the distribution of species and tree sizes in a forest area (Husch *et al*., 1993). Distribution of diameters and the heights of trees, in a specific stand, is a good criterion not only for describing the horizontal and vertical structure of the stand but to also provide basic information for forest resource management. Moreover, trees of different diameters may be used for different purposes and have different values per cubic meter of wood (Philip, 1994). In the present study, the height frequency distribution is approximately normal in the dense stratum, yet it is irregular in the other strata. On the other hand, the diameter is approximately normally distributed and the pattern of distribution appears to be similar in the three stand densities. The number of individuals is higher in the second and third diameter classes. In contrast, there are few stems in the small (DBH = 7.5 cm) and large diameter classes (DBH = 22.5^+ cm). Egadu *et al*. (2006), in their study of the population of acacia tree species producing gum Arabic in Karamoja, Uganda, revealed a higher number of stems of *A. seyal* in smaller diameter classes indicating good regeneration. Conversely, in this study few stems were detected in the smaller diameter class indicating poor natural regeneration. The lower number of stems in the 22.5 diameter class and upwards could be attributed to illegal felling in some parts of the forest. Despite protection measures against illegal felling, temporary informal tracks were created inside the forest by loggers to facilitate wood extraction (diameters 22.5^+ cm) for different purposes.

5.1.2 Natural regeneration

A. seyal is a light demander; it is a rapidly growing species and its small seedlings colonize open sites quickly (Figure **3**.**6**). The aggregation of *A. seyal* natural generation (4867 seedlings per hectare) demonstrates that the species, in its natural habitats, successfully compete with other vegetation types (woody and/or grass species). The species grows fast and mature trees tend to close the canopy which may lessen the growth efficiency of other vegetation. In the present investigation, the number of natural regeneration per unit area in all strata is quite poor (maximum 50 seedlings per hectare), which is not promising. The unsatisfactory natural regeneration may be due to the seedlings mortality caused by frequent forest disturbances such as continuous grazing and fires. These disturbance factors are very common in the area of investigation. The situation exemplifies the absence of tending operations to assist natural regeneration.

5.1.3 Height-diameter relationship

Height and diameter are the most frequent measurements made by foresters in order to estimate growth and/or the yield of trees in forest stands. El-Juhany and Aref (2001) indicated that, under uniform site conditions, trees of the same age grow in height at roughly the same rate but not necessarily the same in diameter. They further noted that, in uniform site conditions, trees of the same diameter do not necessarily having the same height. However, in tropical natural forest stands, it is difficult to estimate tree age, hence trees growing under the same site conditions do not necessarily grow in height at the same rate. Variation in heights and diameters may be due to competition and difference in tree age.

One of the most important elements of forest structure is the relationship between tree diameters and heights (Zucchini *et al*., 2001). A stand height curve is a mathematical or graphical representation that describes the dependency of tree height on diameter. The height curve can be used to predict individual tree height when only DBH is measured. Moreover, the predicted height can be used together with DBH to derive single tree volume and/or to produce volume table (2-way volume table) of a forest stands. In this investigation, six height functions were proposed for testing the height-diameter relationship of *A. seyal* trees in natural stands. The criteria adopted for examining the performance of the height curves were the R^2 value, AIC, curve shape and asymptote. However, Laar and Akça (2007) and Yuancai and Parresol (2001) suggested that the fit curve should satisfy specific criteria. These criteria are monotonic increment (increasing height with increasing diameter), inflection point (the point(s) where the curve change its direction) and asymptote (when the diameter goes to infinity). In reality, height increases with increasing diameter but not absolute, it should increase to a certain limit. Based on these criteria Michailow height function was selected because in addition to plausible curve shape, about 23% of the total height variability is explained. Nevertheless, the Michailow height curve was compared to parabolic function which was used by Elsiddig (2003b) for estimating height of *A. seyal* in eastern Sudan (**Figure 5.1**). The later function produces R^2 value greater than that of Michailow but does not satisfy the criteria which proposed by the authors (Laar and Akça, 2007; Yuancai and Parresol, 2001). Both models revealed biologically logical trend up to 30 cm DBH, then height by parabolic decreases with increasing DBH which is not acceptable from biological view point. The Michailow height function also satisfies the asymptote which corresponds to the maximum height (10.2 m) when DBH goes to infinity. The parabolic function does not satisfy this criterion. Based on these findings, Michailow height function (Equation 38) was used for predicting height of *A. seyal* trees in Umfakarin natural forest, Sudan and in other areas of similar climatic conditions.

$$H = 1.3 + 8.486 * e^{\left(-\frac{4.604}{d}\right)} \quad (38)$$

Parameter as previously explained.

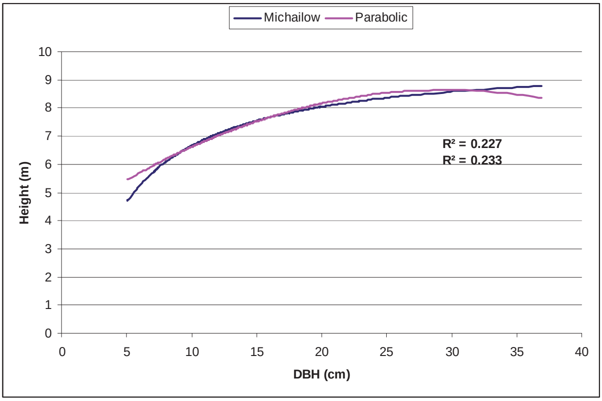


Figure 5.1 Michailow and parabolic height curves used for predicting height of *A. seyal* trees in Umfakarin natural forest, Sudan

5.1.4 Single tree and stand volume functions

In forest stands, yield of wood is usually measured in terms of standing volume of trees which is mostly dependent on site quality and silvicultural management. *A. seyal* in Sudan is considered as one of the original sources for firewood and charcoal since the species is growing rapidly and requiring minimum management (Wickens *et al*., 1995). Findings related to the standing volume in the present investigation, are similar to that estimates obtained by El Dool (1988) at Khor Donya forest (~ 700 mm mean annual rainfall) in Blue Nile province, Sudan, who revealed to an average volume of 20.5 m^3/ha, 5.2 m^2/ha BA and 373 stem/ha of *A. seyal* (10-20 years old). The similarity of these findings is expecting elsewhere in Sudan because *A. seyal* is growing naturally in specific zone of similar climatic conditions.

Mathematical models for estimating timber yields are usually developed by fitting a suitable equation to observed data (Gadow and Hui, 1999). In this investigation, volume of *A. seyal* trees was estimated using the volume function of two-entries (i.e.

DBH and height). This type of volume function was used by Elsiddig (2003b) for estimating the standing volume of *A. seyal* in eastern Sudan. The function produced in the present study was based on DBH and height estimated by Michailow height function. However, DBH and height estimated by parabolic height function was used to produce volume function used by the same author. The functions produced similar parameters despite the differences in height estimated by the Michailow and parabolic functions (Figure **5.2**). The volume function (Equation 39) used, in this study, is able to explain up to 92% of the total volume variations. In this case, this volume function is suitable to be used for prediction of standing volume of *A. seyal* natural stands in Umfakarin forest, South Kordofan, Sudan or other relevant species in other areas of similar climatic conditions.

$$v = 3.936 * 10^{-5} * d^2h - 1.695 * 10^{-5} \quad (39)$$

Parameters were explained in the results chapter.

