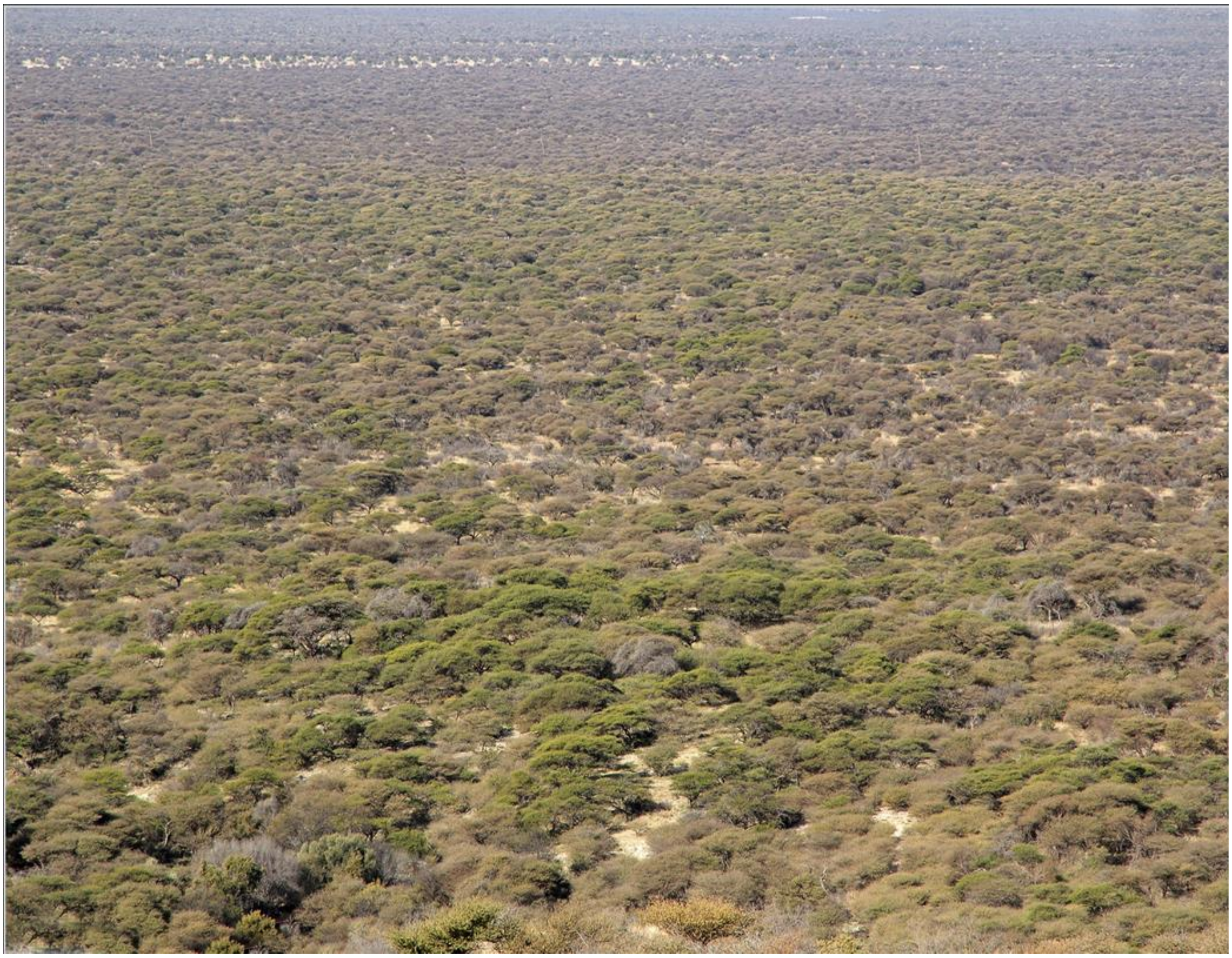
Support to
De-bushing
Project

Detailed Assessment of the Biomass Resource and Potential Yield in a Selected Bush Encroached Area of Namibia



Implemented by
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Detailed Assessment of the Biomass Resource and Potential Yield in a Selected Bush encroached area of Namibia

Imprint

Commissioned by

Support to De-bushing Project
Ministry of Agriculture, Water and Forestry/Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Windhoek, Namibia

Author

Prof. G.N. Smit[1], J.N. de Klerk[2], M.B. Schneider[3] & J. van Eck[4]

[1]Dept. of Animal, Wildlife and Grassland Sciences, University of the Free State, South Africa, E-mail: smitgn@ufs.ac.za
[2]P.O. Box 5846, Ausspannplatz, Windhoek, Namibia, E-mail: 264813647999@mtcmobile.com.na
[3]DRFN-Desert Research Foundation of Namiba,Windhoek, Namibia, E-mail: martin.schneider@drfn.org.na
[4]P.O. Box 5846, Windhoek, Namibia

Design & Layout

Martin Markstein, www.dermarkstein.de

Photo credits

© Prof G.N. Smit, University of the Free State

Printed by

John Meinert Printing

Published

August 2015

TABLE OF CONTENTS

List of Figures

List of Tables

EXECUTIVE SUMMARY

In southern Africa the phenomenon of the increase in woody plant abundance is commonly referred to as "bush encroachment", though the term "bush thickening" is more appropriate. It can be defined as the excessive increase in the density and cover of one or more indigenous woody species that exploit disruptions of the grass/bush balance at the expense of grasses. It has long been considered an ecological and economic problem in the rangelands of Namibia and the area affected by bush thickening in Namibia is estimated to be approximately 260 000 km^2. Enormous amounts of money and effort have already been put into treating the existing symptoms, but many attempts at combating the problem have in effect aggravated the problem. Due to the cost of bush control measures there is an increasing awareness of woody plants as a harvestable resource with a monetary value - such as the possible utilization of woody biomass as a source of energy.

The assignment has two main objectives: (i) to establish a tested and accepted methodology of local biomass resource assessment, and (ii) to prepare and implement a local biomass resource assessment in a selected area of Namibia.

Techniques employed in Namibia to quantify woody plants include simple density data (plants/ha), as well as canopy cover measurements. In the instances where actual biomass figures of woody plants were published, the data were obviously accurate, but the methodology extremely time consuming and labour intensive. What is needed is an accurate and non-destructive technique that can provide estimates of woody biomass prior to any harvesting to enable viability studies and planning. Based on the literature the most appropriate approach will be the use of biomass allometric equations.

Such a non-destructive technique based on biomass allometric equations was used in this study. A quantitative description of woody plant communities that aimed at aiding studies on grass–tree competition interactions, bush thickening and estimation of food to browser herbivore species, was proposed during 1989. It evolved as the BECVOL-model and this model initially provided estimates of leaf volume and leaf dry mass only. The need for accurate estimations of the wood component was addressed in the development of the BECVOL 3-model. Complete trees of a number of savanna tree species were harvested and separated into specific biomass fractions, dried and weighed: leaves, shoots and stems in three diameter classes (>0.5 cm, >0.5–2.0 cm and >2.0 cm). Regression analyses were applied and highly significant regressions ($P<0.001$) were achieved with the curvilinear regression models (exponential and multiplicative) that yielded the highest correlation coefficients. With the incorporation of these regression equations into the BECVOL 3-model, it is now possible to make accurate estimations of the wood component of trees and shrubs from specific measurements of the plants in a transect.

The study area is located north-west of Otjiwarongo. The focus was primarily on privately owned commercial farms in close proximity of Nampower's Gerus substation, but a few sites on the Omatjenne Research Station, as well as a site on municipal land were included. Eight commercial farms were included and all of them are primarily used for extensive cattle farming, with only a limited number of small stock (sheep and goats) present on some of the farms. The long-term annual rainfall of the area is approximately 457 mm.

During the field visit to the study area the general poor condition of the rangelands of which bush thickening played a major role was very obvious. In general the farmers were well informed and aware of the potential pitfalls and requirements of maintaining an open savanna, but more often than not they simply don't have the resources to apply the required measures. The research team also noted less effective measures that may not have been the most appropriate under the circumstances. Presently charcoal production and the production of firewood are the main source of income from excessive woody

biomass on agricultural land in Namibia. Since only wood thicker than 2.0 cm is suitable for this purpose, the selective harvesting of the larger trees has resulted in the invasion of these areas with low biomass species such as *Grewia flava* and *G. flavescens* that form very dense, almost impenetrable, bush clumps with no benefit in terms of increased grass production. An aftercare programme is absolutely essential to keep a thinned/harvested area open, but due to the cost this is not always done.

Limitations of access played a significant role in the number of surveys plots that could be surveyed in a day and a total of 28 plots were selected and surveyed. Google earth imagery and a recent 1 : 250 000 topo-cadastral was consulted, while the research team relied on the extensive local knowledge of the various farm owners to select representative surveys plots. Past management histories as conveyed by the farm owners were also taken into consideration.

A total of 30 woody species (trees and shrubs) were recorded in the survey of the woody plants in the 28 survey plots. These woody species were divided into three groups: (i) scarce and/or desirable species not to be targeted for removal/harvesting; (ii) potential problematic species that may thicken under specific conditions, but with a low biomass potential; and (iii) potential problematic species that may thicken under specific conditions and which have a high biomass potential.

At each identified survey site a standard belt transect of 50 x 2.5 m (125 m^2) was laid out in such a way as to best represent the woody vegetation of that site. In cases where the woody plants were patchy or the area not very homogeneous, the length of the transect was increased to either 75 m (188 m^2) or 100 m (250 m^2) to obtain a more accurate sampling of the vegetation. GPS coordinates were taken at the location of each transect and several photos taken of the vegetation of the site. The dimensions of all rooted, live woody plants >0.5 m in height were measured in the various belt transects according to the BECVOL 3-model. Values calculated with the BECVOL 3-model included: Tree density (plants/ha), Evapotranspiration Tree Equivalents (1 ETTE defined as the leaf volume equivalent of a 1.5 m single-stemmed tree), leaf biomass (kg DM/ha), shoot dry mass - shoots <0.5 cm (kg DM/ha), stem dry mass - stems >0.5-2.0 cm in diameter (kg DM/ha), wood dry mass - wood >2.0 cm in diameter, total wood dry mass (all fractions) (kg DM/ha), and total tree biomass - leaves and wood combined (kg DM/ha).

In order to assess the severity of the bush thickening on any particular site, the calculated tree densities (plants/ha) and ETTE/ha of the survey plots were used as the main criteria. As a general rule of thumb the median number of ETTE/ha that can be supported in a specific rainfall region without adversely affecting the grass layer, should not exceed 10x the mean annual rainfall. Based on a mean annual rainfall of 457 mm for the study area, this implies a target figure of approximately 4 500 ETTE/ha.

The total wood dry mass (all fractions) of the 28 plots varied from a low 7 291 kg/ha to a high of 190 942 kg/ha with an average of 36 222 kg/ha. On average the wood >2.0 cm in diameter made up 70.1 % of the total wood mass, while the stems >0.5-2.0 cm and shoots <0.5 cm made up 20.8 and 9.1 % of the total wood mass respectively. Should the trees be harvested during the summer months when the trees have their full leaf carriage, the leaves on average would add another 6.8 % to the total tree dry mass.

A high wood mass per hectare was without exception related to the presence of very large trees and the wood mass per hectare increased exponentially with an increase in the number of very large trees, while plots of predominantly small to medium sized trees - even at very high densities - yielded a much lower wood mass. It was found that the woody biomass is extremely variable from area to area. The reason for this is partially due to environmental differences (soil type and depth, topography and drainage lines), but also due to past management activities such as mechanical and chemical bush control measures and wood harvesting for charcoal. This resulted in a mosaic pattern of high variability that complicated the extrapolation of the biomass estimations to larger areas. Despite the limitation it was estimated that based on the average of 36 222 kg/ha the study area of 45 000 ha carries a wood biomass of 1 629 990 metric tons (1.63 mil. metric tons).

Three possible harvesting scenarios are presented: (i) Total biomass harvest. This is more of a theoretical option than something that should be considered, (ii) Selective harvesting with a conservative target - retaining 4 500 ETTE/ha, and (iii) Selective harvesting with an optimistic target - retaining 2 700 ETTE/ha that allows for the increased growth of the remaining trees. Based on the conservative approach (target of 4 500 ETTE/ha), an average of 10 811 kg/ha wood can be harvested in the study area, which represents approximately 30 % of the total wood biomass. Reducing the target to 2 700 ETTE/ha will increase the wood harvest with an additional 1 841 kg/ha to 12 653 kg/ha, which represents approximately 35 % of the total wood. Based on information obtained it would appear that even the conservative wood harvesting intensity (4 500 ETTE/ha remaining) will still meet the minimum requirement of 10 000 kg/ha for the viability of an electricity plant.

It is recommended that trees be selectively harvested, starting with the smallest plants and progressively moving to larger plants until the target of retaining 4 500 ETTE/ha or 2 700 ETTE/ha has been reached. Harvesting should concentrate on the potential problem species. If for example only trees larger than 5 m are retained at a target value of 2 700 ETTE/ha, an average of 90 trees/ha will remain since 1 tree >5 m equals approximately 30 ETTE. The final issue that needs to be addressed, is whether the harvested plants be treated or allowed to regrow for purposes of producing another biomass harvest after a number of years. It is suggested that the final decision on this aspect be left to the individual farmer, based on a number of considerations that are discussed in the report.
A total of 15 key stakeholders that included full-time commercial farmers and representatives of the Charcoal Producers Society, Agriculture Employers Association, Namibia National Farmers Union (NNFU), Ohorongo Cement Factory, Directorate Forestry (MAWF) and other role players were interviewed. A summary of their perception on the problem of bush thickening in Namibia, possible solutions and the willingness to participate in wood harvesting for electricity generation is presented in the report.

In terms of the impact of bush thickening, farmers admitted that they have reached an irreversible situation where even the best rangeland management practices will not result in the restoration of the rangeland. Financially, farmers are not in a position to spend more money on efforts to counter the adverse impact of bush thickening. The only solution would be to pursue a win-win strategy where the farmers and the environment will benefit by viable long-term solutions. In general, the news of the envisaged power station that utilizes the biomass of locally harvested woody plants, was favourably received and for many it presented new hope for overcoming the devastating effect of bush thickening. The Namibia National Farmers Union as well as the Namibia Agricultural Union is in strong support of this project, provided that it is done in an environmentally responsible way.

Most of the farmers applied at some stage one or more methods being recommended for combating bush thickening. These included the use of a variety of arboricides (aerial spraying, foliar, stem absorbent and soil applied arboricides). Initial success in terms of increased grass production following the mortality of the woody plants was reported by these farmers, but because of the removal of competition, new seedlings established themselves, while undesired smaller bushes filled the created vacuums. Because labour intensive methods like felling and stumping are believed to be too time consuming and too expensive, they are not considered viable options. In addition, the farmers haven't experienced positive results with mechanical removal (bulldozing, bush rollers) either, since re-infestation was more severe and the areas were in a worse condition than before within only a few years after treatment.

According to the experience of farmers, it will take in the order of 10 to15 years for re-growth to produce the same amount of biomass as before harvesting. Almost all the farmers indicated that they would like to be compensated for the removal of biomass. Currently Namibia is facing serious challenges in terms of future electricity supply. All people interviewed are confident that there is more than enough biomass in the country for running several biomass power stations of 20 MW on a sustainable basis.

Based on the average measured wood biomass available on the commercial farms, the planned harvesting of biomass of indigenous woody plants for electricity generation that requires a minimum of 10 000 kg harvestable wood DM/ha appears to be ecologically viable. Based on the assumption that a 20 MW biomass power plant requires 150 000 tons biomass per annum and that such a power plant will have a life span of at least 15 years, it will require 2 250 000 tons biomass over this time period. Using the two proposed harvesting scenarios (leaving 4 500 ETTE/ha and 2 700 ETTE/ha, respectively) will require a total area of approximately 178 000 ha (leaving 2 700 ETTE/ha) to approximately 208 000 ha (leaving 4 500 ETTE/ha) to supply the required biomass to the power plant over this time period. This represents an area 3.9 to 4.6 times that of the study area (45 000 ha). This calculation, however, does not include the biomass of possible follow-up harvests of areas that were previously harvested and where the trees were allowed to regrow. The assumption by some farmers that the trees will regrow to their original biomass prior to the harvesting in 10 to 15 years may be over optimistic. There is a general lack of scientific information on regrowth rates of woody plants, but based on what is currently known it is unlikely that harvested plots will regrowth to their original biomass in this time period, unless the harvested areas are specifically managed to encourage regrowth of woody species from group 3 (high biomass species), rather that group 2 (low biomass species).

Based on the massive amount of biomass that is required for a 20 MW biomass power plant, it is clear to see that the incentive to harvest more trees than is ecologically desirable, is a definitive reality. For this reason, clear priorities need to be identified prior to the harvesting operation and realistic targets set. Responsibility and accountability are essential to avoid exploitation of natural resources for short-term financial gain at the cost of long-term sustainability. It should also be realized that the harvesting cannot be considered a once-off operation. A continual aftercare program will need to be implemented following the harvesting, regardless of whether the stumps of the harvested plants are treated with an arboricide or allowed to regrow for purposes of producing another biomass harvest after a number of years.