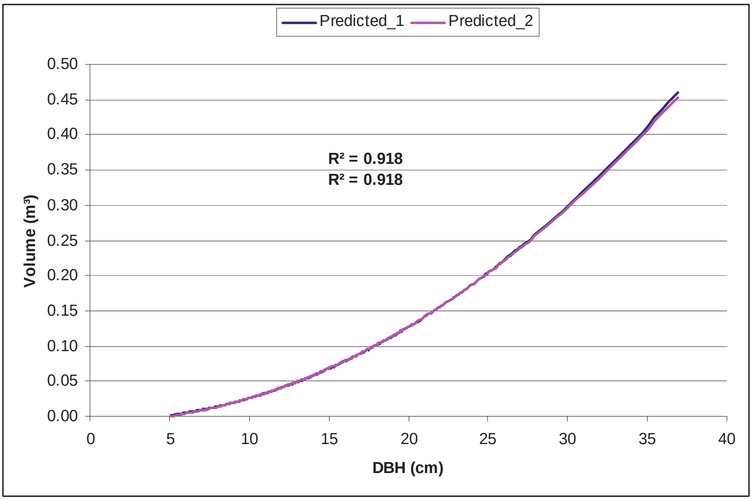


Figure 5.2 Volume functions used for deriving volume of *A. seyal* in Sudan
Predicted_1 based on the predicted height from Michailow height function; Predicted_2 based on height from parabolic height function.

5.1.5 Crown radius-DBH relationship

Crown profile in a stand level is usually measured to study either growth or competition among trees. Crown characteristics, such as crown projection area (CrPA) and crown diameter (CD), are good measures to understand competition and production (Shimano, 1997). Krajicek *et al* (1961) used the crown competition factor as a measure of stand density which indicates that crown characteristics are affected by stand density. Crown radius, for instance, is affected by stand density (Hussein, 2001) but only up to a certain point. In contrast to the findings of these authors, the results of the present investigation revealed a positive association between crown radius and DBH independent to stand density as illustrated by **Figure 3.8** and **Figure 4.5**, bottom right.

5.2 Single tree values

5.2.1 Competition among trees of *A. seyal* natural stands

In this study, eight competition indices (CIs) were quantified using the CroCom program. A two step process was necessary, in order to quantify the CIs; identification of the competitors and quantification of the index values. The method for selecting the competitor trees was based on the assumption that *A. seyal* usually exists as single-layered stands and intra-layer competition occurs within an area referred to the available growing space. The radius of this area was assumed to slightly exceed the height of a single tree. Several approaches have been used to identify which neighbor trees compete with target trees, for example (Biging and Dobbertin, 1992; Hegyi, 1974; Münder and Schröder, 2001; Pretzsch, 1995; Schütz, 2001; Schütz and Röhnisch, 2003; Wykoff *et al*., 1982). Most of these methods are based on the authors' judgment. The competitive stress induced by the neighbor trees on target trees can be obtained by the identification of the dimensions and positions of neighborhood trees and the relationship that these parameters have with those of the target tree. In this study, environmental factors such as soil and water were not evaluated, assessment of which is beyond the scope of this investigation. Nevertheless, Bukhari (1998) pointed out that natural mortality in *A. seyal* trees is a result of root competition. This idea necessitates a general approach for quantifying the competition value that links below and above ground competition.

5.2.2 Competition index in relation to tree dimensions

The relationship between the calculated CIs and tree parameters (DBH, height and crown diameter) was first assessed by the method of partial correlation, in order to highlight the actual correlation between each CI and each dimension after removing the effects of other variables. As long as the partial correlation assumes only linear correlations between variables, a logarithmic model can be used to determine the relationship between CIs and tree dimensions. These dimensions are sensitive variables for a competitive situation. Additionally, variations in tree dimensions are caused by the stand density (number of trees per unit area) and the tree size in addition to the distance between trees. Several scholars have also used these variables to determine the relationship between CI and tree parameters (for instance, Biging and Dobbertin, 1992; Hegyi, 1974; Münder and Schröder, 2001 and Pretzsch, 1995). Competition induced by large adjacent trees may negatively reflect on diameter and crown dimensions (negative competition outcomes) of individual subject trees. Both diameter and crown diameter are negatively correlated with almost all of the competition indices. Growth or production performance of individual trees decreases as the stand density per unit area increases. In dense situations, many trees may not be able to develop their crowns because of competition. Whenever the causes of competition are minimized or removed, trees start to develop their crowns hence, increase their growth and production capability. During competitive situations trees may tend to increase their heights (positive competition outcomes) in order to obtain sunlight, especially light demanding trees in single-layered stands like *A. seyal*, rather than enlarging cross-sectional dimensions such as DBH and crown diameter. This situation is clearly expressed by a positive correlation between tree height and some indices (CI_HEGYI, CI_BD_KF, CI_C66, CI_HEGYI_2 and CI_BAL), as shown in Figure **4**.**7**. This positive association could be attributed to the method of selecting the competitors which was based on the height of subject tree. The radius of influence zone (RIZ) increases as the height of the subject tree increases and consequently additional competitors are included and this will increase the competition index value. Lorimer (1983) used similar to this method to identify the competitor trees in a radius based on mean crown radius (MCR) of overstory trees. The radius was termed as “search radius” and equal to

3.5xMCR. Based on this method the number of competitors and competition stress also increase as MCR increases.

As previously mentioned, a non-linear regression (logarithmic function) model was used for describing the relationship between tree dimensions and competition indices. Based on the results of these models, and using DBH as a predictor, CI_HEGYI_2 is considered to be a suitable index for quantifying the degree of competition in natural stands of *A. seyal* of dense and medium stratum. About 70% of the total variability is explained by the function at the dense stratum. The portion (30%) not explained by the model could be related to other factors such as crown dimensions, site conditions and the method used for selecting the competitors. The selection of methodology is subjective as the judgment of what method is best is based on the investigator, simplicity, and practical applicability of the method.

5.2.3 Gum *talha* production

Gum *talha* has a significant contribution to the total production of gum Arabic in Sudan. Nevertheless, the yield per tree and production per unit area is very low in comparison to that of *Acacia senegal*. The results of this section demonstrate the possibility of managing *A. seyal* natural stands for sustainable production of gum *talha.* In this study, gum *talha* production was carried out under different tapping treatments and the average gum yield was 12-20.59 g per tree per season. These results are similar to those reported by some authors (Ali, 2006; Hineit, 2007). However, these results are greatly different from the estimates (78.51-185.75 g/tree) provided by Fadl and Gebauer (2004). Gum *talha* production per hectare can, however, be increased by increasing the number of trees per ha. But production per hectare in medium stratum is less than that of slight stratum. The production (4.5 kg/ha) in dense stratum is only a matter of number of trees per hectare. Low production could be associated with the capability of a tree to produce gum or other factors such as site conditions. Moreover, the lower price of gum *talha* in comparison with that gum *hashab* produced by *Acacia senegal* may not provide an incentive for local farmers to harvest gum *talha*. The percent of non-yielding trees also contributes to the low production of gum *talha*. In this study, the non-yielding trees constitutes about 47% of the total number of trees (482) selected for gum production. On the other hand, trees that produce less than 50 g of gum represent between 41-53 percent. These results indicate that few individual (4-13%) *Acacia seyal* trees in the Umfakarin Forest produce gum *talha* exceeding 50 grams.

5.2.3.1 Factors affecting gum *talha* yield

To manage *Acacia seyal* natural stands for the production of gum *talha*, factors affecting the production of gum should be identified and assessed. This study suggests an approach for estimating the yield of gum *talha* from *A. seyal* natural stands. This approach is based on a set of independent variables, including stand density, tapping tool and date of tapping in addition to DBH and competition index (CI). It was assumed that these explanatory variables have an influence on gum yield. To test this assumption, different models, i.e., regression tree, regression analysis under univariate GLM (general linear model) and logistic regression, were applied. The influence of these variables on gum production was first tested by regression tree model which able to explain only 6% of the total variation in gum *talha* yield.

Based on the results of regression tree, stand density was the only variable that did not contribute in the tree model (**Figure 4.10**). This means, stand density had no significant influence on gum yield of single trees but has an impact on the total gum yield. On the other hand, tool and date of tapping contributed in tree model, exposing that both variables have an influence on gum yield. The present findings seem to be consistent with those of Fadl and Gebauer (2004) who investigated the effect of tapping tools on the productivity of gum *talha* and revealed that tapping has a positive impact on gum yield. In contrast to the results of this study, other research (e.g. Ali, 2006) revealed that tool and date of tapping have no sigificant effect on gum *talha* productivity.