1. INTRODUCTION

1.1 Problem statement

In southern Africa the phenomenon of the increase in woody plant abundance is commonly referred to as "bush encroachment" (O'Connor & Crow 1999), though the term "bush thickening" is more appropriate. Bush thickening can be defined as the excessive increase in the density and cover of one or more indigenous woody species that exploit disruptions of the grass/bush balance at the expense of grasses (Smit *et al.* 1999; Joubert 2014). It involves indigenous woody species occurring in their natural environment and is thus mainly associated with the savanna biome.

Savannas are constrained by rainfall (amount and temporal distribution), temperature and soil properties, but are also constrained by disturbances such as fire and herbivory (Bond 2008; Joubert *et al.* 2012). Due to the water-limited nature of savannas, bush thickening is considered a major factor contributing towards the low occurrence or even total absence of herbaceous plants in severe cases (Smit *et al*. 1999). The grazing capacity of large areas of the southern African savanna is reported to have declined due to bush thickening, often to such an extent that many previously economic livestock properties are now no longer economically viable (Donaldson 1980; De Klerk 2004).

Bush thickening by woody species such as *Acacia mellifera* and *Dichrostachys cinerea* has long been considered an ecological and economic problem in the rangelands of Namibia (Walter 1971; Barac 2004; De Klerk 2004; Joubert *et al.* 2008) and the area affected by bush thickening in Namibia is estimated to be approximately 260 000 km^2 (De Klerk 2004). Bush thickening affects parts of at least seven vegetation types in Namibia, namely Mopane Savanna, Mountain Savanna and Thornveld, Thornbush Savanna, Highland Savanna, Camelthorn Savanna, Forest Savanna and Woodland (Giess 1998).

According to Joubert (2014) the prevailing perception in Namibia is that bush thickening in arid savannas is a fairly recent phenomenon. Bester (1996) notes that, although it was already observed earlier, it has only been since the late 1950s and early 1960s that the process dramatically accelerated. According to Joubert (2014) there is little or no scientific evidence available to prove or disprove the perception that the major problem has indeed occurred in the last 60s. Joubert (2014) further noted that surprisingly little research, besides the occasional documentation of bush densities and cover (e.g. Bester 1999), has been conducted in Namibia. Despite this lack of scientific data on bush thickening in Namibia, much of the blame for the declines in rangeland and beef production has been placed on bush thickening, and enormous amounts of money and effort have been put into treating the existing symptoms (De Klerk 2004).

Removal of some or all of the woody plants will normally result in an increase in grass production and thus also in the grazing capacity. However, the results of woody plant removal may differ between vegetation types, with the outcome determined by both negative and positive responses to tree removal (Teague & Smit 1992). Cognisance must thus be taken of the ecological importance of woody plants in savanna ecosystems. Directly opposed to competition with herbaceous vegetation, positive contributions of woody plants include food for browsers and soil enrichment that elevate the soil nutrient status on a landscape level (Hagos & Smit 2005). A further aspect that is becoming increasingly important, is the wood component of trees and shrubs as a source of energy which includes firewood, charcoal, biofuel and electricity generation (Luoga *et al.* 2000; Nghikembua 2008). In a survey done in Namibia on the regular usage of different energy sources, 76.4% of the respondents used firewood, 11.7% used charcoal and 3.9% used wood briquettes (Nghikembua 2008).

In view of the often poor understanding of savanna ecosystem functioning, finding solutions to the problem - especially long-term solutions - is often difficult. Restoration of bush thickened areas, and in particular chemical control measures, should comply with two important requirements before they can be considered

successful (Smit 1998). They should be ecologically responsible and economically justifiable. In southern Africa, judged on these two basic requirements, it is conceived that very few attempts at restoring bush thickened areas can be considered successful (Smit 1998). This is either because the cost is too high or the wrong approach was followed with the resultant loss of beneficial woody plants and re-encroachment, often resulting in a state that is worse than before treatment.

1.2 Objectives (as per TOR of the project)

The assignment has two main objectives:

1. Establish a tested and accepted methodology of local biomass resource assessment
    - 1.1. Provide an overview of the existing resource assessment methodologies and assess the applicability for the Namibian context.
    - 1.2. Provide a detailed outline of the proposed methodology to be applied in the context of the Namibian bush biomass.
2. Prepare and implement a local biomass resource assessment in a selected area to be determined by the project office.
    - 1.3. Develop a stakeholders' list/mapping for the area
    - 1.4. Identify the biomass species in the area and their implication for harvesting methodologies and potential end use and value addition opportunities.
    - 1.5. Provide a statistically significant quantification of the biomass resource currently available and expected regrowth in the area.
    - 1.6. Establish the biomass potential yield (e.g. willingness of resource holders to co-operate, taking into consideration the existing alternative uses of the biomass, accessibility of the biomass resource).
    - 1.7. Evaluate the biomass potential for investment (e.g. power generation).

2. METHODOLOGY OF LOCAL BIOMASS RESOURCE ASSESSMENT

2.1 Overview of existing resource assessment methodologies

Accurate estimates of above-ground woody biomass of woody plants are essential for a number of reasons. It is essential for the study of savanna structure, productivity, carbon sequestration, the impact of different land-use practices (Brown *et al.* 1989; Smit 2014) and for assessing structural and functional attributes of forest ecosystems (Chave *et al.* 2005). Estimates of the woody biomass can also aid the quantification of resources such as wood fuel and timber in forests (Sawadogo *et al.* 2010) and savanna ecosystems (Smit 2014).

Biomass can be determined by direct or indirect methods. The most obvious direct measurement of tree biomass involves harvesting a representative number of trees that include all size classes, oven-drying the material and weighing it (Sawadogo *et al.* 2010; Smit 2014). This approach can be costly and impractical, especially when dealing with numerous species and large sample areas (Willebrand *et al.* 1993; Sawadogo *et al.* 2010). Indirect methods involve the use of allometric regression equations that predict the biomass non-destructively from measurements of the plants such as trunk diameter and crown diameter (Whittaker 1968; Meilby & Puri 2009) or measurements from which the spatial canopy volume can be calculated (Smit 18989a, b; Smit 1996, Smit 2014, Richard *et al.* 2012).

Regression equations (linear, logarithmic, exponential or multiplicative) have been used to estimate woody biomass indirectly from specific measurements of the trees (Sawadogo *et al.* 2010; Picard *et al*. 2012; Smit 2014). Several generalized biomass prediction equations have been developed for tropical woody species (Brown *et al.* 1989; Overman *et al.* 1994; Brown, 1997; Chave *et al.* 2005; Cole & Ewel 2006), temperate woody species (Ter-Mikaelian & Korzukhin 1997; Grote 2002) and African savanna species (Stromgaard 1985; Smit 1989a, b; Sawadogo *et al.* 2010; Balehegn *et al.* 2012; Smit 2014) on the basis of measured attributes of trees. The use of these equations for accurate woody biomass estimation for all species is, however, problematic because of structural and size differences between species (Navar 2009). A solution to this problem were proposed by Smit (2014) who developed several “general” regression equations based on structural groups to accommodate species for which a specific regression equation does not exist.

Various structural classifications of woody plants as shrubs, bushes and trees have been used to describe African savanna woody plants, often with diverse criteria as to whether a plant is a shrub, bush or tree. Density data (plants/ha) are commonly used in southern Africa, including Namibia (Bester 1996, 1999), to describe tree communities, but due to size differences density data are generally inadequate to quantify biomass accurately. Compensation for differences in tree height was implemented by Teague *et al.* (1981) who defined a Tree Equivalent (TE) as a tree, 1.5 m high. While this approach compensates in part for size differences, it still underestimates the contribution of large trees due to the fact that growing trees not only increased in height (vertically), but also in canopy diameter and crown volume (horizontally).

Canopy cover of woody plants was measured by Zimmerman (2009) in Namibian rangelands, using a Bitterlich gauge being described by Friedel & Chewings 1988. This is a simple device that is held horizontally with the tip of the handle held just below the eye. The gauge is pointed in the direction of a woody canopy, to determine whether the sighting pins extend beyond the canopy, in which case the canopy is ignored, or whether the canopy extends beyond the sighting pins, in which case the canopy is counted. The method is described by Friedel & Chewings (1988) for various half angles. Zimmerman (2009) used a half angle of 12º 55’, but he noted that the clumped distribution of some bushes made it difficult to determine where the canopy of one plant ended and another began. Such a clump was subsequently treated as if it were one large canopy instead of several smaller canopies, his final result thus giving an estimate of the % soil area covered by woody canopy rather than of the absolute canopy cover.

A desk study was undertaken by Zimmerman & Joubert (2002) to roughly estimate the standing biomass of harvestable wood on bush thickening species in Namibian farmland. This was done by combining spatial data from Bester (1999) with biomass data from Cunningham (1998). This procedure was described as follows by Zimmerman & Joubert (2002):

"The nine bush thickened zones, suitable for wood harvest, were roughly copied from the map of Bester (1999) by computer mouse onto Arcview GIS. The resulting map was then overlain with a land tenure map, to show each zone in commercial farmland and in communal land, while excluding National Parks and Game Reserves. The area of each relevant polygon was then obtained through the GIS software, and added together for each zone per tenure type, in order to estimate the area occupied by each of the nine bush thickening zones in both commercial and communal farmland. The estimates of Cunningham (1998) had been obtained from small sample plots, located on seven farms in or near seven of Bester's bush-thickened zones. They were extrapolated in the current study to the nine bush thickened zones of Bester (1999). Although one of the locations, Uitkomst Research Station, falls within the boundary of zone 7 on Bester's map, its bush species composition shows it to be more representative of zone 8, where it was therefore placed for the purpose of this analysis. For the two bush-thickened zones not represented by Cunningham's sample plots, an estimate was extrapolated from zones dominated by similar bush species, at a conservative rate relative to bush density.

The measurements made by Cunningham (1998) were of fresh weight of wood. Although the measurements were made in the dry season (Cunningham, pers. comm.), for the sake of caution, a moisture content of 25% was used for converting to dry weight (Galloway, pers. comm.) In addition, the sample plots of Cunningham (1998) would not be representative of the whole bush-thickened zone, since bushes had already been cleared from some portions for harvesting wood, improved grazing, crop fields, roads, fencelines, firebreaks, villages, etc., while bushes cannot grow in some of the pans and floodplains that occur within these zones. Therefore a figure of 20% was arbitrarily used, for cleared land plus land without bushes, to come up with a biomass estimate of available wood."

Other techniques employed in Namibia include the degradation gradient method (Bosch & Janse van Rensburg 1987; Bosch & Gauch 1991). This method has been applied by both Strohbach (1992; 2000) and Joubert (1997) in Namibian savannas, often in combination with the Braun-Blanquet survey method that consists of compiling 'relevés', which is a description of a sample site (Strohbach 2000). Both these techniques are, however, descriptive of nature and no biomass estimates are possible.

In the instances where actual biomass figures of woody plants were published, the data were accurate and non-destructive technique that can provide estimates of woody biomass prior to any obtained from the actual harvesting of woody plants such as those published by Cunningham (1998). These values are obviously accurate, but extremely time consuming and labour intensive. What is needed is an accurate and non-destructive technique that can provide estimates of woody biomass prior to any harvesting to enable viability studies and planning.

Based on the review of Picard *et al.* (2012) the most appropriate approach to biomass estimations in Namibia will be the use of biomass allometric equations, but such allometric equations were never developed in Namibia. The BECVOL 3-model that incorporate allometric equations and which was developed in southern African savanna for use in semi-arid savanna vegetation was the only biomass estimation technique that complies with all the requirements for application in Namibian savanna. This technique is subsequently being described.

2.2 Outline of the proposed methodology

Technique based on the following publication: Smit G.N. 2014. BECVOL 3 - an expansion of the above-ground biomass quantification model for trees and shrubs to include the wood component. *African Journal of Range and Forage Science* 31(2): 179-186.

2.2.1 Introduction

Indigenous woody plants are prominent features of African savanna ecosystems and their ecological importance is widely acknowledged (Belsky 1994; Hagos & Smit 2005; Treydte *et al.* 2007). Many of these savanna ecosystems are under increasing threat from either an undesirable increase in woody plant density (bush encroachment/thickening) (Knoop & Walker 1985; Roques *et al.* 2001; Smit 2005; Ward 2005; Joubert *et al.* 2008; Kgosikoma *et al.* 2012) or conversely from the over-exploitation of the woody plant resource (Hoffman *et al.* 2002). The ability to accurately estimate the aboveground biomass of woody plants is thus essential for the study of savanna structure, productivity, carbon sequestration and the impact of different land-use practices. In addition, the need to quantify the available plant material for browsers has become increasingly important with the need for a more scientific approach to the management of wildlife populations in conservation areas and wildlife ranches (Bothma *et al.* 2004), and for a better understanding of plant–herbivore interactions in savanna ecosystems (Hartnett *et al.* 2012).

The BECVOL-model (acronym for 'Biomass Estimates from Canopy Volume') (Smit 1989a; 1989b, 1994; 1996) was originally developed as a scientific tool for the estimation of the aboveground biomass of woody plants. This section reports on the development of version 3.0 of the BECVOL- model, which is the seventh variation of the original model.

An approach to a quantitative description of woody plant communities was proposed by Smit (1989a; 1989b), which evolved as the BECVOL-model (Smit 1994; 1996). Since its inception it has been widely used in ecological studies involving woody plants (Smit 2003; Abule *et al.* 2007; Kalwu *et al.* 2010; Kohi *et al.* 2011) and for the calculation of realistic stocking rates of browsers within specific browsing stratums (Smit 2001; Bothma *et al*. 2004). The previous model (version 2.0) provides estimates of the leaf volume and leaf dry mass (total and vertically stratified into the different browsing heights) at peak biomass, based on the allometric relationship between the plant's spatial canopy volume and its leaf dry mass and leaf volume.

With the development of the original concept of the BECVOL-model, the following three aspects of the agro-ecological implications of woody plants in African savannas were considered the most important (Smit 1989a): (i) competition with herbaceous vegetation for soil water and nutrients (bush encroachment/thickening); (ii) food for browsers, and (iii) creation of sub-habitats suitable for desirable grass species. Subsequently, quantitative descriptive units applicable to each of the former three aspects were proposed by Smit (1989a): (i) Evapotranspiration Tree Equivalent (ETTE) - defined as the leaf volume equivalent of a 1.5 m single-stemmed tree, (ii) Browse Tree Equivalent (BTE) - defined as the leaf mass equivalent of a 1.5 m single stemmed tree, and (iii) Canopied Subhabitat Index (CSI) - defined as the canopy spread area of those trees in a transect under which associated grasses like *Panicum maximum* are most likely to occur, expressed as a percentage of the total transect area. Smit (1989a) has defined the values of an ETTE and BTE as 500 cm^3 leaf volume and 250 g leaf dry mass, respectively (rounded off median values of harvested trees), based on harvested 1.5 m *Acacia karroo* trees.

The BECVOL-model follows a regression analysis approach using standard statistical least square regression analyses. The calculation of the ETTE and BTE values is based on the relationships between the spatial canopy volume of a tree and its true leaf dry mass and true leaf volume, respectively. The spatial canopy volume is calculated from several measurements of the tree as explained below. While various other studies reported equations relating tree dimensions to above-ground biomass (Mason & Hutchings 1967; Barnes *et al.* 1976; Rutherford 1979; Sawadogo *et al.* 2010; Balehegn *et al.* 2012), the BECVOL-model differs by being able to provide estimates for both complete plants and plant portions by employing the

calculation of partial canopy volumes (Smit 1989b). This is of particular importance in the estimation of available browse within different height strata. In addition to total leaf DM, stratified estimates of the leaf DM below 1.5 m, 2.0 m and 5.0 m are also calculated by the BECVOL-model. These heights were selected because they represent the mean maximum browsing heights of specific groups of African browsers. The height of 1.5 m represents the mean maximum browsing height of the domestic goat (Aucamp 1976) and impala (*Aepyceros melampus*) (Dayton 1978), while 2.0 m and 5.0 m represent the mean maximum browsing heights of the kudu (*Tragelaphus strepciseros*) and giraffe (*Giraffa camelopardalis*) (Skinner & Chimimba 2005), respectively.

Regarding estimates of the browseable component of woody plants, the previous model only estimated the leaves, whereas young, new season's shoots less than 0.5 cm in diameter also constitute an important component of the browseable part of woody plants (Rutherford 1979; Topps 1997). In addition to competition with herbaceous vegetation, food for browsers and creation of suitable sub-habitats for grasses, a fourth aspect that was not considered in the previous model is the importance of the wood component of trees and shrubs, specifically for firewood, charcoal and biofuel production (Luoga *et al.* 2000; Nghikembua 2008). To meet the basic energy needs for cooking, heating and lighting, more than half a billion people in Africa rely on plant biomass, with one of the major sources being wood of indigenous trees (Karekezi & Kithyoma 2006; United Nations Department of Economic and Social Affairs 2007). Wood originating from several savanna woody species - especially those with dense heartwood - is known to have excellent fuel properties and these species yield excellent charcoal as well. In a survey done in Namibia on the regular usage of different energy sources, 76.4% of the respondents used firewood, 11.7% used charcoal and 3.9% used wood briquettes (Nghikembua 2008). The branches of spiny woody species are also used to construct fencing kraals for livestock, while the branches not suitable for firewood are used for brush packing on bare areas to aid in the restoration of degraded rangelands (Smit 2004).

The most important addition to the BECVOL-3 model is the development of additional regression models for the estimation of the dry mass of the wood component in different diameter classes.