The regression tree model was also used to calculate the mean value of the gum yield based on the threshold of the DBH. The mean gum yield below the DBH threshold is only 13.53 g/tree/season which represents in more than 97% of the total observations (482) and the rest (only 3%) produced gum with a mean equal to 81.10 g (Figure **5.3**). In this figure, the vertical dotted line denotes the threshold value (23.95) of DBH. The two horizontal lines show the mean values of gum yield 13.53 and 81.10 below and above the threshold, respectively. As can be seen from this figure, the right-hand side of the vertical dotted line contains only 13 individuals, making further subdivision ineffective. However, further subdivision for the data below the threshold is necessary. These results demonstrate the importance of the number of trees to be selected for the purpose of gum *talha* production experiments. Both studies conducted by the authors Ali (2006) and Fadl and Gebauer (2004) used only 5 and 2 trees per tapping treatment, respectively.

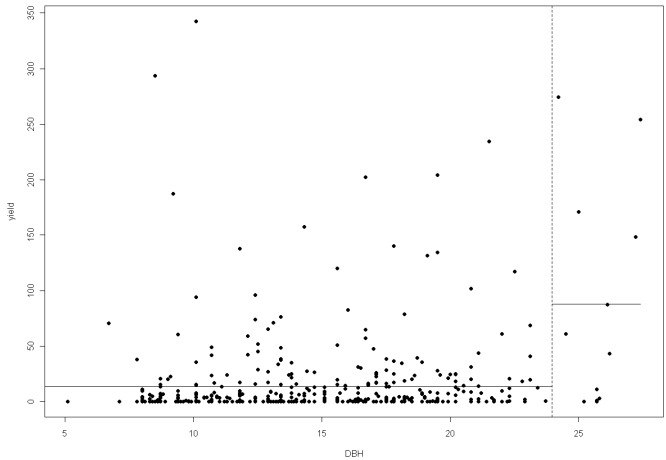


Figure 5.3 Regression tree model: DBH threshold and the mean gum *talha* yield (g)
The vertical dotted line denotes the threshold value (23.95 cm) of DBH. The two horizontal lines show the mean values of gum yield (g) 13.53 and 81.10 below and above the threshold, respectively.

The results of the GLM indicate that the tree size (DBH) and the time of tapping have a profound effect on the production of gum *talha* in medium stratum. Consequently, a mathematical model (Equation 34) was developed for the prediction of gum *talha* yield. However, this model only used the data from trees with gum yield, which may not clearly express the real situation of *A. se*yal in natural stands. This may underscore a weak point in the model as it does not include all observations.

The classification results of the logistic regression analysis were used to evaluate the predictive performance of the logistic regression model. In the classification table (Table **4.13**), the observed gum yield values and the predicted ones (at a cut value of

0.50) are cross-classified. This classification table shows that the logistic regression model overall predictions do not exceed 65% for any of the three strata.

The parameters´ coefficient exhibited in Table **4.14** can be used in logistic regression models for the prediction of gum yield probability in all three strata. For these models, the predictions (*P*) would be as follows for dense, medium and slight stratum, respectively:

$$\mathrm{P_{dense}} = 1/(1 + \frac{1}{\mathrm{e}^{(0.707-1.251*\mathrm{untapped})}}) \quad (40)$$

$$\mathrm{P_{medium}} = 1/(1 + \frac{1}{\mathrm{e}^{(0.081*\mathrm{DBH}+0.711*\mathrm{sonki}+0.999*\mathrm{first\ of\ October}-1.927)}}) \quad (41)$$

$$\mathrm{P_{slight}} = 1/(1 + \frac{1}{\mathrm{e}^{(0.111*\mathrm{DBH}-1.738*\mathrm{untapped}+1.043*\mathrm{first\ of\ October}-1.316)}}) \quad (42)$$

$$\mathrm{untapped} = \begin{cases} 0 & \text{if the tree is untapped} \\ 1 & \text{if the tree is tapped} \end{cases}$$

$$\mathrm{sonki} = \begin{cases} 0 & \text{if the tapping tool is not sonki} \\ 1 & \text{if the tapping tool is sonki} \end{cases}$$

$$\mathrm{first\ of\ October} = \begin{cases} 0 & \text{if the tapping date is not the first of October} \\ 1 & \text{if the tapping date is the first of October} \end{cases}$$

5.2.3.2 Gum yield in relation to tree diameter

The correlation coefficient (r) is a good criterion for testing the relationship between two variables. Based on the results of a simple correlation ($r = 0.315$; $p = 0.000$), gum *talha* yield was found to be positively associated with DBH at medium stand density. This means tree size, i.e. DBH, has a positive effect on the yield of gum *talha*. The present results indicate that there is a moderate correspondence between the observed gum yield and predictions when using DBH as a predictor. Similarly, a weak positive correlation ($r = 0.138$) was reported by Ali (2006) between gum *talha* yield and DBH. However, the findings of the current study do not support previous research conducted by Hineit (2007) who found no significant relationship between yield of gum *talha* and DBH. The weak correlation between gum *talha* yield and tree diameter could be attributed to genetic and environmental factors. Further studies on the gum yield of *A. seyal* under different site conditions could be of importance in order to proof this assumption. For example, the affect of environmental factors on gum Arabic yield (gum from *A. senegal*) was investigated by Ballal *et al*. (2005b).

Their study revealed that gum arabic yield is highly affected by rainfall and is positively correlated with annual rainfall.

5.2.3.3 Gum yield in relation to CI value

CI quantification stemmed from the assumption that competition has a clear negative impact on the productivity of gum *talha*. In this case, a correlation analysis was performed. The purpose of correlation analysis was to measure the strength and direction of association between competition index values and gum yield. Among the eight competition indices, correlation analysis found a negative linear combination ($r = -0.164$; $p = 0.038$) between BAL index and gum yield in medium stratum.

5.2.4 Future prospects of gum *talha*

Gum *talha* is an important natural exudates produced by *A. seyal*. Rural people in Sudan collect the product, in regions where the species exists naturally. Despite the low production of gum *talha* per unit area, the present study has shown that it is possible for gum *talha* production from natural stands of *A. seyal* in the Umfakarin Forest, South Kordofan, Sudan. Conservation and the improvement of natural forests in Sudan, and *A. seyal* in particular, is paramount due to two obvious reasons. First, *A. seyal* provides multiple services for both rural and urban populations. The tree species is the main source of fuel-wood, fodder and gum in addition to other services. The species provides income for rural people living in the vicinity of *A. seyal* forested areas, through the sale of fuel-wood and gum. Second, the natural stands of *A. seyal* could perform significant protective functions if managed properly, especially in marginal areas such as the northern parts of South Kordofan, Sudan.

To assess the potential of gum *talha* production in Sudan, several variables need to be identified:

- areas where *A. seyal* is currently present
- stocking density in terms of the number of trees
- yield per tree and production per unit area

The first and second variables could be measured by means of remote sensing and ground inventories. The last variable could be assessed by conducting gum experiments in permanent plot trials in different climatic regions of the Sudan.

Finally, the findings presented in this thesis present new perspectives for future research in order to promote the production of gum *talha* from *Acacia seyal* and gums from other tree species. For the future development of research on gum *talha* production the following suggestions are made:

- Further investigation and experimentation into gum *talha* production is strongly recommended.
- Conducting experiments on the production of gum *talha* in permanent plot trials in different climatic regions of the Sudan is highly recommended.
- Further investigation on the influence of a combination of environmental factors and managerial ones (such factors investigated in this thesis) on the production of gum *talha* would be very interesting.
- The thesis has thrown up ideas in need for further investigation. Further research regarding whether the competition among trees has an impact on the production of gum *talha* during the life span of *Acacia seyal* tree is highly recommended. In this regard, a careful method of selecting the competing trees during the life span of a single tree of *Acacia seyal* is needed.