2.2.2 Procedure

The tree species included in the study were *Acacia karroo, Combretum apiculatun, Dichrostachys cinerea, Terminalia sericea, Colophospermum mopane* and *Grewia flava*. These tree species were selected based on their ecological and economical importance, either as potential encroacher species (e.g. *D. cinerea*) or their value as fodder plants (e.g. *C. apiculatum* and *G. flava*) in a southern African context.

The *A. karroo, D. cinerea, T. sericea* and *G. flava* trees were collected on the Towoomba Agricultural Development Centre near Bela-Bela in the Limpopo Province of South Africa (28°21'E, 24°25'S; 1 184 m above sea level). The vegetation is described as a transition zone between the Springbokvlakte Thornveld and Loskop Thornveld (Mucina & Rutherford 2006). The *C. apiculatum* trees were collected on the farm "Durban", approximately 30 km east of Lephelale in the Limpopo Province of South Africa (28°2'E, 23°40'S, 950 m above sea level). The vegetation is described as Limpopo Sweet Thornveld (Mucina & Rutherford 2006). The *C. mopane* trees were collected on the Limpopo Venetia nature reserve near Pontdrift in the Limpopo Province of South Africa (29°12'E, 22°19'S, 560 m above sea level). The vegetation of the area is described as Musina Mopane Bushveld (Mucina & Rutherford 2006).

The spatial canopy volume is calculated from measurements of each tree, consisting of the following: (i) tree height, height of the maximum canopy diameter, (iii) height of the first leaves or potential leaf bearing stems, (iv) maximum canopy diameter, and (v) base diameter of the foliage at the height of the first leaves (Smit 1989a; 2004; 2006). Since the theoretical canopy is considered circular, the maximum canopy diameter is calculated as the average of two measurements rectangular to each other and the same principle is applied to the measurement of the base diameter of the foliage at the height of the first leaves. The spatial volume of any tree (cm^3), regardless of its shape or size, is calculated from the dimension measurements by using the volume formulas of an ellipsoid, a right circular cone, a frustum of right circular

cone or a right circular cylinder (Smit 1989b). These shapes correspond well with varying shapes of different trees or parts of a tree. Depending on the shape of the tree, any one of these volume formulas may be used, or more likely two of them in combination.

With the development of the original BECVOL-model only the leaves from the harvested trees were collected and measured. As a requirement for the development of the additional regression models of the BECVOL 3-model, 20 additional undamaged plants of each tree species were selected for harvesting. These selected individuals included all size classes representative of the population. The criteria for "undamaged" was that there should be no visible signs of damage by fire, cutting or heavy browsing that may have altered the growth form of the plants.

Harvesting of the woody plants started during 1988 when only the leaves of a limited number of species were harvested for inclusion into the regression equations of the original tree quantification technique (Smit 1989a; 1989b). The data from this initial sampling were retained for the BECVOL 3-model, and combined with the data from the additional harvested trees, which will improve the accuracy of the regression models pertaining to the leaf fraction. The additional and more comprehensive sampling of the woody plants was conducted between 1994 and 2008. The plants were only harvested at peak biomass and harvesting was thus only conducted between November and March of each year. In view of the labour involved in the harvesting of the trees, it was possible to harvest the woody component of only four of the original six tree species. The leaf data of the two species of which the woody component was not harvested (*C. mopane* and *G. flava*) were retained since they contribute to the accuracy of the leaf prediction models.

The dimensions of each tree, as described in the previous section, were measured prior to being felled and their spatial canopy volume calculated (cm^3). The leaves were separated by hand from the woody component. The woody component in turn was separated into three diameter categories: shoots <0.5 cm, stems >0.5-2.0 cm and stems >2.0 cm using an accurate calliper. The shoots <0.5 cm are considered part of the browseable component of woody plants. The stems >0.5-2.0 cm are generally not considered suitable for firewood or charcoal production, but can be used for brush packing during veld restoration operations, while the stems >2.0 cm constitute that fraction suitable for use as firewood and charcoal production.

Moisture loss from the leaves was limited by working under shade and keeping the leaves covered with wet sacks for purposes of measuring leaf volume. This was done by measuring the volume of water being displaced in a large measuring cylinder. After the volume measurements, the leaves were first air-dried on sieves, then dried to constant mass in a drying oven (70^{o}C) and weighed. The leaves were dried for 24 hours, while the time required for the wood to dry was much longer (7-12 days). The woody component (shoots and stems) were also dried to constant mass in a drying oven (70^{o}C) and weighed.

Regression analyses (Draper & Smith 1981; Statgraphics 1999) were applied with the different plant dry mass fractions (g) as dependent variables (four categories: leaves, shoots <0.5 cm, stems >0.5-2.0 cm and stems >2.0 cm) and the calculated spatial canopy volume (cm^3) as the independent variable. Three regression models were tested: linear ($y=a+bx$), exponential ($\ln y=a+bx$) and multiplicative ($y=ax^b$) (Statgraphics 1999).

In the case of the curvilinear regression equations (exponential and multiplicative), best line fitting to the data was obtained by transforming the spatial canopy volumes to their normal logarithmic values. In most cases logarithmic transformations are done to obtain linearity of non-linear data. This partial transformation did not alter the curvilinearity of the plotted lines, but merely changed the relationship from convex to concave. In this form the data was well suited for fitting both the exponential and multiplicative regression equations. By resorting to a partial logarithmic transformation only, the problem of biased estimates by simply taking antilogarithms of values from a log-log regression line or regression function (Beauchamp & Olson 1973) was largely avoided.

Due to the labour intensive nature of the tree harvesting, it is unrealistic to attempt the development of a dedicated regression model for all the African savanna tree species. For this reason two "general" regression models were also developed to accommodate the prediction of above-ground biomass of other tree species not included in this study. Based on leaf structure, two broad categories were distinguished, viz. microphyllous species (*A. karroo, D. cinerea* combined) and broad-leaved species (*C. apiculatum, T. sericea, C. mopane, G. flava* combined). This approach as used in previous versions of the BECVOL-model has proven very useful (Smit 1996).

2.2.3 Results and Discussion

Results of the regression analyses of the relationship between the calculated spatial canopy volume (independent variable) of the harvested trees and the different measured plant fractions (dependant variables) of *A. karroo* is presented in Table 2.1, and those of *D. cinerea, C. apiculatum, T. sericea, C. mopane* and *G. flava* are presented in Tables 2.2-2.6, respectively. The results of the regression analyses involving the combined tree species are presented in Table 2.7 (microphyllous species) and Table 2.8 (broad-leaved species).

From Tables 2.1-2.8 it is clear that for all plant fractions (leaves, shoots <0.5 cm, stems >0.5-2.0 cm, stems >2.0 cm) and all species, highly significant regressions ($P<0.001$) with coefficients of determinations as high as $r^2 = 0.98$ were achieved. Regarding the three tested regression models, there is not a clear pattern as to which model provided the best fit to the data, and some variability between plant biomass fractions and tree species is noticeable. As a general rule it would appear as if both curvilinear regression models (exponential and multiplicative) provided a better fit to the data. In the case of the leaves (leaf mass and leaf volume) the reason for the trend towards curvilinearity is due to the fact there are normally fewer leaves per unit canopy volume with increasing tree size. In most savanna tree species the leaves are concentrated at the outer perimeter of the foliar canopy and with increasing tree size there is an increasing area in the centre of the canopy without any leaves (Van der Meulen & Werger 1984). In the case of the wood component, it became clear from the harvested trees that the greatest weight resides in the thick main stems and dense heartwood, which only develop in older, larger trees. Differences between the various regression models was, however, small and the decision as to which regression model should be used will be a matter of personal preference and ease of use.

Table 2.1: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees (range: 0.5-8.4 m in height) and the different measured plant fractions (dependant variables) of *Acacia karroo*: linear (y=a+bx), exponential (ln y=a+bx) and multiplicative (y=ax^b), where y = estimated leaf volume (cm^3) / dry mass fraction (g), x = spatial canopy volume (cm^3).

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept)		*b* (slope)	
						Value	SE	Value	SE
Leaf volume (cm³)	Linear	65	0.85	0.72	<0.001	1 813.14	481.159	0.0001795	0.0000142
	Exponential		0.95	0.90	<0.001	−2.82646	0.438269	0.693414	0.0292608
	Multiplicative		0.94	0.88	<0.001	−20.0476*	1.2011	10.2335	0.446155
Leaf dry mass (g)	Linear	65	0.86	0.74	<0.001	909.231	222.264	0.0000877	0.0000066
	Exponential		0.95	0.90	<0.001	−3.84491	0.460117	0.712723	0.0307194
	Multiplicative		9.94	0.88	<0.001	−21.563*	1.25326	10.525	0.465532
Shoot dry mass (shoots <0.5 cm in diameter) (g)	Linear	20	0.94	0.88	<0.001	51.2957	440.102	0.0002313	0.0000196
	Exponential		0.93	0.97	<0.001	−6.57278	1.2686	0.887834	0.0804096
	Multiplicative		0.93	0.86	<0.001	−30.1215*	3.43185	13.6321	1.24674
Stem dry mass (stems >0.5–2.0 cm in diameter) (g)	Linear	20	0.91	0.83	<0.001	−662.919	1 729.09	0.0007155	0.0000771
	Exponential		0.93	0.86	<0.001	−7.68076	1.44271	1.01235	0.0914453
	Multiplicative		0.93	0.86	<0.001	−34.5205*	3.91018	15.5398	1.42051
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	20	0.92	0.85	<0.001	−7 883.3	4 342.77	0.0018934	0.0001936
	Exponential		0.89	0.79	<0.001	−17.4884	3.16515	1.63743	0.200621
	Multiplicative		0.90	0.81	<0.001	−61.7877*	8.126	25.4573	2.95205
Total wood dry mass (all fractions) (g)	Linear	20	0.93	0.86	<0.001	−8 670.07	6 109.71	0.0028448	0.000272
	Exponential		0.89	0.79	<0.001	−12.7454	2.61595	1.3855	0.16581
	Multiplicative		0.89	0.79	<0.001	−49.6601*	6.97412	21.3338	2.53359

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

Table 2.2: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees (range: 0.5-4.6 m in height) and the different measured plant fractions (dependant variables) of *Dicrostachys cinerea*: linear (y=a+bx), exponential (ln y=a+bx) and multiplicative (y=ax^b), where y = estimated leaf volume (cm^3) / dry mass fraction (g), x = spatial canopy volume (cm^3).

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept)		*b* (slope)	
						Value	SE	Value	SE
Leaf volume (cm³)	Linear	40	0.95	0.90	<0.001	933.167	324.183	0.0002583	0.0000142
	Exponential		0.95	0.90	<0.001	−4.1303	0.689778	0.765784	0.0473463
	Multiplicative		0.95	0.90	<0.001	−24.6556*	1.93576	11.8364	0.701738
Leaf dry mass (g)	Linear	40	0.95	0.90	<0.001	4 444.79	148.358	0.0001104	0.0000065
	Exponential		0.95	0.90	<0.001	−5.36776	0.717094	0.790328	0.0451844
	Multiplicative		0.94	0.88	<0.001	−26.5675*	2.00315	12.2218	0.726171
Shoot dry mass (shoots <0.5 cm in diameter) (g)	Linear	20	0.94	0.88	<0.001	−752.249	618.033	0.0002507	0.0000214
	Exponential		0.97	0.94	<0.001	−7.53549	0.918487	0.941583	0.0562661
	Multiplicative		0.96	0.92	<0.001	−33.1561*	2.61653	14.6954	0.938747
Stem dry mass (stems >0.5-2.0 cm in diameter) (g)	Linear	20	0.96	0.92	<0.001	−1 890.88	1 136.4	0.000573	0.0000395
	Exponential		0.98	0.96	<0.001	−8.31187	0.772513	1.03457	0.0473238
	Multiplicative		0.98	0.96	<0.001	−36.511*	2.23919	16.164	0.803366
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	20	0.93	0.86	<0.001	−13 882.8	4 727.28	0.001809	0.000164
	Exponential		0.88	0.77	<0.001	−19.558	3.55957	1.73123	0.218058
	Multiplicative		0.88	0.77	<0.001	−66.9204*	9.56428	27.1112	3.43143
Total wood dry mass (all fractions) (g)	Linear	20	0.94	0.88	<0.001	−16 599.1	6 207.64	0.002636	0.0002158
	Exponential		0.98	0.96	<0.001	−10.143	0.919088	1.21392	0.0563029
	Multiplicative		0.98	0.96	<0.001	−43.1686*	2.72288	18.9439	0.976903

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

Table 2.3: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees (range: 0.5-6.4 m in height) and the different measured plant fractions (dependant variables) of *Combretum apiculatum*: linear (y=a+bx), exponential (ln y=a+bx) and multiplicative ($y=ax^b$), where y = estimated leaf volume (cm^3) / dry mass fraction (g), x = spatial canopy volume (cm^3). * a = log a (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model.

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept)		*b* (slope)	
						Value	SE	Value	SE
Leaf volume (cm^3)	Linear	40	0.97	0.94	<0.001	1 255.97	313.441	0.0001767	0.0000084
	Exponential		0.97	0.94	<0.001	−5.73831	0.687686	0.85555	0.0433758
	Multiplicative		0.97	0.94	<0.001	−29.0547*	1.67497	13.3716	0.608026
Leaf dry mass (g)	Linear	40	0.97	0.94	<0.001	538.46	142.665	0.0000799	0.0000038
	Exponential		0.97	0.94	<0.001	−6.66795	0.676104	0.862375	0.0426452
	Multiplicative		0.97	0.94	<0.001	−30.1525*	1.65159	13.4718	0.599539
Shoot dry mass (shoots <0.5 in diameter) (g)	Linear	20	0.99	0.98	<0.001	272.028	110.383	0.0001034	0.0000035
	Exponential		0.99	0.98	<0.001	−6.15306	0.472481	0.834679	0.0303917
	Multiplicative		0.99	0.98	<0.001	−28.3389*	1.33512	12.8445	0.488426
Stem dry mass (stems >0.5-2.0 cm in diameter) (g)	Linear	20	0.99	0.98	<0.001	162.135	158.964	0.0002113	0.0000051
	Exponential		0.98	0.96	<0.001	−6.16786	0.693129	0.868063	0.0445846
	Multiplicative		0.97	0.94	<0.001	−29.148*	2.01459	13.3242	0.736996
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	20	0.84	0.71	<0.001	553.009	5 399.97	0.0011109	0.0001719
	Exponential		0.91	0.83	<0.001	−13.6015	2.38255	1.39531	0.153254
	Multiplicative		0.92	0.85	<0.001	−51.3154*	6.15969	21.7012	2.25339
Total wood dry mass (all fractions) (g)	Linear	20	0.98	0.96	<0.001	−4 021.35	3 394.8	0.0021499	0.0001081
	Exponential		0.99	0.98	<0.001	−9.01684	0.590477	1.15315	0.0379816
	Multiplicative		0.99	0.98	<0.001	−39.5717*	1.83095	17.7102	0.669815

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

Table 2.4: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees (range: 0.5-7.8 m in height) and the different measured plant fractions (dependant variables) of *Terminalia sericea*: linear (y=a+bx), exponential (ln y=a+bx) and multiplicative ($y=ax^b$), where y = estimated leaf volume (cm^3) / dry mass fraction (g), x = spatial canopy volume (cm^3). * a = log a (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model.

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept)		*b* (slope)	
						Value	SE	Value	SE
Leaf volume (cm^3)	Linear	40	0.93	0.86	<0.001	1 708.21	453.334	0.000216	0.0000174
	Exponential		0.92	0.85	<0.001	−4.39578	0.998259	0.792703	0.0659369
	Multiplicative		0.92	0.85	<0.001	−24.8058*	2.81807	11.9463	1.03974
Leaf dry mass (g)	Linear	40	0.92	0.85	<0.001	168.575	177.31	0.000078	0.0000068
	Exponential		0.91	0.83	<0.001	−5.27024	1.10004	0.781664	0.0726597
	Multiplicative		0.90	0.81	<0.001	−25.3187*	3.11433	11.7513	1.14904
Shoot dry mass (shoots <0.5 cm in diameter) (g)	Linear	20	0.96	0.92	<0.001	149.62	44.649	0.0000783	0.0000059
	Exponential		0.90	0.81	<0.001	−3.21263	1.14035	0.617778	0.0775608
	Multiplicative		0.88	0.77	<0.001	−17.7576*	3.21468	8.79869	1.19787
Stem dry mass (stems >0.5-2.0 cm in diameter) (g)	Linear	20	0.98	0.96	<0.001	19.5089	57.9415	0.0001382	0.0000077
	Exponential		0.88	0.77	<0.001	−4.38941	1.44635	0.701576	0.0983738
	Multiplicative		0.86	0.74	<0.001	−20.8142*	4.06918	9.95749	1.51628
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	20	0.98	0.96	<0.001	−654.737	217.917	0.0005657	0.0000289
	Exponential		0.78	0.61	<0.001	−4.30144	2.26722	0.747867	0.154205
	Multiplicative		0.76	0.58	<0.001	−21.6673*	6.2176	10.5613	2.31684
Total wood dry mass (all fractions) (g)	Linear	20	0.99	0.98	<0.001	−458.764	242.501	0.000782	0.0000322
	Exponential		0.88	0.77	<0.001	−3.36766	1.51284	0.731861	0.102896
	Multiplicative		0.86	0.74	<0.001	−20.4566*	4.2744	10.3706	1.59275

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

Table 2.5: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees (range: 0.5-7.8 m in height) and the different measured plant fractions (dependant variables) of *Colophospermum mopane*: linear (y=a+bx), exponential (ln y=a+bx) and multiplicative ($y=ax^b$), where y = estimated leaf volume (cm^3) / leaf dry mass (g), x = spatial canopy volume (cm^3).