SUMMARY AND ZUSAMMENFASSUNG

SUMMARY

The present study was conducted in Umfakarin natural forest reserve, South Kordofan, Sudan. The main objective was to investigate the possibility of managing *Acacia seyal* Del. variety *seyal* for the production of gum *talha*. Three stand densities (strata), namely dense, medium, and slight, were distinguished based on the number of trees per hectare. During the sampling phase, the study adopted the method of identifying the competitors (neighboring trees) from the subject one (trees selected for gum production experiments). From the three stand densities, a total of 482 subject trees, covering variable diameter ranges (*d*= 9-11.5, 13.5-16, 18-20.5 and above 21 cm) were selected, based on the diameter at 0.25 m height ($d_{0.25}$). In each stratum, competitor trees were identified within a radius equal to the height of subject tree multiplied by a factor (1.25). The diameter at breast height, height to crown base, height, crown radii, and tree coordinates were measured for each of the subject trees and its competitors. Subject trees were exposed to tapping on first of October, the fifteenth of October, and the first of November, using local tools (*Sonki* and *Makmak*). Additionally, untapped trees were used as controlling-variables. The initial gum collection was completed fifteen days after the tapping, while the subsequent (7-9 pickings) were done at an interval of fifteen days.

Six stand height functions were tested and the results illustrated that the Michailow stand height function was suitable for predicting the height of *Acacia seyal* in Umfakarin natural forest. The predictive ability of this height function ranged from 19.3% to 24%. The volume function used in this study was able to predict the volume of standing trees with more than 92 percent accuracy.

Competition among trees of *Acacia seyal* was assessed in terms of competition indices. Eight competition indices were quantified using the CroCom program. The relationship between these indices and tree dimensions (diameter at breast height, height and crown diameter) was tested using logarithmic models. Among these indices, the Hegyi_2 index is considered a suitable index to be applied for estimating the degree of competition in natural stands of *A. seyal* of dense stratum when using diameter at breast height as a predictor. About 70% of the total variability is explained by this logarithmic model.

Gum yielded by each subject tree per season was obtained by summing up the gum samples collected from all pickings. Gum production per unit area was also determined. Regression tree, general linear model (GLM) and logistic regression techniques were used for analyzing the obtained data. The results of the study indicated that the gum yield is independent of stand density. Tapping has influence on gum yield. Trees tapped by sonki on the first of October at medium stand density have the highest gum with an average value of about 56 g/tree/season. Significant difference ($p = 0.021$) was detected between two groups of dates; the first of October and first of November in medium stand density. The results also revealed that the most important variable influencing gum production was found to be diameter at breast height with 23.95 cm threshold. Between 41-53 percent of subject trees produce gum less than 50 g/season. The results indicated that *A. seyal* species produces a very low quantity of gum *talha* (3.6-4.8 kg/ha) and for economic reasons, its tapping is not recommended. The findings of the regression analysis revealed to a model which could be used to estimate the yield of gum *talha* from *A. seyal* natural stands in the Umfakarin forest, South Kordofan, Sudan. Conducting experiments on the production of gum *talha* in permanent plot trials in different climatic regions of the Sudan is highly recommended.

ZUSAMMENFASSUNG

Die vorliegende Studie wurde im Umfakarin Naturwaldreservat in Südkordofan, Sudan, durchgeführt. Hauptziel war die Untersuchung möglicher Bewirtschaftungsstrategien im Bezug auf die Gum talha Produktion von *Acacia seyal* Del. Varietät *seyal*. Basierend auf der Stammzahl pro ha wurden drei Bestandesdichten (Straten, dicht, mittel und licht) definiert. Bei der Probennahme wurde unterschieden zwischen den Zentralbäumen (ausgewählte Individuen zur Untersuchung der Gummiproduktion) und Konkurrenten (Nachbarbäume). In den drei Straten wurden insgesamt 482 Zentralbäume ausgewählt. Diese Bäume repräsentierten, auf Basis des Durchmessers in 0.25 m Höhe ($d_{0.25}$), ein weites Durchmesserspektrum, das in vier Durchmesserklassen unterteilt wurde (d=9-11.5, 13.5-16, 18-20.5 und über 21 cm). Zur Identifizierung der Konkurrenten wurde um

jeden Zentralbaum ein Kreis mit einem Radius aus „Höhe des Zentralbaumes x 1.25“ gelegt. Es wurden von jedem Zentralbaum und dessen Nachbarn BHD, Höhe, Kronenradius, Kronenansatzhöhe und die Stammfußkoordinaten gemessen. Die Zentralbäume wurden am 1. Oktober, am 15. Oktober und am 1. November mit lokal üblichen Geräten (Sonki und Makmak) geritzt. Zusätzlich wurden ungeritzte Bäume als Kontrolle ausgewählt. Die erste Exudaternte (Gummisammlung) war 15 Tage nach dem Ritzen (Anzapfen) beendet, und alle folgenden Ernten (sieben bis neun Nachsammlungen) wurden in Intervallen von jeweils 15 weiteren Tagen vorgenommen.

Es wurden sechs Funktionen zur Konstruktion von Bestandeshöhenkurven getestet. Dabei stellte sich heraus, dass die Michailow-Funktion am besten geeignet ist, um die Durchmesser-Höhenbeziehung von *Acacia seyal* im Umfakarin Naturwaldreservat zu beschreiben. Mit dieser Höhenfunktion konnten zwischen 19.3% bis 24% der Variation der Baumhöhen erklärt werden. Die Volumenfunktion, die in dieser Arbeit verwendet wurde, erklärt dagegen mehr als 92 % der Variation des Volumens stehender Bäume.

Die Konkurrenzverhältnisse in den Untersuchungsbeständen wurden mit Hilfe von Konkurrenzindizes beurteilt. Dazu wurden mit dem Programm CroCom acht Konkurrenzindizes berechnet und die Beziehungen zwischen diesen Indizes und den Baumdimensionen (BHD, Höhe und Kronendurchmesser) mit logarithmischen Ansätzen analysiert. Für die Schätzung des Konkurrenzdrucks in dichten Beständen von *Acacia seyal* erwies sich der Hegyi_2 Index mit dem BHD als unabhängiger Variable als gut geeignet, mehr als 70% der Variation der Zielgröße konnten erklärt werden.

Der gesamte Gummiertrag jedes Zentralbaums in einer Vegetationsperiode (Saison) wurde durch Addition der Exudatmengen aus der ersten Ernte und aller Nachsammlungen ermittelt. Damit konnte auch der Ertrag pro Flächeneinheit bestimmt werden. Zur statistischen Analyse der Messwerte wurden das Regressions-Baum-Verfahren, allgemeine lineare Modelle (GLM) und die logistische Regression herangezogen. Die Ergebnisse dieser Studie zeigen, dass die Gummiproduktion unabhängig von der Bestandesdichte ist. Andererseits hat die Anzapftechnik einen Einfluss auf die Gummiproduktion. Bäume in Beständen mittlerer Dichte, die am 1. Oktober mit dem Sonki geritzt wurden, erbrachten mit durchschnittlich 56 g pro Baum und Saison den höchsten Ertrag. Signifikante Ertragsunterschiede ($p = 0.021$) in Beständen mittlerer Dichte wurden auch zwischen den Anzapfterminen 1. Oktober und 1. November festgestellt. Die Ergebnisse zeigten außerdem, dass der BHD einen entscheidenden Einfluss auf die Gummiproduktion ausübt und hier dem Schwellenwert von 23.95 cm große Bedeutung zukommt.

In den drei Straten produzierten zwischen 41 bis 53 % der Zentralbäume weniger als 50 g Gummi pro Saison. Die Ergebnisse zeigen, dass Bäume der Art *Acacia seyal* Del. Varietät *seyal*. mit, je nach Stratum, 3.6 bis 4.8 kg pro Hektar und Saison nur geringe Mengen an Gum talha produzieren, weshalb ein Anzapfen der Bäume auf diesem Standort aus ökonomischen Gesichtspunkten nicht empfohlen wird.
Abschließend gelang die Formulierung eines Regressionsmodells, das zu einer ersten, orientierenden Schätzung des Ertrags von Gum talha im Umfakarin Naturwaldreservat in Südkordofan, Sudan, verwendet werden kann.

Zur Durchführung weiterer Untersuchungen bezüglich Gummiproduktion wird die Anlage von Dauerversuchsflächen in Regionen mir unterschiedlicher Klimaausprägung in Sudan dringend empfohlen.

REFERENCES

Abdelnour, H. O. (1999). Gum arabic in Sudan: production and socio-economic aspects. In FAO (Editor), Medicinal, culinary and aromatic plants in the Near East. Proceedings of the International Expert Meeting organized by the Forest Products Division FAO Forestry Department and the FAO Regional Office for the Near East 19-21 May 1997 Cairo, Egypt. Rome: FAO.

Abdelnour, H. O., and Osman, M. E. (1999). Management and organization of gum Arabic industry in Sudan. In Mugah, J. O. Chikamai, B. N. Mbiru, S. S. and Casad, E. (Editors), Conservation, management and utilization of plant gums, resins, and essential oils: Proceedings of a regional conference for Africa held in Nairobi, Kenya 6-10 October 1997. Forestry Department, FAO.

Ahmed, M. E. (2006). The socio-economic role of Acacia senegal in sustainable development of rural area in the gum belt of the Sudan. Tharandt, Germany: Institut für Internationale Forst- und Holzwirtschft, Technische Universität Dresden.

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transaction on Automatic Control AC , 19*, 716-723.

Alder, D. (1995). Growth modelling for mixed tropical forests. Forestry research Programme. Tropical Forestry Papers 30. Oxford Forestry Institute, Department of Plant Sciences, University of Oxford.

Ali, E. Y. (2006). Yield potential of *Acacia seyal* Del. variety *seyal* in relation to growth parameters, methods and position of tapping. Master Thesis. Faculty of Natural Resources and Environmental Studies, University of Kordofan.

Allaby, M. (2006). A dictionary of plant sciences. Revised edition. Oxford University Press.

Anderson, D. M., Bridgeman, M. M., and De Pinto, G. (1984). Acacia gum exudates from species of the series gummiferae. *Phytochemistry*, 575-577.

Arney, J. D. (1973). Tables for quantifying competitive stress on individual trees. Victoria, B.C: Pacific Forest Research Centre.

Aruan, A. L. (2004). The future of plantation forests and forest-based industry in Indonesia. In E. M. Donoghue, G. L. Benson, and J. L. Chamberlain (Editors), Sustainable production and of wood and non-wood forest products: proceedings of the IUFRO Division 5 Research Groups 5.11 and 5.12, March 11–15, 2003 (pp. 5-

13). Rotorua, New Zealand: General Technical Report PNW-GTR-604. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Badi, K. H., Ahmed, A. E., and Bayoumi, A. M. (1989). The forests of the Sudan. Khartoum, Sudan: Agricultural Research Council.

Ballal, M. E. (2002). Yield trends of gum Arabic from *Acacia senegal* as relation to some environmental and managerial factors. PhD Thesis. Faculty of Forestry, University of Khartoum.

Ballal, M. E., El Siddig, E. A., Elfadl, M. A., and Luukkanen, O. (2005a). Gum arabic yield in differently managed *Acacia senegal* stands in western Sudan. *Agroforestry Forum, 63*, 237–245.

Ballal, M. E., El Siddig, E. A., Elfadl, M. A., and Luukkanen, O. (2005b). Relationship between environmental factors, tapping dates, tapping intensity and gum arabic yield of an *Acacia senegal* plantation in western Sudan. *Journal of Arid Environments, 63*, 379–389.

Barbier, E. B., Markandya, A., and Pearce, D. W. (1990). Sustainable agricultural development and project appraisal. *European Review of Agricultural Economics, 17*, 181-196.

Begon, M., Townsend, C. R., and Harper, J. L. (2006). Ecology: from individuals to ecosystems. Oxford: Blackwell Publishing.

Bella, I. E. (1971). A new competition model for individual trees. *Forest Sci., 17*, 364-372.

Bellefontaine, R., Gaston, A., and Petrucci, Y. (2000). Management of natural forests of dry Tropical zones. FAO Conservation Guide 32. FAO, CIRAD, SLU and Sida.

Berg, L. (2008). Introductory botany: plants, people and the environment (2nd edition). Thomson Brooks/Cole.

Bi, H. (1994). Southeast re-growth forest growth and yield modelling: design, methods and preliminary results. Research Paper 24. State Forests of N.S.W.

Biging, G. S., and Dobbertin, M. (1992). A comparison of distance-dependent competition measures for height and basal area growth of individual conifer trees. *Forest Science, 38* (3), 695-720.

Bjarnadottir, B., Inghammar, A. C., Brinker, M., and Sigurdsson, B. D. (2007). Single tree biomass and volume functions for young Siberian larch trees (*Larix sibirica*) in eastern Iceland. *ICEL. AGRIC. SCI., 20*, 125-135.

Booth, F. E., and Wickens, G. E. (1988). Non-timber uses of selected arid zone trees and shrubs in Africa. FAO concservation guide 19. Rome: FAO.

Brown, C. (2000). The global outlook for future wood supply from forest plantations. Paper prepared for the 1999 Global Forest Products Outlook Study. GFPOS Working Paper No. 3. Rome: FAO.

Bukhari, Y. M. (1998). Tree-root influence on soil physical conditions, seedling establishment and natural thinning of *Acacia seyal* var. *seyal* on clays of Central Sudan. *Agroforestry Systems, 42*, 33–43.

Burnham, K. P., and Anderson, D. R. (2002). Model selection and multimodel inference: a practical information-theoretic approach (2nd edition). Springer-Verlag, New York.

Cappelli, C., and D’Elia, A. (2006). A tree-based method for selection of variables in models for ordinal data. *Quaderni di Statistica, 8*, 125-126.

Chikamai, B. (1999). Production, markets and quality control of gum Arabic in Africa: findings and recommendations from an FAO project. In J. O. Mugah, B. N. Chikamai, S. S. Mbiru, and E. Casad (Editors), Conservation, management and utilization of plant gums, resins and essential oils. Proceedings of a regional conference for Africa held in Nairobi, Kenya: 6-10 October 1997. Forestry Department, FAO.

Chikamai, B., Tchatat, M., Tieguhong, J. C., and Ndoye, O. (2009). Forest management for non-wood forest products and services in Sub-Saharan Africa. *Discovery and Innovation, 21 (SFM Special Edition No. 1)*, 50-59.

Crawley, M. J. (2007). The R book. West Sussex, England: John Wiley & Sons, Ltd.

Dawelbait, N., Yousif, S., Branthomme, A., Elmahi, A. G., Lungo, A. D., and Abdelnour, H. (2006). Global forest resources assessment 2005: estimating forest cover and forest cover change in Sudan. FRA Working Paper 109/E. Rome: FAO.

De Luis, M., Raventos, J., Cortina, J., Moro, M. J., and Bellot, J. (1998). Assessing components of a competition index to predict growth in an evenaged Pinus nigra stand. *New Forests, 15*, 223–242.

Dimov, L. D. (2004). Spatial analyses and growth of trees in selected bottomland hardwood stands. Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College.

Du, X., Guo, Q., Gao, X., and Ma, K. (2007). Seed rain, soil seed bank, seed loss and regeneration of Castanopsis fargesii (Fagaceae) in a subtropical evergreen broad-leaved forest. *Forest Ecology and Management, 238*, 212–219.

Egadu, S. P., Mucunguzi, P., and Obua, J. (2006). The population of acacia tree species producing gum arabic in the Karamoja region, Uganda. *African Journal of Ecology, 45*, 236–241.

El Amin, H. M. (1990). Trees and Shrubs of the Sudan. Ithaca Press.

El Dool, Y. M. (1988). Status report on existing reserved forests. Prepared for the World Bank/IDA Sudan Forestry Project. Khartoum: Forests Administration, Sudan.

El-Juhany, L. I. and Aref, I. M. (2001). Spacing effects on relative growth rates of diameter, height and biomass production in *Leucaena leucocephala* (Lam.) de Wit. before and after pruning. *JKAU: Met., Env. & and Arid Land Agric. Sci., 12*, 77-87.