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept)		*b* (slope)	
						Value	SE	Value	SE
Leaf volume (cm^3)	Linear	50	0.89	0.79	<0.001	861.92	231.558	0.000164	0.0000124
	Exponential		0.96	0.92	<0.001	−4.34074	0.477172	0.760682	0.0314953
	Multiplicative		0.96	0.92	<0.001	−23.2102*	1.35207	11.2064	0.499192
Leaf dry mass (g)	Linear	50	0.91	0.83	<0.001	395.824	110.443	0.0000903	0.0000059
	Exponential		0.96	0.92	<0.001	−4.98373	0.493893	0.759345	0.032599
	Multiplicative		0.95	0.90	<0.001	−23.797*	1.40413	11.1781	0.518415

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

Table 2.6: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees (range: 0.4-2.6 m in height) and the different measured plant fractions (dependant variables) of *Grewia flava*: linear (y=a+bx), exponential (ln y=a+bx) and multiplicative ($y=ax^b$), where y = estimated leaf volume (cm^3) / leaf dry mass (g), x = spatial canopy volume (cm^3).

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept)		*b* (slope)	
						Value	SE	Value	SE
Leaf volume (cm^3)	Linear	20	0.85	0.72	<0.001	329.161	386.606	0.0003977	0.0000823
	Exponential		0.92	0.85	<0.001	−1.63945	1.2945	0.605623	0.0866269
	Multiplicative		0.91	0.83	<0.001	−15.2155*	3.40513	8.37467	1.26105
Leaf dry mass (g)	Linear	20	0.76	0.58	<0.001	124.293	200.187	0.0001577	0.0000426
	Exponential		0.89	0.79	<0.001	−3.58694	1.64666	0.670455	0.110193
	Multiplicative		0.89	0.79	<0.001	−18.6867*	4.24103	9.29696	1.57062

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

Table 2.7: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees and the different measured plant fractions (dependant variables) of microphyllous species (*A. karroo* and *D. cinerea* combined): linear (y=a+bx), exponential (ln y=a+bx) and multiplicative ($y=ax^b$), where y = estimated leaf volume (cm^3) / dry mass fraction (g), x = spatial canopy volume (cm^3).

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept)		*b* (slope)	
						Value	SE	Value	SE
Leaf volume (cm^3)	Linear	105	0.86	0.74	<0.001	1 746.45	343.753	0.000191	0.0000113
	Exponential		0.95	0.90	<0.001	−2.9334	0.361257	0.696712	0.0236084
	Multiplicative		0.94	0.88	<0.001	−20.3491*	0.997989	10.3199	0.367454
Leaf dry mass (g)	Linear	105	0.87	0.76	<0.001	814.772	155.553	0.0000911	0.0000051
	Exponential		0.94	0.88	<0.001	−3.88021	0.390906	0.708109	0.0255459
	Multiplicative		0.94	0.88	<0.001	−21.5758*	1.07586	10.4868	0.396125
Shoot dry mass (shoots <0.5 cm in diameter) (g)	Linear	40	0.94	0.88	<0.001	−299.863	368.398	0.000239	0.0000142
	Exponential		0.95	0.90	<0.001	−6.92725	0.75592	0.907163	0.0470702
	Multiplicative		0.95	0.90	<0.001	−31.3273*	2.0832	14.0542	0.75194
Stem dry mass (stems >0.5–2.0 cm in diameter) (g)	Linear	40	0.91	0.83	<0.001	−1 099.12	1 133.12	0.000617	0.0000438
	Exponential		0.95	0.90	<0.001	−7.66381	0.821886	1.00266	0.0511779
	Multiplicative		0.95	0.90	<0.001	−34.6678*	2.24975	15.5465	0.812058
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	40	0.92	0.85	<0.001	−10 371.0	3 211.58	0.0018085	0.000124
	Exponential		0.87	0.76	<0.001	−17.8342	2.33673	1.64165	0.145505
	Multiplicative		0.88	0.77	<0.001	−62.557*	6.15977	25.638	2.22339
Total wood dry mass (all fractions) (g)	Linear	40	0.93	0.86	<0.001	−11 900.1	4 425.22	0.002669	0.000171
	Exponential		0.93	0.86	<0.001	−11.2839	1.3451	1.28811	0.0837579
	Multiplicative		0.93	0.86	<0.001	−46.0665*	3.61735	20.0052	1.3057

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

Table 2.8: Results of the regression analyses of the relation between the calculated spatial canopy volume (independent variable) of the harvested trees and the different measured plant fractions (dependant variables) of broad-leaved species (*C. apiculatum, T. sericea, C. mopane* and *G. flava* combined): linear (y=a+bx), exponential (ln y=a+bx) and multiplicative ($y=ax^b$), where y = estimated leaf volume (cm^3) / dry mass fraction (g), x = spatial canopy volume (cm^3).

Dependent variable	Regression model	*n*	*r*	r^2	*P*	*a* (intercept) Value	*a* (intercept) SE	*b* (slope) Value	*b* (slope) SE
Leaf volume (cm^3)	Linear	150	0.93	0.86	<0.001	1 136.89	177.088	0.0001849	0.0000069
	Exponential		0.94	0.88	<0.001	−4.48519	0.393655	0.780803	0.0257059
	Multiplicative		0.94	0.88	<0.001	−24.4673*	1.07695	11.7271	0.395909
Leaf dry mass (g)	Linear	150	0.94	0.88	<0.001	506.402	70.9239	0.0000817	0.0000027
	Exponential		0.95	0.90	<0.001	−5.34866	0.376799	0.783502	0.0246051
	Multiplicative		0.94	0.88	<0.001	−25.3464*	1.04748	11.748	0.385074
Shoot dry mass (shoots <0.5 in diameter) (g)	Linear	40	0.99	0.98	<0.001	134.076	51.6183	0.0001047	0.0000024
	Exponential		0.96	0.92	<0.001	−6.02162	0.540693	0.816309	0.0363256
	Multiplicative		0.95	0.9	<0.001	−26.8885*	1.6107	12.2501	0.598319
Stem dry mass (stems >0.5-2.0 cm in diameter) (g)	Linear	40	0.99	0.98	<0.001	36.1807	90.5885	0.0002102	0.0000042
	Exponential		0.90	0.81	<0.001	−5.12079	0.850227	0.787581	0.057121
	Multiplicative		0.89	0.79	<0.001	−25.0371*	2.47015	11.7386	0.917575
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	40	0.86	0.74	<0.001	−964.101	2 136.25	0.001113	0.000101
	Exponential		0.87	0.76	<0.001	−10.1161	1.50464	1.16649	0.101086
	Multiplicative		0.86	0.74	<0.001	−40.0429*	4.18877	17.5454	1.55598
Total wood dry mass (all fractions) (g)	Linear	40	0.97	0.94	<0.001	−3 648.82	1 605.82	0.002092	0.0000756
	Exponential		0.94	0.88	<0.001	−7.28251	0.825561	1.0279	0.0554639
	Multiplicative		0.93	0.86	<0.001	−33.3114*	2.49211	15.3336	0.925734

* *a* = log *a* (for multiplicative regression model only), spatial canopy volume transformed to its normal logarithmic value, except for linear model

The original BECVOL-model was written in dBase IV (Borland), from which evolved the BECVOL 3-model written in Visual dBase and dBase Plus (dBase LLC). Incorporation of the newly developed regression equations presented here into the BECVOL 3-model will enable users to make more accurate estimates of the browseable component of tree populations, and also provide estimates of the biofuel production potential of woody plants, especially in bush encroached areas. In response to the established usage of the BECVOL-model, complimentary resources and software are under constant development. A good example is the use of digital photography as an aid in the collection of field data and calculation of canopy volume as reported by Barret & Brown (2012).

2.2.4 Conclusion

On a landscape level where a representative sample of the tree population is measured, the BECVOL 3-model will thus enable the user to calculate the following values:

- Tree density (plants/ha)
- Evapotranspiration Tree Equivalents (ETTE ha^{-1})
- Total leaf dry mass (kg ha^{-1})
- Leaf biomass below a browsing height of 1.5 m (kg ha^{-1})
- Leaf dry mass below a browsing height of 2.0 m (kg ha^{-1})
- Leaf dry mass below a browsing height of 5.0 m (kg ha^{-1})
- Shoot dry mass - shoots <0.5 cm below a browsing height of 1.5 m (kg ha^{-1}),
- Shoot dry mass - shoots <0.5 cm below a browsing height of 2.0 m (kg ha^{-1}),
- Shoot dry mass - shoots <0.5 cm below a browsing height of 5.0 m (kg ha^{-1}),
- Stem dry mass - stems >0.5-2.0 cm in diameter (kg ha^{-1}),
- Stem dry mass - stems >2.0 cm in diameter (kg ha^{-1}),
- Total wood dry mass (all fractions) (kg ha^{-1}), and
- Total tree dry mass - leaves and wood combined (kg ha^{-1})
- Canopy subhabitat index

2.2.5 Practical application and field testing

Since the inception of the BECVOL 3-model which also includes estimates of the wood, it has been used in two successful and comprehensive studies of wood biomass:

> Smit GN, Janse van Rensburg G, Deacon F. 2011. Final report: Estimation of the above ground biomass of woody plants on representative sites in the vicinity of the Ulco mine, Northern Cape (51 pages). Report commissioned by MBB Consulting Services South (Pty) Ltd, Stellenbosch.
>
> Smit GN, Janse van Rensburg G, Deacon F. 2012. Final report: An assessment of the extent of bush encroachment on the property of the Sishen South (Kolomela) mine, Postmasburg (110 pages). Report commissioned by the Centre of Environmental Management, University of the Free State, Bloemfontein and Sishen Iron Ore Company (Kolomela), Postmasburg.

3. LOCAL BIOMASS ASSESSMENT IN A SELECTED AREA OF NAMIBIA

3.1 Study area (stakeholders list/mapping of area)

The study area is located north-west of Otjiwarongo in an area described as the North-central plateau of Namibia (Mendelsohn *et. al.* 2002) and the vegetation type as Thorn-bush shrubland (Mendelsohn & el Obeid 2005). The focus was primarily on privately owned commercial farms in close proximity of Nampower's Gerus substation, but a few sites on the Omatjenne Research Station, as well as a site on municipal land were included (Figures 3.1 & 3.2).

The eight commercial farms included Buffelhoek (342), Tokai (348), Waverley (347), Knoll (201), Randveld (167), Arcadia (320), Rusthof (353) and Ombarahewe (22) (Figure 3.1) these farms combined represent an area of approximately 45 000 ha. The farm Naribus (166) was excluded from the survey since the largest part of the farm was recently aerially sprayed with an arboricide that killed all the trees. A limited survey was conducted on the farm Ombarahewe (22) since the research team could not obtain free access (the owner does not live on the farm and could not be contacted). The Omatjenne Research Station and municipal land were opportunistically included, primarily because these sites represented areas that had never been subjected to any prior form of bush control.

Limitations of access (traveling time, limited road network, formal appointments and discussions with the farm owners and numerous farm gates that needed to be opened), played a significant role in the number of survey plots that could be surveyed in a day. Subsequently a total of 28 plots were selected and surveyed during the time allowance granted by the project for field work (Table 3.1, Figure 3.2). Unfortunately neither a detailed vegetation map, nor a detailed soil map that could assist the research team in selecting sites was available for the study area. Instead, Google earth imagery (Figure 3.2) and a recent (2002) 1:250 000 topo-cadastral map published by the Directorate of Survey and Mapping of Namibia was consulted. In addition, the research team relied on the extensive local knowledge of the various farm owners who accompanied the research team to potential survey sites. Mr T. Bredenham accompanied the research team on the farm Buffelhoek; Mr J.L. Botha on the farms Tokai and Knoll; Mr H.S. Kretzschmar on the farm Waverley; Mr J.P. Swart on the farm Randveld; Mr J. Erasmus on the farm Rusthof and Mr P. Krohne on the farm Arcadia. Past management histories as conveyed by the farm owners were also taken into consideration. The 28 plots were subsequently selected based on all the resources available to the research team to ensure the best possible representation of soil, vegetation type and available biomass in the area.

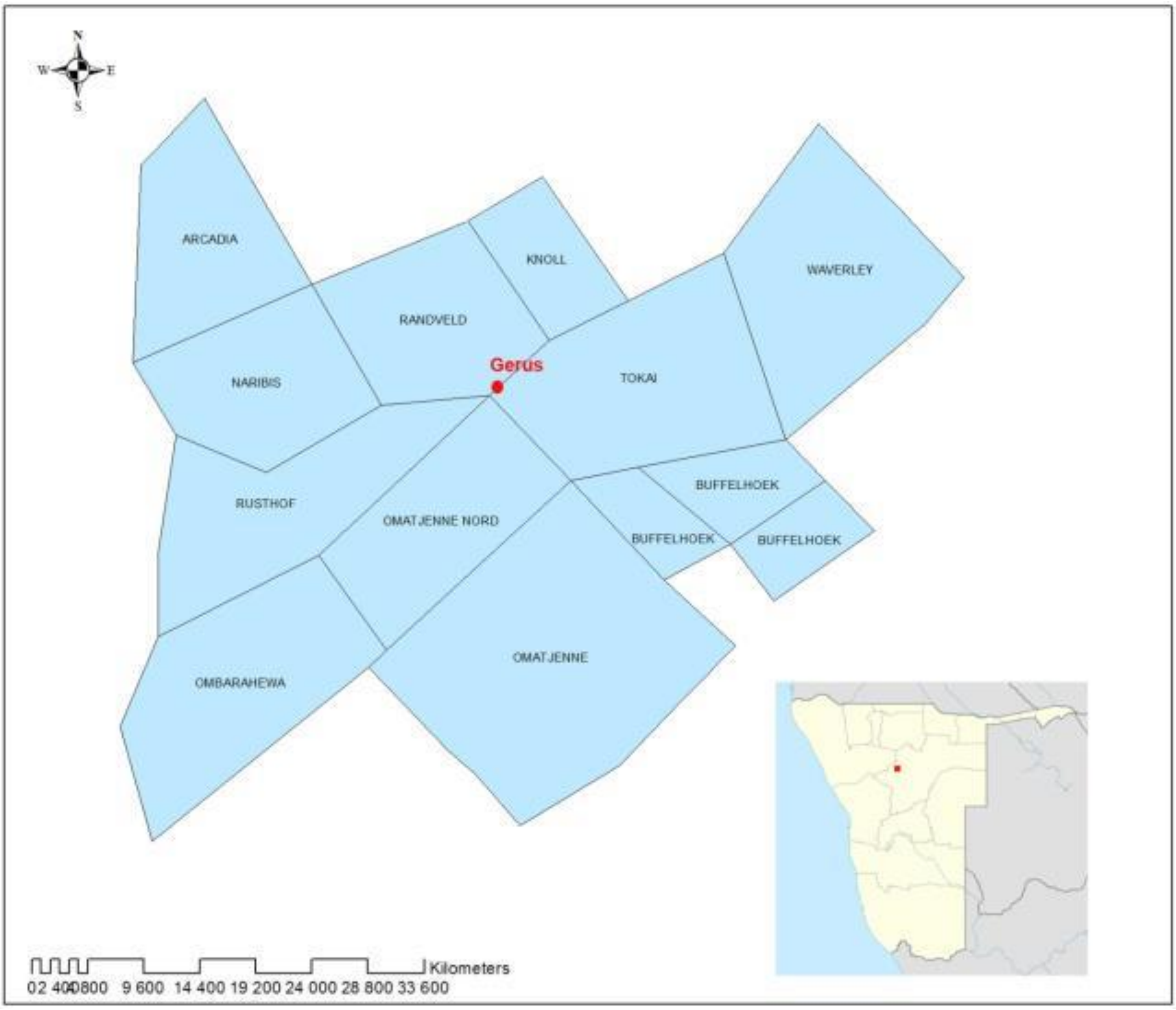


Figure 3.1 Map of the farms in the study area north-west of Otjiwarongo, Namibia.