Elmqvist, B., Olsson, L., Elamin, E. M., and Warren, A. (2005). A traditional agroforestry system under threat: an analysis of the gum arabic market and cultivation in the Sudan. *Agroforestry Systems, 64*, 211–218.

Elsiddig, E. A. (2003a). Aboveground wood weight and volume relationships for *Acacia seyal* in Eastern Sudan. *Sudan Silva, 9* (1), 25-39.

Elsiddig, E. A. (2003b). Development of volume and height-diameter equations for *Eucalyptus camaldulensis*, *Acacia nilotica* and *Acacia seyal* in the Sudan. *Sudan Silva, 9* (2), 1-13.

Fadl, K. M., and Gebauer, J. (2004). Effect of different tapping tools and different tapping positions on 'talh gum' yield of *Acacia seyal* var. *seyal* in South Kordofan, Sudan. Conference on International Agricultural Research for Development. Berlin, October 5-7, 2004. Deutscher Tropentag.

FAO (1978). Forestry for local community development. Forestry Paper 7. Rome: FAO.

FAO (1995). Gums, resins and latexes of plant origin. Non-wood forest products 6. Rome: FAO.

FAO (2001). FRA 2000 global ecological zoning for the global forest resources assessment 2000. Final report. FRA Working Paper 56. Rome: FAO.

FAO (2005). Nutrition country profile: Republic of the Sudan. FAO.

FAO (2006). Global Forest Resources Assessment 2005. Progress towards sustainable forest management. FAO Forestry Paper 147. Rome: FAO.

FAO (2010). Global forest resources assessment 2010: Country report Sudan. Rome: FAO.

Faraway, J. J. (2006). Extending the Linear Model with R: generalized linea, mixed effects and nonparametric regression models. Boca Raton London New York: Chapman & Hall/CRC Taylor & Francis Group.

Forests National Corporation, FNC. (2007). A brief account on the forests of the Sudan. Retrieved July 15, 2010, from http://www.fnc.gov.sd/Preif_account.htm

Gadow, K. v., and Hui, G. (1999). Modelling forest development (Vol. 57). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Glantz, A. S. (2005). Primer of biostatistics (6th edition). Mcgraw-Hill Professional.

Gorashi, A. R. (2001). State of forest genetic resources in Sudan. The sub-regional workshop FAO/IPGRI/ICRAF on the conservation, management, sustainable utilization and enhancement of forest genetic resources in Sahelian and North-Sudanian Africa. Working papers FGR/20E. FAO, IPGRI/SAFORGEN, DFSC and ICRAF.

Grote, R. (2003). Estimation of crown radii and crown projection area from stem size and tree position. *Ann. For. Sci., 60*, 393–402.

Gum Arabic Company, GAC. (2008). Annual reports 1970-2008. Khartoum, Sudan: Gum Arabic Company Ltd, GAC.

Hall, J. B., and McAllan, A. (1993). *Acacia seyal:* a monograph. Bangor, UK: School of Agricultural and Forest Sciences, Univesrity of Wales.

Harrison, M. N., and Jackson, J. K. (1958). Ecological classification of the vegetation of the Sudan. Forest Bulletin No. 2. Khartoum, Sudan: Forest Department.

Hasenauer, H. (2006). Concepts within tree growth modelling. In H. Hasenauer, Sustainable forest management: growth models for Europe (pp. 3-17). Berling Heidelberg: Springer.

Hegyi, F. (1974). A simulation model for managing jack-pine stands. In J. Fries (Editor), Growth models for tree and stand simulation (pp. 74–90). Stockholm, Sweden: Royal College of Forestry.

Hineit, B. M. (2007). Effect of type, time of tapping and tree size of *Acacia seyal* var. *seyal* on the production of gum *talha* in Rawashda forest, Gedarif State, Sudan. Master Thesis. Faculty of Forestry, University of Khartoum.

Hosmer, D. W., and Lemeshow, S. (2000). Applied logistic regression (2nd edition). John Wiley & Sons, Inc.

Husch, B. (1963). Forest mensuration and statistics. New York: The Ronald Press Company.

Husch, B., Miller, I. C., and Beers, T. W. (1993). Forest mensuration (3rd edition). Krieger Publishing Company, Malabar, FL.

Husch, B., Miller, I. C., and Beers, T. W. (2003). Forest mensuration (4th edition). Hoboken, New Jersey: John Wiley & Sons, Inc.

Hussein, K. A. (2001). Parameter/parsimonious models fro crown and stem profiles. PhD thesis. Faculty of Forest Sciences and Forest Ecology, Geog-August-University Göttingen.

International Institute for Environment and Development and Institute of Environmental Studies, IIED and IES. (1990). Gum arabic belt rehabilitation in the Republic of the Sudan. Stage 1 report volume 2: main report and recommendations for action for the project preparation unit of the Ministry of Finance and Economic Planning (Planning) The Republic of the Sudan. International Institute for Environment and Development (IIED), England, London and Institute of Environmental Studies, University of Khartoum, Sudan.

Iqbal, M. (1993). International trade in non-wood forest products: an overview. FO: Misc/93/11 Working Paper. Rome: FAO.

Joint FAO/WHO Expert Committee on Food Additives, JECFA. (1997). Compendium of food additive specifications. Addendum 5. (FAO Food and Nutrition Paper - 52 Add. 5). Rome: FAO.

Kimmins, J. P. (2004). Forest Ecology: a foundation for sustainable forest management and environmental ethics in forestry (3rd edition) Prentice Hall.

Krajicek, J. E., Brinkman, K. A., and Gingrich, S. F. (1961). Crown competition: a measure of density. *Forest Science, 7*, 35-42.

Kramer, H., und Akça, A. (2008). Leitfaden zur waldmesslehre (5. überarbeitete Ausg.). Frankfurt am Main: J.D. Sauerländer´s Verlag.

Lemenih, M., Abebe, T., and Olsson, M. (2003). Gum and resin resources from some Acacia, Boswellia and Commiphora species and their economic contributions in Liban, south-east Ethiopia. *Journal of Arid Environments, 55*, 465–482.

Lorimer, C. G. (1983). Tests of age-independent competition indices for individual trees in natural hardwood stands. *Forest Ecology and Management, 6*, 343-360.

Macrae, J., and Merlin, G. (2002). The prospects and constraints of development of gum arabic in Sub-Saharan Africa. Washington, D.C.: World Bank.

McAllan, A. (1993). *Acacia seyal:* a handbook for extension workers. Bangor, UK: School of Agricultural and Forest Sciences, University of Wales.

Mohamed, A. G. (2005). Improvement of traditional *Acacia senegal* agroforestry: ecophysiological characteristics as indicators for tree-crop interaction on sandy soil in western Sudan. Faculty of Agriculture and Forestry, University of Helsinki.

Mohamed, M. S. (2006). Mapping and assessment of land use/land cover using remote sensing and GIS in North Kordofan State, Sudan. PhD Dissertation. Fakultät Forest-, Geo- und Hydrowissenschaften, Technische Universität Dresden.

Münder, K. (2005). Konkurrenzuntersuchungen und Wachstumsmodellierung in Waldumbaubeständen des Mittleren Erzgebirges. PhD Dissertation. Fakultät Forst-, Geo- und Hydrowissenschaften der Technischen Universität Dresden.

Münder, K., Schildbach, M., und Schröder, J. (2008). CroCom Version 3.0 (unveröffentlicht). Institut für Waldwachstum und Forstliche Informatil, TU-Dresden.

Münder, K., und Schröder, J. (2001). Modellierung von Konkurrenz und Zuwachs in Kiefern-Buchen-Umbaubeständen im nordwestsächsischen Tiefland. Vortrag zu den Tharandter Hochschultagen 2001. TU Dresden, Fachrichtung Forstwissenschaften.

Mustafa, A. F. (1997). Regeneration of Acacia seyal forests on the dryland of the Sudan caly plain. Tropical Forestry Report No. 15. Department of Forest Ecology, Helsinki University Printing House.

Myers, G. P., Newton, A. C., and Melgarejo, O. (2000). The influence of canopy gap size on natural regeneration of Brazil nut (Bertholletia excelsa) in Bolivia. *Forest Ecology and Management, 127*, 119-128.