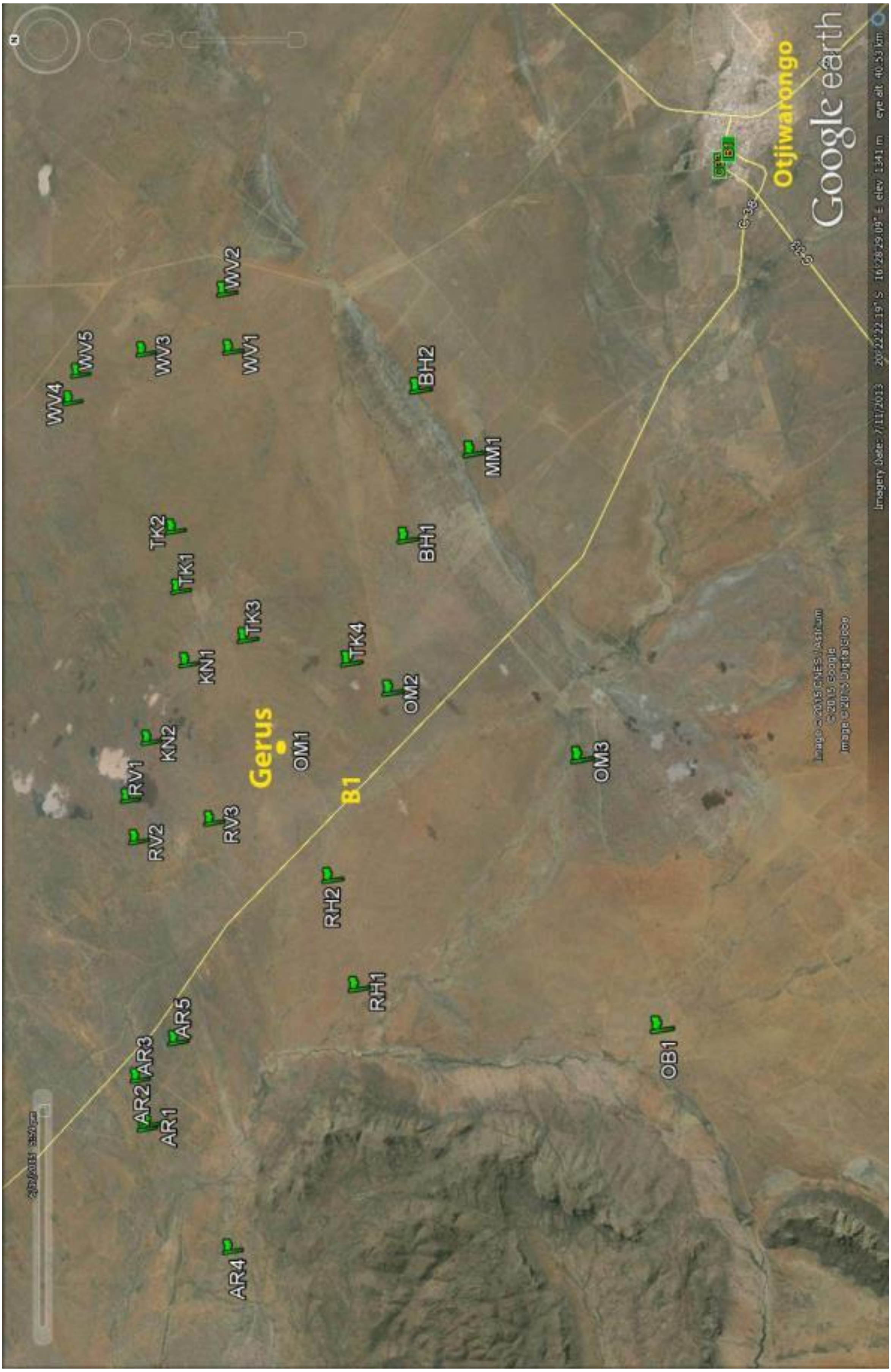


Figure 3.2 Google earth image of the location of the 28 survey plots (see Table 3.1).

Table 3.1 Naming convention and GPS coordinates of the 28 survey plots in the Thorn-bush shrubland of Namibia

Survey plot	Farm	Size (ha)	Transect (m)	GPS coordinates
BH1	Buffelhoek (342)	5 000	75	S20 21 52.6 E16 31 32.5
BH2			75	S20 22 08.4 E16 34 34.0
TK1	Tokai (348) (including Knoll & Randveld section 1)	12 000	75	S20 16 50.6 E16 30 39.3
TK2			75	S20 16 43.3 E16 31 58.7
TK3			100	S20 18 23.8 E16 29 33.3
TK4			50	S20 20 41.1 E16 29 02.1
WV1	Waverley (347)	7 000	50	S20 18 04.5 E16 35 47.1
WV2			50	S20 17 56.1 E16 37 03.4
WV3			50	S20 16 00.6 E16 35 57.6
WV4			50	S20 14 10.0 E16 35 02.4
WV5			50	S20 14 22.3 E16 35 39.0
KN1	Knoll (201)	Included with Tokai	75	S20 17 02.2 E16 29 02.3
KN2			50	S20 16 07.1 E16 27 19.1
RV1	Randveld (167)	4 000 (excludes section 1)	75	S20 15 36.1 E16 26 00.4
RV2			50	S20 15 48.2 E16 25 05.5
RV3			75	S20 17 36.1 E16 25 35.0
AR1	Arcadia (320) (including Paresis)	10 000	75	S20 16 03.9 E16 18 46.7
AR2			50	S20 15 57.9 E16 18 40.3
AR3			50	S20 15 48.0 E16 19 44.8
AR4			50	S20 17 59.8 E16 16 17.7
AR5			50	S20 16 43.7 E16 20 41.5
RH1	Rusthof (353)	7 000	50	S20 20 49.2 E16 22 15.7
RH2			50	S20 20 15.7 E16 24 29.7
OM1	Omatjenne (21)	N/A	50	S20 19 11.2 E16 27 07.8
OM2			50	S20 21 33.1 E16 28 25.5
OM3			50	S20 25 15.6 E16 27 07.9
OB1	Ombarahewe (22)	N/A	50	S20 26 41.4 E16 22 02.8
MM1	Municipal land	N/A	50	S20 23 12.6 E16 33 12.3

All the commercial farms are primarily used for extensive cattle farming, with only a limited number of small stock (sheep and goats) present on some of the farms. Free ranging game species such as springbok, gemsbok, red hartebeest, kudu and warthogs are still common on all the farms. As extensive cattle farms, the productivity of the natural vegetation - specifically the grasses - is critical to the success of these farming enterprises and thus heavily dependant on the annual rainfall.

The long-term annual rainfall of the area is approximately 457 mm. The rainy season usually extends from October to April inclusively, but rainfall is irregularly distributed and unpredictable. The area is well known for its high summer temperatures and moderate winter temperatures. A summary of the average long-term climate variables of the Otjiwarongo district is presented in Figure 3.3.

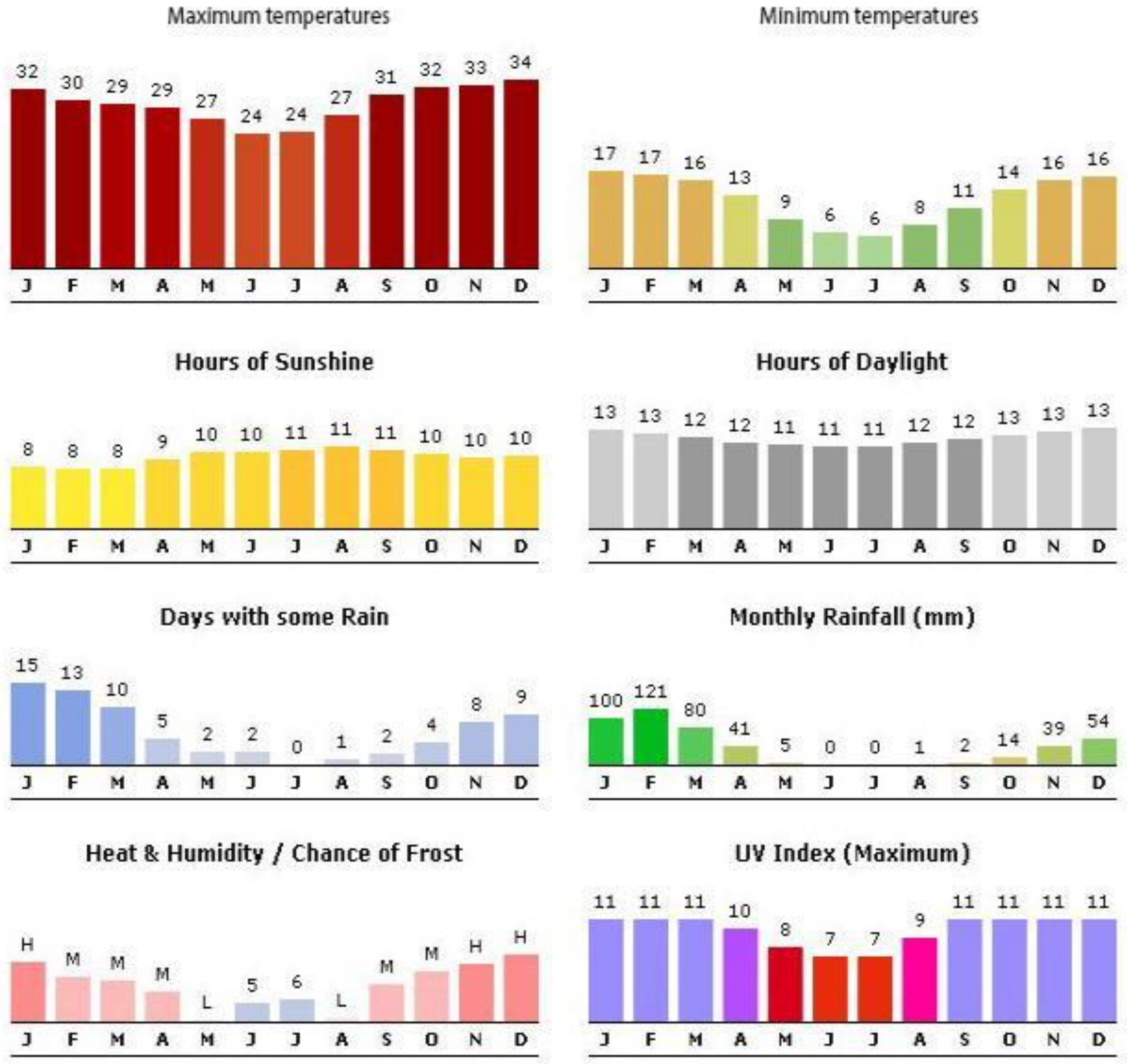


Figure 3.3 Summary of the average long-term climate variables of the Otjiwarongo district of Namibia (source: World Climate Guide).

3.2 Woody species (trees and shrubs)

3.2.1 List of woody species

A total of 30 woody species (trees and shrubs) were recorded in the survey of the woody plants in the 28 survey plots. A list of these woody species is presented in Table 3.2.

Table 3.2 Combined list of tree and shrub species recorded in all the survey plots (nomenclature and names from Mannheimer & Curtis 2009).

Scientific name	Common name (English)	Common name (Afrikaans)	Common name (German)
Family: Aizoaceae			
Phaeoptilum spinosum	Brittle-thorn	Brosdoring	-
Family: Asteraceae			
Tarchonanthus camphoratus	Camphor Bush	Kamferbos	Kampferbusch
Family: Bignoniaceae			
Catophractes alexandri	Trumpet-thorn	Ghabbabos	Gawa-Busch
Rhigozum brevispinosum	Simple-leaved rhigozum	Geelkordoring	Gelber Kurzdorn
Family: Boraginaceae			
Ehretia alba	White puzzle bush	Deurmekaarbos	Wirrstrauch
Family: Burseraceae			
Commiphora pyracanthoides	Common corkwood	-	-
Family: Capparaceae			
Boscia albitrunca	Shephard's tree	Witgat	Omunkunzi
Boscia foetida	Smelly shepherds-bush	Stinkbos	Stinkbusch
Maerua parvifolia	Small-leaved maerua	-	-
Family: Combretaceae			
Combretum apiculatum	Kudu-bush	Koedoebos	Glanzblättrige buschweide
Terminalia prunoides	Purple-pod terminalia	Deurmekaarbos	Blutfrachtbaum
Terminalia sericea	Silver cluster-leaf	Geelhout / Vaalboom	Gelbholz / Fahlbaum
Family: Fabaceae			
**Acacia erioloba*	Camel-thorn	Kameeldoring	Kameldornbaum
**Acacia erubescens*	Yellow-bark acacia	Withaak	-
**Acacia fleckii*	Sand-veld acacia	-	-
**A. hebelacada* subsp. *hebeclada*	Candle-pod acacia	Trassiebos	Kerzenakazie
**Acacia luederitzii*	Kalahari acacia	Baster kameeldoring	Lüderitz acacia
**Acacia mellifera* subs. *mellifera*	Black-thorn acacia	Swarthaak	-
**Acacia reficiens*	Red umbrella-thorn	Rooihaak	Rotrindenakazie
**Acacia senegal*	Three-hook acacia	Driehaakdoring	Dreidornakazie
**A. tortilis* subsp. *heteracantha*	Umbrella-thorn	Krulpeul	Ringelhülsenakazie
Albizia anthelmintica	Worm-cure albizia	Oumaboom	Wurmrindenbaum
Dicrostachys cinerea	Sickle-bush	Sekelbos	Farbkätzchenstrauch
Philenoptera nelsii	Kalahari apple-leaf	Appelblaar	Apfelblattbaum
Family: Rhamnaceae			
Ziziphus mucronata	Buffalo-thorn	Blinkblaar-wag-'n-bietjie	-
Family: Solanaceae			
Lycium spp.	-	-	-
Family: Tiliaceae			
Grewia flava	Velvet raisin bush	Rosyntjiebos	-
Grewia flavescens	Rough-leaved raisin bush	-	-
Grewia retinervis	Kalahari raisin bush	-	-
Grewia villosa	Malow raisin bush	Malvarosyntjie	

* The African genus *Acacia* was recently split into two genera: *Vachellia* and *Senegalia* (see Kyalangalilwa, *et al.* 2013), but for the sake of familiarity the genus name *Acacia* was retained for this report.

3.2.2 Desirability and biomass classification of the woody species

The woody species presented in Table 3.2 can broadly be divided into three groups: (i) scarce and/or desirable species not to be targeted for removal/harvesting; (ii) potential problematic species that may thicken under specific conditions, but with a low biomass potential; and (iii) potential problematic species that may thicken under specific conditions and which have a high biomass potential (Table 3.3).

Table 3.3 Broad classification of woody species based on desirability, potential to thicken and biomass potential.

Group 1 Scarce and/or desirable species	Group 2 Potential problematic species - low biomass	Group 3 Potential problematic species - high biomass
Acacia erioloba	*Grewia flava*	*Acacia erubescens*
Boscia albitrunca	*Grewia flavescens*	*Acacia fleckii*
Boscia foetida	*Grewia retinervis*	*A. hebelacada* subsp. *hebeclada*
Ehretia alba	*Grewia villosa*	*Acacia luederitzii*
Commiphora pyracanthoides	*Lycium* spp.	*Acacia mellifera* subsp. *mellifera*
Maerua parvifolia	*Catophractes alexandri*	*Acacia reficiens*
Philenoptera nelsii	*Rhigozum brevispinosum*	*Acacia senegal*
Ziziphus mucronata	*Phaeoptilum spinosum*	*A. tortilis* subsp. *heteracantha*
	Tarchonanthus camphoratus	*Dicrostachys cinerea*
	Terminalia prunoides	*Combretum apiculatum*
		Terminalia sericea

3.3 Quantification of the biomass of woody plants on selected sites

3.3.1 Procedure

At each identified survey site a standard belt transect of 50 x 2.5 m (125 m^2) was laid out in such a way as to best represent the woody vegetation of that site (Figure 3.4). In cases where the woody plants were patchy or the area not very homogeneous, the length of the transect was increased to either 75 m (188 m^2) or 100 m (250 m^2) to obtain a more accurate sampling of the vegetation (see Table 3.1). GPS coordinates were taken at the location of each transect (see Table 3.1) and several photos taken of the vegetation of the site.

The dimensions of all rooted, live woody plants (trees and shrubs) >0.5 m in height were measured (Figure 3.5) in the various belt transects according to the BECVOL 3 procedure as described in detail in section 2.2.

These measurements include the following: (i) maximum tree height, (ii) height where the maximum canopy diameter occurs, (iii) height of first leaves or potential leaf bearing stems, (iv) maximum canopy diameter, and (v) base diameter of the foliage or stem at the height of the first leaves (Figure 3.6). Since the theoretical canopy is considered circular, the maximum canopy diameter (D) was calculated as the average of two measurements rectangular to each other (D_1 & D_2) and the same principle was applied to the measurement of the base diameter of the foliage/stem (E) at the height of the first leaves (E_1 & E_2).

Woody plants <0.5 m were counted on a species basis and classified as "seedlings".

Figure 3.4 An example of a belt transect (50-100 x 2.5 m) demarcated by a tape measure and 2.5 m measuring pole.

Figure 3.5 Measurements taken of all rooted woody plants (trees and shrubs >0.5 m) in the belt transects of 50-100 x 2.5 m of each plot for analysis with the BECVOL 3-model.

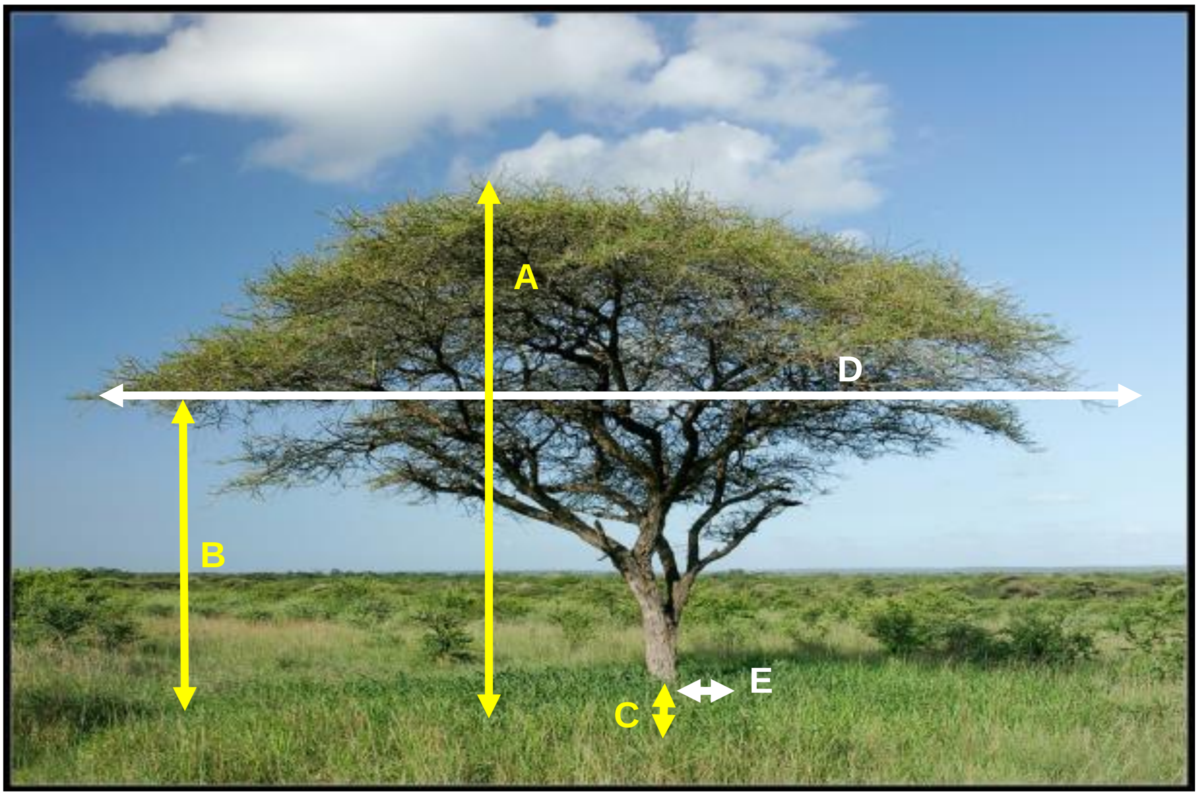


Figure 3.6 Illustration of the measurements taken of each woody plant according to the BECVOL 3-method (Smit 2014).

Values that were calculated with the BECVOL 3-model (Smit 2014) are:

i. Tree density (plants/ha)
ii. Evapotranspiration Tree Equivalents (ETTE/ha)**
iii. Leaf biomass (kg DM/ha)
iv. Shoot dry mass - shoots <0.5 cm (kg DM/ha),
v. Stem dry mass - stems >0.5-2.0 cm in diameter (kg DM/ha),
vi. Wood dry mass - wood >2.0 cm in diameter,
vii. Total wood dry mass (all fractions) (kg DM/ha), and
viii. Total tree biomass - leaves and wood combined (kg DM/ha)

** An Evapotranspiration Tree Equivalent (ETTE) is defined as the leaf volume equivalent of a 1.5 m single-stemmed tree (Smit 1989a).

3.3.2 Assessment criteria

Taking into account the ecological implications of trees in savannas, the following four aspects are considered the most important from an agro-ecological point of view (Smit 2014): (i) competition with herbaceous vegetation for soil water and nutrients; (ii) soil enrichment and creation of sub-habitats suitable for desirable grass species, (iii) food for browser and mixed-feeder herbivores (livestock, as well as wildlife), and (iv) a source of energy (firewood, charcoal, biofuel and other potential uses such as electricity generation). Add to this the whole issue of "ecological services" of woody plants in terms of carbon sequestration (Shively *et al.* 2004; Ciais *et al.* 2011) and it is clear that the negative consequences of bush thickening is only part of a much bigger picture. An appropriate conceptual model of vegetation dynamics is also an important prerequisite for effective and predictive management of Namibian rangelands (Joubert *et al.* 2008). The key to the successful implementation of the planned wood harvesting and restoration of bush thickened areas is thus to take cognisance of both the negative and positive aspects of the trees in

their specific savanna ecosystems, and how ecological processes within the total ecosystem will be influenced by drastic measures such as harvesting.

In Appendix 1 a comprehensive approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment is being presented (Smit 2004). It is important to read this paper to obtain a thorough understanding of the complexity of the problem. The abstract of the paper are presented below to provide a brief overview of the main considerations:

> Smit G.N. 2004. An approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment. J*ournal of Environmental Management* 71(2): 179-191.
>
> Due to bush encroachment the grazing capacity of large areas of the southern African savanna has declined, often to such an extent that many previously economic livestock properties are now no longer economically viable. Attempts at restoring encroached areas by the removal of some or all of the woody plants will normally result in an increase in grass production and thus also the grazing capacity. However, the results of woody plant removal may differ between vegetation types, with the outcome determined by both negative and positive responses to tree removal. The rapid establishment of tree seedlings after the removal of some or all of the mature woody plants may reduce the effective time span of restoration measures. In many cases the resultant re-establishment of new woody seedlings may in time develop into a state that is worse than the original state. This paper is an attempt to summarize existing knowledge on the importance of woody plants in savanna and explore measures, based on ecosystem dynamics, which can be utilized to restore encroached areas more successfully. It is hypothesized that a more stable environment can be created by maintaining or restoring savanna structure (large trees). In a structured savanna, large trees are able to suppress the establishment of new seedlings, while maintaining the other benefits of woody plants like soil enrichment and the provision of food to browsing herbivore species. Effective restoration of encroached areas should not be considered a once-off event, but rather a long-term commitment.

From the discussion above it is clear that the presence of woody plants in savanna ecosystems is associated with both positive and negative aspects, which are closely related to tree densities (plants/ha) and Evapotranspiration Tree Equivalents per ha (ETTE/ha). It is thus important to acknowledge that any tree harvesting program that also includes restoration of thickened areas as an objective, should prioritize selective harvesting rather than total harvesting of all woody plants.

In order to assess the severity of the bush thickening on any particular site the calculated tree densities (plants/ha) and ETTE/ha of the survey plots were used as the main criteria. The question regarding the ideal number of trees that should be retained is complex and is influenced by many considerations. The aridity of the area needs to be borne in mind since more woody plants can be retained in wet than in dry areas without affecting herbaceous yields.

In general, the average long term rainfall is a deciding factor. Based on research done elsewhere (Dye & Spear 1982; Richter *et al.* 2001; Smit 2005) as well as from general experience, a "general rule of thumb" stipulates that the median number of ETTE/ha that can be supported in a specific rainfall region without adversely affecting the grass layer, should not exceed 10x the mean annual rainfall. The reason why it is called a "general rule of thumb" is because it is not intended or even suggested to be an exact value because it is not possible to define such a value. Since the rainfall varies from season to season the tree density (in terms of ETTE/ha) where trees will negatively compete with grasses will vary from season to season. This presents a problem and the use of this "general rule of thumb" provides a practical solution. This value is thus used as a guideline only and should not be considered fixed or non-negotiable. The value of this approach is that it provided a reference point that had already been used in other areas, which makes comparisons possible.

If we assume a mean annual rainfall of 457 mm for the study area, this "general rule of thumb" implies a target figure of approximately 4 500 ETTE/ha. Anything above this figure presents a possible problem in terms of negative grass-tree competition.

Selective thinning/harvesting of woody plants will not only reduce competition between the tree- and the grass layer, but also among the remaining trees. This will result in increased growth of the remaining trees until they reach another state of equilibrium where the tree growth will stagnate/reduce due to inter-tree competition (Smith & Goodman 1986; Smit *et al.* 1996; Smit 2001). This is generally a desirable effect since this will also increase the area in which new tree seedlings will be suppressed by the larger trees (Smith & Goodman 1986; Grundy *et al.* 1994; Smit 2004). To allow for this expected increased growth of the remaining trees and to maximize the wood harvest, it may thus be justified to thin/harvest the woody plants to a density below 4 500 ETTE/ha. In this case it can be reduced to 60% of the theoretical maximum allowable ETTE/ha, which is calculated at approximately 2 700 ETTE/ha. The 60% is based on the findings of Smit (2001) who reported that the mean canopy diameter of trees increased 38 % after selective tree thinning. However, it must be noted that the suggestion of the 2 700 ETTE/ha is not absolute. It merely serves as an alternative reference for a less conservative approach to tree harvesting.

If this approach is followed it must just be noted that at this level of thinning/harvesting the remaining trees will initially provide insufficient competition to prevent woody plants from regenerating in the cleared area and additional, follow-up measures will be required to prevent this from happening. In fact, re-thickening of woody plants after the initial bush control application is the single biggest reason why so many attempts at solving the problem in Namibia have failed.

A situation may present itself where the absolute ETTE/ha value is below the critical value of 4 500, but the tree density is very high. Based on the mean equivalent ETTE-values of woody plants within the 2.0-3.0m height class (Table 3.35), the tree density of plants should not exceed 600 plants/ha. If the tree density exceeds this number, but the ETTE/ha value is below 4 500 ETTE/ha, it is often due to a large number of very small plants, which is also undesirable.

3.3.3 Results

3.3.3.1 Farm Buffelhoek (342)

The 5 000 ha farm Buffelhoek is characterized by a western section with heavier sandy-loam soil and an eastern section that is more sandy. *Dichrostachys cinerea* is a major problem on the heavier soil and the farm has a long history of attempts to combat the problem of bush thickening that goes back as early as 1988. It would appear that areas where woody plants were historically killed with a non-selective aerial application of an aboricide (tebuthurion), followed by further mechanical action to curb regrowth, now suffer from a more serious problem of bush thickening with *D. cinerea* that has now invaded large areas of land. More information is presented in Appendix 2.

BUFFELHOEK - PLOT 1 (BH1)

A comprehensive breakdown of the woody plant biomass of plot BH1 is presented in Table 3.4. The site is characterized by a dense stand of mainly *A. mellifera* and *A. luederitzii* trees of medium size (Figure 3.7). The area was aerially sprayed with an arboricide (tebuthiuron) during 1988. The tree density and ETTE/ha of the site are high (8 883 ETTE/ha) which present a problem density and will benefit from thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 3.4 m can be harvested, which will render a total wood harvest of 5 468 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 4.2 m can be harvested, which will render a total wood harvest of 9 626 kg dry wood per hectare (52.7 % of the total wood mass). There is a moderate number of seedlings (586 seedlings/ha) - notably *D. cinerea* and *C. alexandri* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.4 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site BH1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii		160	2 013	473	5 285	5 758	648	1 562	3 075
Acacia mellifera subsp. *mellifera*		479	4 637	1 088	11 094	12 182	1 447	3 439	6 208
Boscia albitrunca	53	53	6	1	3	5	1	2	1
Catophractes alexandri	213	851	844	185	799	984	151	246	401
Commiphora pyracanthoides		266	110	24	78	102	19	32	28
Dicrostachys cinerea	320	585	683	142	572	714	151	278	143
Grewia flava		266	590	108	442	550	80	129	232
Totals	**586**	**2 660**	**8 883**	**2 022**	**18 273**	**20 294**	**2 497**	**5 688**	**10 088**

Figure 3.7 View of survey site BH1 (Buffelhoek)

BUFFELHOEK - PLOT 2 (BH2)

A comprehensive breakdown of the woody plant biomass of plot BH2 is presented in Table 3.5. The site is located on deep sandy soil and is characterized by a fairly dense stand of mainly *D. cinerea, G. flavescens* and *T. sericea* trees of medium size (Figure 3.8). The area has never been treated with any arboricides, but the area was mechanically flattened with a heavy roller during 1990/91. It is believed that this mechanical action encouraged the establishment of *D. cinerea*, which should normally not be present in this type of habitat. The tree density and ETTE/ha of the site are high (9 956 ETTE/ha), which present a problem density and will benefit from thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 3.4 m can be harvested, which will render a total wood harvest of 5 340 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 3.6 m can be harvested, which will render a total wood harvest of 9 906 kg dry wood per hectare (64.3 % of the total wood mass). There is a very high number of seedlings (2 399 seedlings/ha) - notably *R. brevispinosum* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.5 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site BH2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia fleckii		53	872	206	2 628	2 833	297	730	1 601
Acacia luederitzii		106	907	212	1 525	1 736	254	572	699
Acacia mellifera subsp. *mellifera*		53	735	173	1 876	2 049	237	570	1 069
Commiphora pyracanthoides		319	182	40	141	181	31	53	57
Dicrostachys cinerea	53	532	2 072	445	3 170	3 614	575	1186	1 409
Grewia flava		53	266	52	292	344	45	70	177
Grewia flavescens	53	479	1 569	299	1 483	1 781	240	382	860
Rhigozum brevispinosum	2 293	479	333	75	126	200	44	72	10
Terminalia sericea		638	3 019	701	4 176	4 877	772	1 680	1 724
Totals	**2 399**	**2 713**	**9 956**	**2 201**	**15 416**	**17 617**	**2 495**	**5 315**	**7 606**

Figure 3.8 View of survey site BH2 (Buffelhoek)

3.3.3.2 *Farm Tokai (348)*

The farm Tokai with a size of 12 000 ha that also includes the farms Knoll and Randveld section 1, is quite diverse in terms of soil and woody species. It is also one of the farms where tree harvesting for charcoal production is still actively taking place. Unlike Buffelhoek, *Dichrostachys cinerea* is not a major problem, but *Grewia* species (*G. flava* and *G. flavescens*) have invaded large areas of land where larger trees (mainly *Acacia* species) were selectively harvested for charcoal production. More information is presented in Appendix 2.

TOKAI - PLOT 1 (TK1)

A comprehensive breakdown of the woody plant biomass of plot TK1 is presented in Table 3.6. The site is located on heavier soil and is characterized by medium sized *A. luederitzii* trees and a high density of *G. flava* and *G. flavescens* that form dense bush clumps in places (Figure 3.9). The tree density and ETTE/ha of the site are medium high (6 163 ETTE/ha), which present a moderate problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 2.2 m can be harvested, which will render a total wood harvest of only 936 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 3.6 m can be harvested, which will render a total wood harvest of 2 809 kg dry wood per hectare (27.5 % of the total wood mass). There is a moderate number of seedlings (478 seedlings/ha) - notably *A. luedertzii* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.6 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site TK1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii	266	426	3 979	932	8 532	9 464	1 188	2 770	4 575
Acacia mellifera subsp. *mellifera*	53								
Boscia albitrunca	106	53	3	1	1	2	0	1	0
Commiphora pyracanthoides		53	22	5	15	20	4	6	5
Dicrostachys cinerea	53	53	39	8	18	25	6	10	1
Grewia flava		372	908	169	769	938	130	208	432
Grewia flavescens		532	1 187	216	849	1 064	157	254	438
Maerua parvifolia		106	26	6	16	21	4	7	4
Totals	**478**	**1 596**	**6 163**	**1 335**	**10 200**	**11 535**	**1 489**	**3 257**	**5 455**

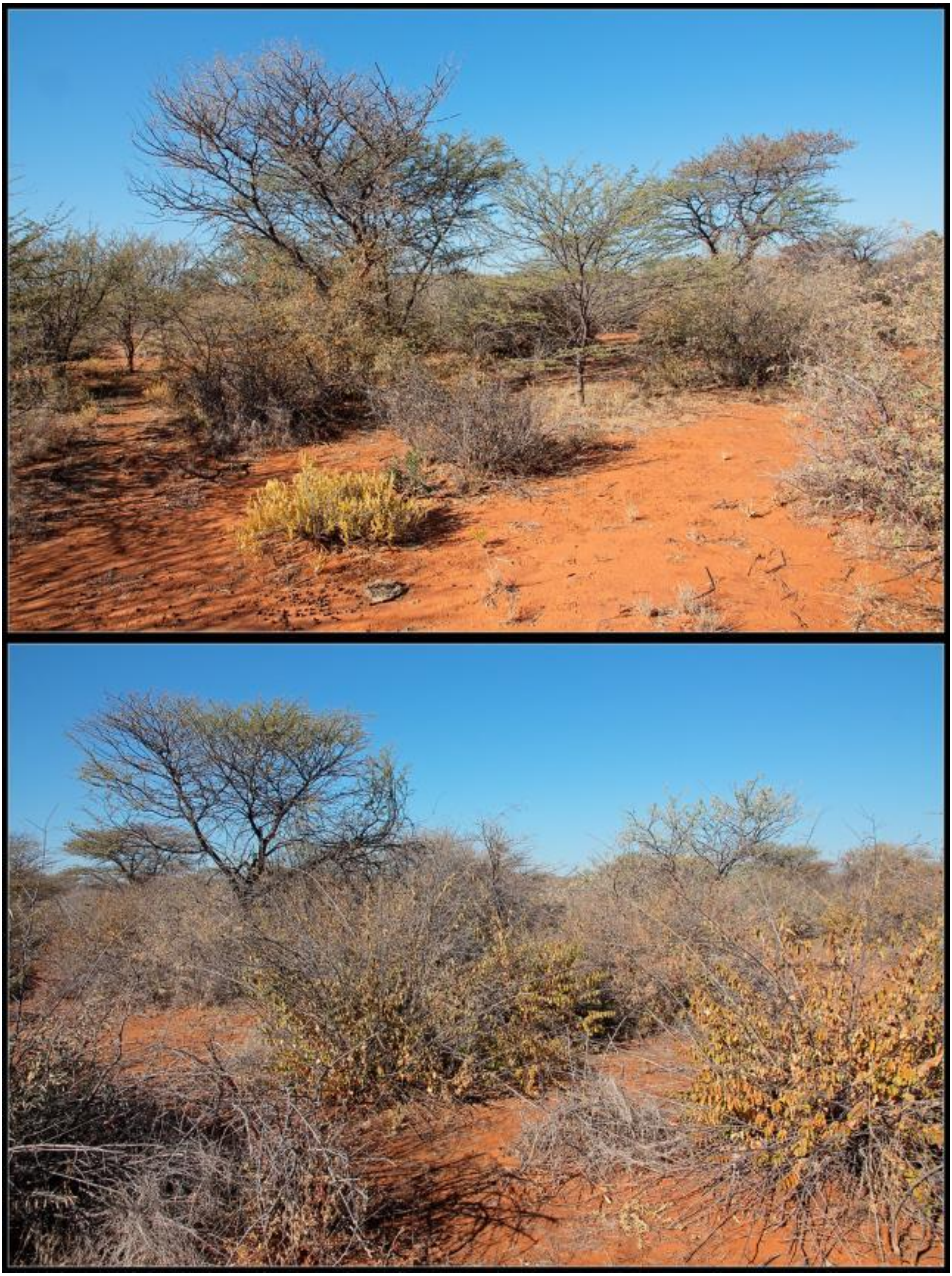


Figure 3.9 View of survey site TK1 (Tokai)

This site is a classic example of an area with an ETTE/ha-value that exceeds the critical value for negative grass-tree competition, but with very low biomass due to the dominance of species such as *Grewia* species with a low biomass potential. Most of the biomass is located in the few *A. luederitzii* trees, which at these densities should ideally be retained during harvesting.