Nagel, J. (1999). Konzeptionelle Ünerlegungen zum schrittweisen Aufbau eines waldwachstumskundlichen Simulationssystems für Nordwestdeutschland. Schriften aus der Forstlichen Fakultät der Universtität Göttingen und der Niedersächsichen Forstlicehn Versuchsanstalt. Frankfurt am Main: J.D. Sauerländer´s.

National Academy of Sciences, NAS. (1979). Tropical legumes: resources for the future. Washington, D.C: NAS.

National Academy of Sciences, NAS (1980). Shrubd and tree species for energy production. Washington, D.C., USA: National Academy of Sciences.

Nitrogen Fixing Tree Association, NFTA (1994). *Acacia seyal* - multipurpose tree of the Sahara desert. NFTA 94-07. Waimanalo: Nitrogen Fixing Tree Association.

Orchard, A E; WilsonX, A J G (editors). (2001). Flora of Australia Volume 11A, Mimosaceae, Acacia part 1. Melbourne: ABRS/CSIRO Publishing.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., and Simons, A. (2009). Agroforestree Database: a tree reference and selection guide. Retrieved June 11, 2010, from http://www.worldagroforestry.org/

Philip, M. S. (1994). Measuring trees and forests (2nd Edition). CABI Publishing.

Pretzsch, H. (1995). Zum Einfluß des Baumverteilungsmusters auf den Bestandeszuwachs. *Allgemeinen Forst- und Jagdzeitung, 166* (9-10), 190-201.

Pretzsch, H. (2009). Forest dynamics, growth and yield from measuremnt to model. Springer.

R Development Core Team (2008). R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. URL: http://www.R-project.org.

Rahim, A. H. (2006). Economic analysis of deforestation: the case of the gum Arabic belt in Sudan. PhD-thesis . Wageningen University.

Rivas, J. J. C., Alvarez, J. G., Aguirre, G. O. Hernandez, F. J. (2005). The effect of competition on individual tree basal area growth in mature stands of *Pinus cooperi* Blanco in Durango (Mexico). *Eur J Forest Res*. 124: 133–142.

Röhle, H. (1986). Vergleichende Untersuchungen zur Ermittlung der Genauigkeit bei der Ablotung von Kronenradien mit dem Dachlot und durch senkrechtes Anvisieren des Kronenrandes. *Forstarchiv, 57*, 67–71.

Röhle, H., Gerold, D., Münder, K., und Schröder, J. (2003). Jahrestagung der Sektion Ertragskunde 2003 in Torgau- Exkursion in das Sächsische Forstamt Falkenberg. Konkurrenz und Wachstum in der voranbauschicht (Poster). Tharandt: Institut für Waldwachstum und Forstliche Informatik, TU-Dresden.

Sachs, L., und Hedderich, J. (2006). Angewandte Statistik: Methodensammlung mit R. Berlin Heidelberg: Springer-Verlag.

Sahni, K. C. (1968). Important trees of northern *Sudan.* Khartoum: UNDP/FAO.

Salih, S. A. (1994). Sustainable ecosystem in Africa: managing natural forest in Sudan. Working paper No. 117. World Institute for Development Economics Research WIDER, The United Nations University.

Schröder, J. (2003). Zur modellierung von wachstum und konkurrenz in Kiefern/Buchen-Waldumbaubeständen Nordwestsachsens. PhD Dissertation. Fakultät Forst-, Geo- und Hydrowissenschaften der Technischen Universtät Dresden.

Schröder, J., Röhle, H., Gerold, D., and Münder, K. (2007). Modeling individual-tree growth in stands under forest conversion in East Germany. *Eur J Forest Res, 126*, 459–472.

Schultz, J. (1995). The ecozones of the world: the ecological divisions of the geosphere. Berlin: Springer-Verlag.

Schultz, J. (2005). The ecozones of the world: the ecological divisions of the geosphere (2nd edition). Berlin, Heidelberg: Springer.

Schütz, J.-P. (2001). Der Plenterwald: Und weitere Formen strukturierter und gemischter Wälder. Berlin: Verlag Parey.

Schütz, J.-P., und Röhnisch, F. (2003). Steuerung des Nachwuchses während der Überführung von gleichförmigen Fichten-Aufforstungsbeständen in Plenterwälder. In G. Kenk (editor), *Sektion Ertagskunde: Beiträge zur Jahrestagung 2003* (pp. 184-194). Torgau: Deutscher Verband Forstlicher Forschungsanstalten.

Schwinning, S., and Weiner, J. (1998). Mechanisms determining the degree of size asymmetry in competition among plants. *Oecologia, 113*, 447-455.

Seif el Din, A. G., and Zarroug, M. (1998). Production and commercialization of gum arabic in Sudan. In FAO (editor), International conference on domestication and commercialization of non-timber forest products in agroforestry systems. Non-Wood Forest Products 9. Held on 19-23 February 1996: Nairobi, Kenya. Rome: FAO.

Shimano, K. (1997). Analysis of the relationship between DBH and crown projection area using a new model. *J. For. Res., 2*, 237-242.

Smith, T. M., and Goodman, P. S. (1986). The effect of competition on the structure and dynamics of Acacia savannas in Southern Africa. *Journal of Ecology, 74*, 1031-1044.

SPSS Statistics 17.0. Release 17.0.0 . (Aug 23, 2008).

Sulieman, H. M. (2008). Mapping and modelling of vegetation changes in the Southern Gadarif Region, Sudan, using remote sensing: land-use impacts on biophysical processes. Dresden: TUD press, Verlag der Wissenschaften GmbH.

Tadesse, W., Desalegn, G., and Alia, R. (2007). Natural gum and resin bearing species of Ethiopia and their potential applications. *Investigación Agraria: Sistemas y Recursos Forestales, 16* (3), 211-221.

Unanaonwi, O. E. (2009). Estimation of gum Arabic yield and total production in Zamfara State, Nigeria. *PAT, 5* (2), 335-344.

Vanclay, J. K. (1994). Modelling forest growth and yield: application to mixed tropical forests. Wallingford, UK: CABI International.

Van Laar, A. and Akça, A. (2007). Forest mensuration: managing forest ecosystems. Dordrecht, The Netherlands: Springer.

Venables, W N; Smith, D M; The R Developmen Core Team (2009). An Introduction to R. Notes on R: a programming environment for data analysis and graphics. Version 2.9.0 available at: http://www.r-project.org/.

Vink, A T. (1990a). Growth of *Acacia seyal* analysis of 1987-1990 measurements in Rawashda forest. Field Document No. 38. Fuelwood Development for Energy in Sudan, GCP/SUD/033/NET. Government of the Republic of Sudan/ Netherlands Government/FAO.

Vink, A. T. (1990b). Growth of *Acacia seyal* analysis of 1963-1972 measurements in Garri forest, Blue Nile Province. Field Document No. 39. Fuelwood Development for Energy in Sudan, GCP/SUD/033/NET. Government of the Republic of Sudan/Netherlands Government/FAO.

Vogt, K. (1995). Common trees and shrubs of dryland Sudan. SOS Sahel International. UK.

von Maydell, H. (1990). Trees and shrubs of the Sahel, their characteristics and uses. Weikersheim, Germany: GTZ. Verlag Josef Margraf Scientific Books.

Wenger, K. F. (1984). Forestry handbook (2nd edition). John Wiley & Sons, Inc.

West, P. W. (2004). Tree and forest measurement. Springer-Verlag Berlin Heidelberg New York.

Wichmann, L. (2002). Modelling the effects of competition between individual trees in forest stands. PhD thesis. Copenhagen, Denmark: Unit of Forestry, Department of Economics and Natural Resources, The Royal Veterinary and Agricultural University.

Wickens, G. E., Seif El Din, A. G., and Nahal, I. (1995). Role of acacia species in the rural economy of dry Africa and the Near East. FAO Conservation Guide 27. Rome: FAO.