TOKAI - PLOT 2 (TK2)

A comprehensive breakdown of the woody plant biomass of plot TK2 is presented in Table 3.7. The site is very similar to TK1, but with a higher tree density. A characteristic feature of this plot is the large *A. luederitzii* trees (up to 5.6 m in height), which account for the very high wood biomass (70 376 kg DM/ha) of this site. Similar to plot TK1 there is a high density of *G. flava* and *G. flavescens* that form dense bush clumps in places (Figure 3.10). The tree density and ETTE/ha of the site are very high (13 939 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 6.0 m can be harvested, which will render a total wood harvest of 28 522 kg dry wood per hectare (40.5 % of the total wood mass). Due to the size of the trees, it is not recommended to harvest beyond this target. There is a high number of seedlings (1 358 seedlings/ha) - notably *G. flava* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.7 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site TK2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia fleckii		160	236	53	124	177	39	17	69
Acacia luederitzii	213	532	10 559	2 512	66 901	69 414	4 295	51 028	11 578
Acacia mellifera subsp. *mellifera*		160	612	143	1 208	1 351	178	618	412
Albizia anthelmintica	160	106	29	6	18	25	5	5	8
Boscia albitrunca	160	53	4	1	2	3	1	0	1
Commiphora pyracanthoides		53	28	6	20	26	5	7	8
Dicrostachys cinerea	160	213	120	24	56	80	20	5	32
Ehretia alba	106	106	14	3	8	11	2	2	4
Grewia flava	453	532	642	112	392	505	76	192	125
Grewia flavescens	106	532	1 113	201	765	966	144	387	234
Maerua parvifolia		106	71	15	57	72	12	24	20
Philenoptera nelsii		160	512	119	823	942	138	377	308
Totals	**1 358**	**2 713**	**13 939**	**3 197**	**70 376**	**73 574**	**4 915**	**5 2662**	**12 799**

Figure 3.10 View of survey site TK2 (Tokai)

TOKAI - PLOT 3 (TK3)

A comprehensive breakdown of the woody plant biomass of plot TK3 is presented in Table 3.8. The site is located on shallower soil with underlying limestone and is characterized by medium sized *A. luederitzii* and *A. mellifera* trees and an abundance of *G. flavescens* and *Catophractes alexandri* (Figure 3.11). The tree density and ETTE/ha of the site are medium high (7 664 ETTE/ha), which present a moderate problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 3.5 m can be harvested, which will render a total wood harvest of 3 492 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 4.0 m can be harvested, which will render a total wood harvest of 5 867 kg dry wood per hectare (31.0 % of the total wood mass). There is a very large number of seedlings (4 840 seedlings/ha) - notably *A. luederitzii* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.8 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site TK3

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia hebelcada subsp. *hebeclada*		40	505	119	1 184	1 302	159	376	649
Acacia luederitzii	2 760	480	3 619	850	11 121	11 972	1 178	2 886	7 057
Acacia mellifera subsp. *mellifera*	240	280	2 186	512	5 221	5 734	670	1 589	2 962
Albizia anthelmintica		120	381	84	572	656	73	113	386
Boscia albitrunca	40								
Catophractes alexandri	120	240	106	23	81	104	18	31	32
Commiphora pyracanthoides		40	5	1	3	4	1	1	1
Dicrostachys cinerea	560	80	31	6	12	18	5	7	1
Ehretia alba		40	18	4	12	16	3	5	4
Grewia flava		80	166	30	109	139	21	34	54
Grewia flavescens	840	280	646	121	587	708	95	152	340
Lycium spp.	160								
Maerua parvifolia	120								
Totals	**4 840**	**1 680**	**7 664**	**1 751**	**18 903**	**20 654**	**2 224**	**5 194**	**11 485**

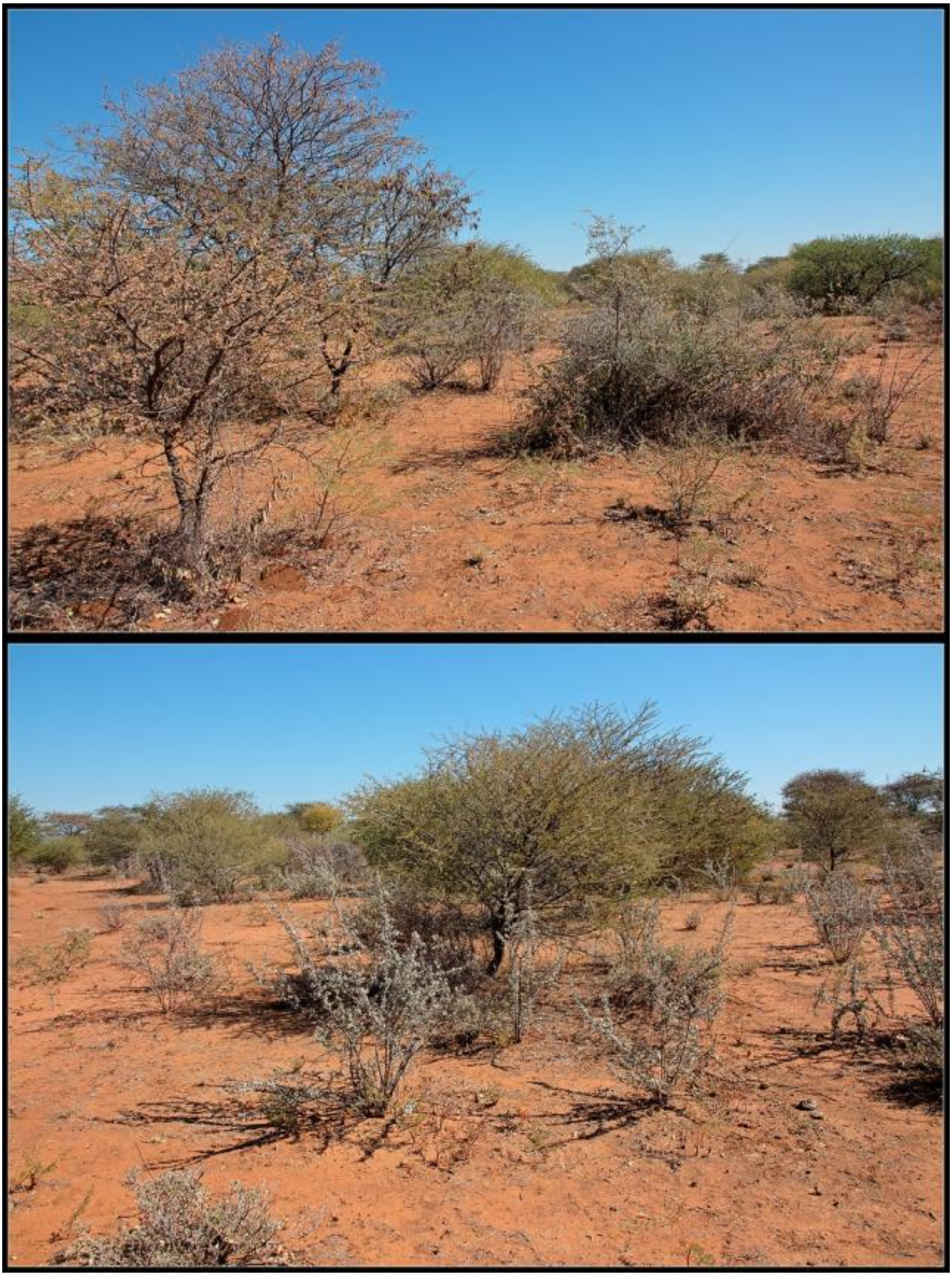


Figure 3.11 View of survey site TK3 (Tokai)

TOKAI - PLOT 4 (TK4)

A comprehensive breakdown of the woody plant biomass of plot TK4 is presented in Table 3.9. The site is located on sandy soil. The area was previously used for the selective harvesting of trees for charcoal production. It has since been invaded by *G. flava* and *G. flavescens* that form very dense, almost impenetrable, bush clumps (Figure 3.12). The tree density and ETTE/ha of the site are high (8 585 ETTE/ha), which present a problem density.

This site is another classic example of an area with an ETTE/ha-value that exceeds the critical value for negative grass-tree competition, but with a relatively low biomass due to the dominance of species such as *G. flava* and *G. flavescens* with a low biomass potential. Since this is a disturbed area it is recommended that the *Grewia* species be targeted for harvesting (all size classes), while all individuals of the few other species should be retained. This will render a total wood harvest of 9 561 kg dry wood per hectare. Since the area is currently of little value due to a lack of grazing, drastic measures are required to restore it as productive rangeland again. There is not a large number of seedlings (240 seedlings/ha), but due to the suggested high intensity of harvesting, an aftercare programme will be essential to prevent rapid re-thickening by aggressive and invasive woody species.

Table 3.9 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site TK4

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia fleckii		80	199	46	139	185	38	73	28
Boscia albitrunca	240	400	58	13	34	47	9	17	8
Commiphora pyracanthoides		400	216	47	156	203	37	62	57
Grewia flava		1 120	6 015	1 204	7 793	8 998	1 084	1 685	5 024
Grewia flavescens		640	2 097	394	1 768	2 162	306	491	970
Totals	**240**	**2 640**	**8 585**	**1 704**	**9 890**	**11 594**	**1 475**	**2 328**	**6 087**

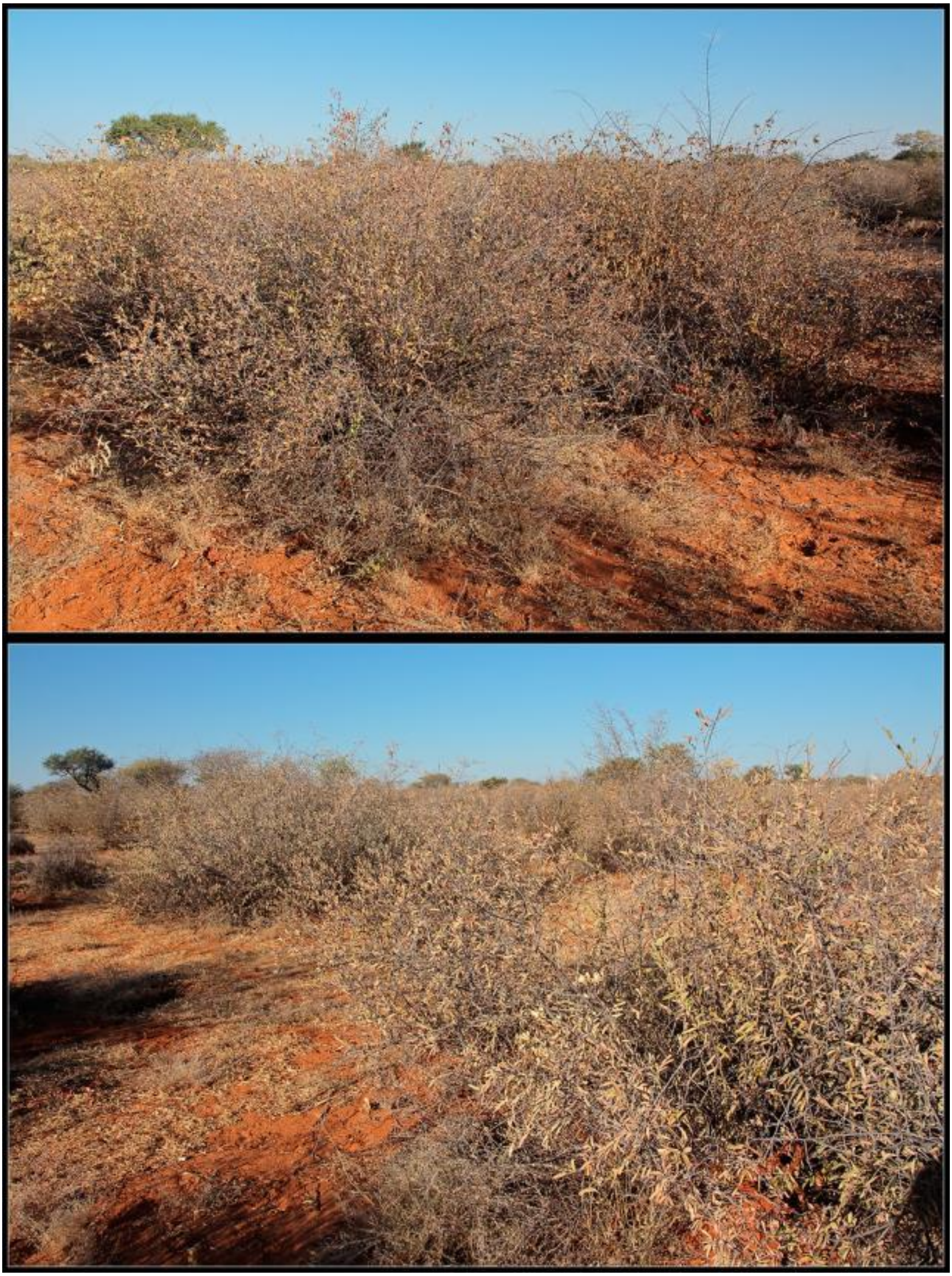


Figure 3.12 View of survey site TK4 (Tokai)

3.3.2.3 Farm Waverley (347)

The 7 000 ha farm Waverley is characterized by a western section with heavier soil and an eastern section that is more sandy. Various attempts at bush control were applied on different sections of the farm. It was noted that bush thickening is more likely on the heavier soil, and these areas also support a much higher wood biomass due to the abundance of species with a high biomass potential (*Acacia* species). From a grazing point of view the heavier soil is also valued higher by the farm owner due to the higher palatability of grasses on this soil type. On the sandy soil, species such as *Terminalia sericea* are browsed by cattle. More information is presented in Appendix 2.

WAVERLEY - PLOT 1 (WV1)

A comprehensive breakdown of the woody plant biomass of plot WV1 is presented in Table 3.10. The site is located on deep sandy soil and is characterized by *Philenoptera nelsii* and *T. sericea* trees of medium size (Figure 3.13). The area has never been treated with any arboricides. The tree density and ETTE/ha of the site are high (8 643 ETTE/ha), which present a problem density, though the farmer does not consider it a problem due to the value of the trees as a browse resource.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 1.9 m can be harvested, which will render a total wood harvest of only 1 887 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 3.0 m can be harvested, which will render a total wood harvest of 4 269 kg dry wood per hectare (35.4 % of the total wood mass). There are a moderate number of seedlings (640 seedlings/ha) - notably *R. brevispinosum* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.10 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site WV1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Boscia albitrunca		160	28	6	17	23	5	8	4
Commiphora pyracanthoides		640	295	65	223	287	50	85	87
Dicrostachys cinerea		240	140	28	61	89	23	35	4
Ehretia alba		80	11	2	6	9	2	3	1
Grewia flava		560	2 136	409	2 006	2 415	330	525	1 151
Grewia flavescens	80	240	1 232	243	1 379	1 621	209	328	842
Philenoptera nelsii		560	2 007	470	5 754	6 223	626	1 521	3 607
Rhigozum brevispinosum	560	1 520	1434	324	704	1 028	221	384	100
Tarchonanthus camphoratus		160	148	32	119	151	26	43	50
Terminalia sericea		160	1 212	267	1 779	2 046	233	358	1 188
Totals	**640**	**4 320**	**8 643**	**1 845**	**12 048**	**13 892**	**1 724**	**3 290**	**7 034**

.