Wimberly, M. C. and Bare, B. B. (1996). Distance-dependent and distance-independent models of Douglas-fir and western hemlock basal area growth following silvicultural treatment. *Forest Ecology and Management*, 89, pp 1- 11.

World Bank (1986). Sudan: forestry sector review. Report No. 5911-SU. World Bank, Washington, D.C.. In Mustafa, A.F (1997) regneration of Acacia seyal forestson the dryland of the Sudan clay plain. Doctoral thesis. Tropical Forestry Reports 15. University of Kelsinki.

Wykoff, W. R., Crookston, N. L., and Stage, A. L. (1982). User's guide to the stand prognosis model. General Technical Report INT-122. Ogden: United States Department of Agriculture, Forest Service.

Yuancai, L. and Parresol, B. R. (2001). Remarks on height-hiameter modeling. Southern Research Station, Research Note SRS-IO. United States Department of Agriculture, Forest Service.

Zar, J. H. (1999). Biostatistical analysis (4th edition). New Jersey: Prentice Hall Upper Saddle River.

Zar, J. H. (2009). Biostatistical analysis (5th edition). Pearson Education International.

Zucchini, W., Schmidt, M., and Gadow, K. v. (2001). A model for the diameter-height distribution in an uneven-aged Beech forest and a method to assess the fit of such models. *Silva Fennica*, 35 (2), pp 169–183.

APPENDICES

Appendix 1 Tree measurement and mapping form

Stratum No. …………………………………… ……. Plot No. …………………
Plot radius (in m, r = height of target tree*1.25)……. Date: …………………….

Tree No.	Species	$D_{0.25}$ (cm)	$D_{0.50}$ (cm)	DBH (cm)	CB (m)	Ht (m)	Coordinates		Crown radii (in, m)				Remarks
							Dist.(m)	α	N	E	S	W	
Target	x						0.0	0.0					
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
11													
12													

$D_{0.25}$ and $D_{0.50}$ are diameters (in, cm) at 0.25 and 0.50 m height, respectively; DBH is the diameter at breast height (in, cm); CB is the height to the crown base (in, m); ht is tree height (in, m); Dist. (distance, in m) and α (angle) are polar coordinates of the competitors (the serial numbers) to the target tree; and N, E, S and W are directions, i.e. North, East, South and West respectively.

Natural regeneration form:

Species	Number	
	< 1.3 m height	> 1.3 m height

Other remarks ....

Appendix 2 Gum tapping and collection form

Stratum No. ……. ………………………… Plot No. ………………
Tapping date: □ 1st October □ 15th October □ 1st November

Target tree	Tapping tool	DBH (cm)	Height (m)	Crown base	Crown radii (m)				Gum quantity (g) per collection						
					N	E	S	W	1st	2nd	3rd	4th	5th	6th	7th
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
13															
14															
15															
16															
17															
18															
19															
20															
21															
22															
23															
24															
25															
26															
27															
28															
29															

Remarks:
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………

Appendix 3 Normality test of *A. seyal* tree dimensions

Stratum	Index	Mean	Median	SD	Min.	Max.	Skewness	Shapiro-Wilk	
								Statistic	P-value
Dense	DBH	12.2	12.9	3.8	5.1	36.9	1.12	0.945	0.000
	Height	7.2	7.0	1.2	4.5	11.5	0.22	0.988	0.000
Medium	DBH	13.4	13.8	4.5	5.8	34.1	0.71	0.967	0.000
	Height	7.6	7.5	1.3	4.0	12.0	0.09	0.989	0.000
Slight	DBH	12.2	12.9	4.0	5.1	33.9	0.87	0.958	0.000
	Height	6.7	6.7	1.3	2.3	10.0	-0.02	0.989	0.000

Number of observations per stratum (dense = 1781; medium = 1235; slight = 783); SD = standard deviation

Appendix 4 Results of regression tree analysis for predicting gum talha yield

Node number	Variable	Split criterion	N	Deviance	Gum yield (g)
1	Root node		482	751000	15.35
2	DBH	< 23.95 cm	469	574200	13.53
4*	Tool	Untapped	105	29090	5.87
5	Tool	Makmak, sonki	364	537200	15.74
10*	Date	15th Oct, 1st Nov	250	295800	12.61
11	Date	1st Oct	114	233600	22.59
22*	CI	< 3.915	109	158400	20.80
23*	CI	> 3.915	5	67210	61.69
3	DBH	> 23.95 cm	13	119000	81.10
6*	CI	< 0.125	5	1330	11.40
7*	CI	> 0.125	8	78200	124.70

*. Denotes for terminal node; N = number of observations per split; nodes´ number are ordered according to the regression tree model; CI = Hegyi_2 competition index

Appendix 5 Scheffe test (Post-hoc-test) after ANOVA for gum *talha* yield derived from natural *A. seyal* using different tapping tools in the Umfakarin Forest, South Kordofan, Sudan

Stratum	Tool (I)	Tool (J)	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Dense	Makmak	Sonky	9.480	6.238	0.318	-5.943	24.903
		Untapped	12.798	6.337	0.134	-2.870	28.466
	Sonky	Untapped	3.318	6.476	0.877	-12.694	19.330
Medium	Makmak	Sonky	-10.100	5.613	0.201	-23.975	3.775
		Untapped	5.758	7.940	0.769	-13.871	25.386
	Sonky	Untapped	15.858	8.139	0.153	-4.262	35.977
Slight	Makmak	Sonky	.023	8.615	1.000	-21.270	21.316
		Untapped	18.939	9.870	0.162	-5.455	43.333
	Untapped	Sonky	-18.916	10.329	0.190	-44.445	6.613

Results are based on observed means.
The error term is Mean Square (Error) = 2337.915

Appendix 6 GLM results: tests of between-subjects effects

Stratum	Source	SS	DF	MS	F-value	Sig.	η^2
	Corrected Model	11680.673	10	1168.067	1.107	0.361	0.070
	Intercept	470.807	1	470.807	0.446	0.505	0.003
	BHD	2322.279	1	2322.279	2.201	0.140	0.015
	CI	715.687	1	715.687	0.678	0.412	0.005
Dense	Tool	4413.710	2	2206.855	2.091	0.127	0.028
	Date	1782.141	2	891.071	0.844	0.432	0.011
	Tool*Date	2898.767	4	724.692	0.687	0.602	0.018
	Error	155132.502	147	1055.323			
	Total	189780.795	158				
	Corrected Total	166813.175	157				
	Corrected Model	60091.638	9	6676.849	7.293	0.000	0.304
	Intercept	8558.918	1	8558.918	9.349	0.003	0.059
	BHD	21085.447	1	21085.447	23.032	0.000	0.133
	CI	2618.599	1	2618.599	2.860	0.093	0.019
Medium	Tool	7383.671	2	3691.836	4.033	0.020	0.051
	Date	22363.719	2	11181.859	12.214	0.000	0.140
	Tool*Date	19305.564	3	6435.188	7.029	0.000	0.123
	Error	137325.695	150	915.505			
	Total	225481.077	160				
	Corrected Total	197417.333	159				
	Corrected Model	33695.824	10	3369.582	1.489	0.148	0.089
	Intercept	5975.268	1	5975.268	2.641	0.106	0.017
	BHD	14864.197	1	14864.197	6.570	0.011	0.041
	CI	10492.793	1	10492.793	4.638	0.033	0.029
Slight	Tool	12009.690	2	6004.845	2.654	0.074	0.034
	Date	5093.358	2	2546.679	1.126	0.327	0.015
	Tool*Date	3166.788	4	791.697	0.350	0.844	0.009
	Error	346145.902	153	2262.392			
	Total	449283.545	164				
	Corrected Total	379841.726	163				

Dependent variable: gum *talha* yield (g)
Dense: R^2 = 0.070 (Adjusted R Squared = 0.007)
Medium: R^2 = 0.304 (Adjusted R Squared = 0.263)
Slight: R^2 = 0.089 (Adjusted R Squared = 0.029)
CI = Hegyi_2 competition index; η^2 = Partial Eta squared; SS = sum of squares; MS = mean square; DF = degrees of freedom.