Figure 3.13 View of survey site WV1 (Waverley)

WAVERLEY - PLOT 2 (WV2)

A comprehensive breakdown of the woody plant biomass of plot WV2 is presented in Table 3.11. The site is also located on deep sandy soil and is characterized by a dominance of *T. sericea* trees of medium size (Figure 3.14). It is very similar to plot WV1 and the area has also never been treated with any arboricides. The tree density and ETTE/ha of the site are high (10 595 ETTE/ha), which present a problem density, though the farmer does not consider it a problem due to the value of the trees as a browse resource.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 2.8 m can be harvested, which will render a total wood harvest of only 2 542 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 3.0 m can be harvested, which will render a total wood harvest of 6 010 kg dry wood per hectare (47.0 % of the total wood mass). There are a low number of seedlings (160 seedlings/ha) but any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.11 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site WV2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		80	1 166	274	3 132	3 406	382	926	1 823
Commiphora pyracanthoides		320	246	54	206	260	43	72	91
Dicrostachys cinerea	80	80	18	3	5	9	2	3	0
Grewia flava		80	121	21	62	83	13	22	27
Grewia flavescens		960	3 218	610	2 936	3 546	485	773	1 679
Rhigozum brevispinosum	80	240	93	21	28	48	11	16	1
Tarchonanthus camphoratus		160	241	53	218	271	43	70	105
Terminalia sericea		1 760	5 492	1 207	6 210	7 417	1 016	1 613	3 581
Totals	**160**	**3 680**	**10 595**	**2 243**	**12 797**	**15 040**	**1 996**	**3 495**	**7 307**

Figure 3.14 View of survey site WV2 (Waverley)

WAVERLEY - PLOT 3 (WV3)

A comprehensive breakdown of the woody plant biomass of plot WV3 is presented in Table 3.12. The site is located on heavier soil with a dominance of *Acacia* species and the absence of *T. sericea*. A characteristic feature of this plot is the large *A. luederitzii* and *A. reficiens* trees (up to 4.7 m in height), which account for the higher wood biomass (30 275 kg DM/ha) of this site. *G. flava* and *G. flavescens* form bush clumps in places (Figure 3.15). The tree density and ETTE/ha of the site are very high (15 937 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 4.5 m can be harvested, which will render a total wood harvest of 10 516 kg dry wood per hectare (34.7 % of the total wood mass). Due to the size of the trees it is not recommended to harvest beyond this target. There is a moderate number of seedlings (800 seedlings/ha) - notably *G. flavescens* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.12 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site WV3

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		960	6 872	1 607	15 679	17 286	2 040	4 785	8 854
Acacia reficiens		960	6 065	1 415	11 688	13 103	1 714	3 925	6 049
Albizia anthelmintica		160	833	184	1 277	1 461	161	246	870
Boscia albitrunca	320	80	43	9	31	41	7	13	11
Dicrostachys cinerea		80	30	6	11	17	4	6	0
Ehretia alba		160	46	10	31	41	8	13	10
Grewia flava	80	480	984	177	648	825	125	204	320
Grewia flavescens	480	320	1 064	200	909	1 110	156	250	502
Totals	**880**	**3 200**	**15 937**	**3 608**	**30 275**	**33 882**	**4 215**	**9 442**	**16 617**

Figure 3.15 View of survey site WV3 (Waverley)

WAVERLEY - PLOT 4 (WV4)

A comprehensive breakdown of the woody plant biomass of plot WV4 is presented in Table 3.13. The site is also located on heavier soil with a dominance of *Acacia* species and and the absence of *T. sericea*. A characteristic feature of this plot is the widely spaced *A. luederitzii* and *A. reficiens* trees of medium size (Figure 3.16). The few established *D. cinerea* plants all appear to be dead, probably due to cold. The tree density and ETTE/ha of the site (4 314 ETTE/ha) is below the threshold value of 4 500 ETTE/ha.

Based on a target of 4 500 ETTE/ha (see section 3.3.2) there is no wood to be harvested. Based on a target of 2 700 ETTE/ha woody, plants of the designated groups up to 3.5 m can be harvested, which will render a total wood harvest of only 1 519 kg dry wood per hectare (13.6 % of the total wood mass). There is a moderate number of seedlings (720 seedlings/ha) - notably *Acacia* species and also *D. cinerea* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.13 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site WV4

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*	160	80	1 609	381	5 947	6 328	582	1 472	3 893
Acacia reficiens	160	320	2 378	556	4 998	5 554	694	1 609	2 695
Albizia anthelmintica		80	19	4	12	16	3	5	3
Boscia albitrunca	160								
Dischrostachys cinerea	160								
Grewia flava	80	160	309	57	253	310	44	70	139
Totals	**720**	**640**	**4 314**	**998**	**11 210**	**12 208**	**1 322**	**3 157**	**6 730**

Figure 3.16 View of survey site WV4 (Waverley)

WAVERLEY - PLOT 5 (WV5)

A comprehensive breakdown of the woody plant biomass of plot WV5 is presented in Table 3.14. The site is located on heavier soil with a dominance of *Acacia* species. A characteristic feature of this plot is the very large *A. luederitzii* trees (up to 7.2 m in height), which account for the exceptionally high wood biomass (119 585 kg DM/ha) of this site. *G. flava* and *G. flavescens* form bush clumps in places (Figure 3.17). The tree density and ETTE/ha of the site are very high (13 689 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 7.2 m can be harvested, which will render a total wood harvest of 47 468 kg dry wood per hectare (39.7 % of the total wood mass). Due to the size of the trees it is not recommended to harvest beyond this target. There is a moderate number of seedlings (800 seedlings/ha) - notably *Grewia* species - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.14 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site WV5

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii		400	12 495	2 991	118 696	121 686	5 648	15 959	97 089
Albizia anthelmintica	240								
Boscia albitrunca	80								
Ehretia alba	160	160	27	6	16	22	4	8	4
Grewia flava	160	400	907	169	750	919	130	208	412
Grewia flavescens	160	160	173	30	94	124	20	32	42
Lycium spp.		80	55	12	20	32	7	11	1
Phaeoptilum spinosum		80	31	7	9	16	3	5	0
Totals	**800**	**1 280**	**13 689**	**3 215**	**119 585**	**122 799**	**5 812**	**16 224**	**97 549**

Figure 3.17 View of survey site WV5 (Waverley)

3.3.3.4 Farm Knoll (201)

This farm is also owned by Mr J.L. Botha and thus forms part of Tokai.

KNOLL - PLOT 1 (KN1)

A comprehensive breakdown of the woody plant biomass of plot KN1 is presented in Table 3.15. The site is located on sandy soil as indicated by the presence of *A. fleckii.* The site has a diverse species composition with *A. mellifera* the dominant species. The area has never been treated with any arboricides and bush thickening is not a serious problem as indicated by an ETTE/ha value 4 728 that is marginally above the threshold value of 4 500 ETTE/ha (Figure 3.18).

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 1.9 m can be harvested, which will render a total wood harvest of only 50 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha woody plants of the designated groups up to 3.5 m can be harvested, which will render a total wood harvest of only 1 556 kg dry wood per hectare (14.7 % of the total wood mass). There is a low number of seedlings (478 seedlings/ha) - notably *D. cinerea* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.15 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site KN1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia fleckii		53	454	106	756	862	127	285	344
Acacia hebelcada subsp. *hebeclada*	53	53	150	34	113	147	30	58	25
Acacia luederitzii	53	53	17	4	5	8	2	3	0
Acacia mellifera subsp. *mellifera*		319	3 605	847	9 271	10 118	1 144	2 743	5 385
Albizia anthelmintica	160	53	29	6	21	28	5	9	8
Boscia albitrunca	53	106	30	7	20	27	5	9	6
Dicrostachys cinerea	106	106	197	41	176	217	46	86	43
Lycium spp.	53								
Phaeoptilum spinosum		53	82	19	44	63	14	24	6
Ziziphus mucronata		53	163	36	178	214	30	48	100
Totals	**478**	**851**	**4 728**	**1 100**	**10 583**	**11 683**	**1 402**	**3 264**	**5 917**

Figure 3.18 View of survey site KN1 (Knoll)

KNOLL - PLOT 2 (KN2)

A comprehensive breakdown of the woody plant biomass of plot KN2 is presented in Table 3.16. The site is located on heavier soil with a dominance of *Acacia* species. A characteristic feature of this plot is the high density of very large *A. mellifera* trees (up to 5.4 m in height), as well as a few very large *A. reficiens* trees, which account for the exceptionally high wood biomass (190 942 kg DM/ha) (Figure 3.17). The tree density and ETTE/ha of the site are very high (25 143 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 7.0 m can be harvested, which will render a total wood harvest of 53 760 kg dry wood per hectare (28.2 % of the total wood mass). Due to the size of the trees it is not recommended to harvest beyond this target. There is a low number of seedlings (240 seedlings/ha), but an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species is still recommended.

Table 3.16 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site KN2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		1 200	16 126	3 801	51 299	55 101	5 481	13 556	32 262
Acacia reficiens	80	320	8 572	2 061	139 417	141 478	4 321	12 969	12 2127
Boscia albitrunca		80	6	1	3	4	1	2	1
Catophractes alexandri		240	57	12	36	48	9	16	10
Commiphora pyracanthoides		320	118	26	80	106	20	34	27
Grewia flava		160	79	12	22	34	6	10	6
Grewia flavescens	160	160	187	31	85	116	19	32	34
Totals	**240**	**2 480**	**25 143**	**5 946**	**190 942**	**196 888**	**9 857**	**2 6619**	**154 466**

Figure 3.19 View of survey site KN2 (Knoll)

3.3.3.5 Farm Randveld (167)

As the name of the farm indicates, the 4 000 ha farm Randveld is characterized by rocky ridges with very shallow soil. There are, however, low lying areas with deeper and heavier soil, as well as sandy sections. Since 2009 various attempts at bush control were applied on different sections of the farm. Currently no trees are harvested for charcoal production, but there are such plans for this in the near future. More information is presented in Appendix 2.

RANDVELD - PLOT 1 (RV1)

A comprehensive breakdown of the woody plant biomass of plot RV1 is presented in Table 3.17. The site is located on sandy soil with a dominance of *Acacia* species. The area has never been treated with any arboricides. A characteristic feature of this plot is the high density of very large *A. mellifera* trees (up to 6.0 m in height), which account for the very higher wood biomass (97 675 kg DM/ha) (Figure 3.20). The tree density and ETTE/ha of the site are very high (19 772 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 5.5 m can be harvested, which will render a total wood harvest of 30 571 kg dry wood per hectare (31.3 % of the total wood mass). Due to the size of the trees it is not recommended to harvest beyond this target. There is a low number of seedlings (159 seedlings/ha), but an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species is still recommended.

Table 3.17 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site RV1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii	106	106	2 117	502	10 309	10 811	808	2 111	7 390
Acacia mellifera subsp. *mellifera*	53	745	15 563	3 695	82 558	86 253	6 054	15 958	60 546
Acacia reficiens		53	1 116	264	4309	4 573	409	1 040	2 860
Grewia flava		798	938	161	486	647	103	171	213
Grewia flavescens		53	39	6	13	20	3	6	4
Totals	**159**	**1 755**	**19 772**	**4 629**	**97 675**	**102 303**	**7 377**	**19 285**	**71 013**

Figure 3.20 View of survey site RV1 (Randveld)

RANDVELD - PLOT 2 (RV2)

A comprehensive breakdown of the woody plant biomass of plot RV2 is presented in Table 3.18. The site is located on a rocky ridge with very shallow soil and is characterized by a dense stand of mainly *A. mellifera* and *A. reficiens* trees of medium size (Figure 3.21). The area has never been treated with any arboricides, but was previously mechanically cleared with a bulldozer. It is believed that this mechanical action encouraged the development of a very dense stand of woody plants, yet with a relatively low wood biomass. The tree density and ETTE/ha of the site are very high (14 415 ETTE/ha), which present a problem density and will benefit from thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 3.5 m can be harvested, which will render a total wood harvest of 10 588 kg dry wood per hectare (57.0 % of the total wood mass). In order to preserve the few larger trees, it is not recommended to harvest beyond this target. There were no seedlings observed, but an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species is still recommended.

Table 3.18 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site RV2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		1 600	6 869	1 589	8 444	10 032	1 658	3 522	3 265
Acacia reficiens		800	4 753	1 107	8 144	9 251	1 297	2 917	3 930
Acacia senegal		80	70	16	28	44	10	16	2
Boscia foetida		480	401	88	321	409	70	116	135
Ehretia alba		80	6	1	3	4	1	2	1
Grewia flava		800	1 426	253	887	1 140	174	286	426
Grewia flavescens		240	834	158	732	890	124	199	409
Lycium spp.		80	57	13	21	34	8	12	2
Totals	**0**	**4 160**	**14 415**	**3 225**	**18 581**	**21 805**	**3 342**	**7 070**	**8 169**

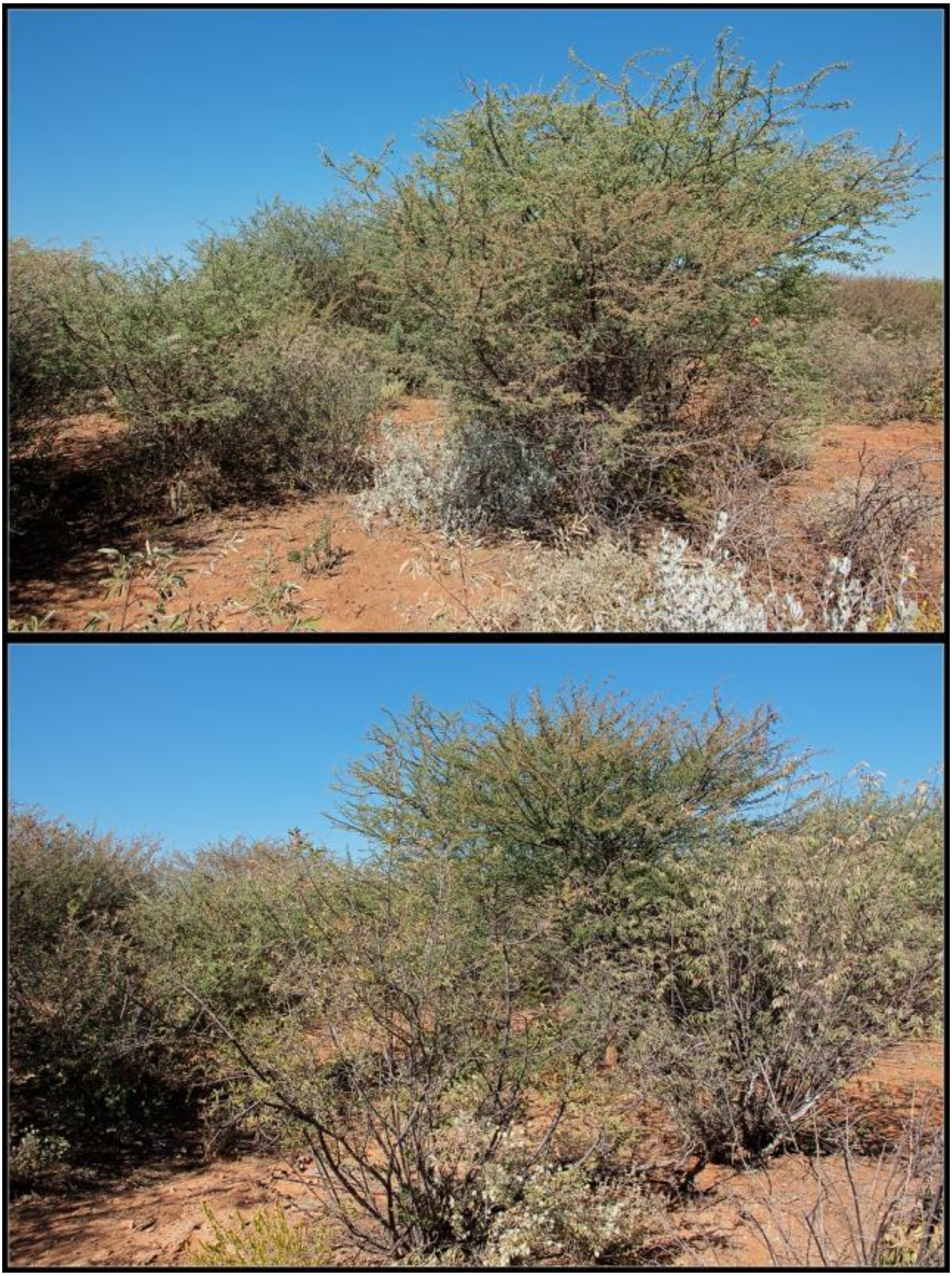


Figure 3.21 View of survey site RV2 (Randveld)

RANDVELD - PLOT 3 (RV3)

A comprehensive breakdown of the woody plant biomass of plot RV3 is presented in Table 3.19. The site is located on shallower soil with underlying limestone and is characterized by medium sized *A. mellifera* trees and some *Catophractes alexandri* (Figure 3.22). The area was previously flattened with a heavy roller. The tree density and ETTE/ha of the site are slightly high (5 283 ETTE/ha), which present a moderate problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 1.0 m can be harvested, which will render a total wood harvest of only 451 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 2.6 m can be harvested, which will render a total wood harvest of only 2 475 kg dry wood per hectare (33.9 % of the total wood mass). There is a low number of seedlings (373 seedlings/ha) - notably *A. mellifera* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.19 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site RV3

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia hebelcada subsp. *hebeclada*		106	128	29	68	97	21	37	10
Acacia mellifera subsp. *mellifera*	213	904	4 971	1 155	7 125	8 281	1 294	2 834	2 997
Catophractes alexandri		106	21	5	13	18	4	6	4
Dicrostachys cinerea	160	160	54	11	19	29	8	11	1
Grewia flava		53	108	19	66	85	13	22	31
Totals	**373**	**1 330**	**5 283**	**1 219**	**7 291**	**8 510**	**1 339**	**2 910**	**3 043**

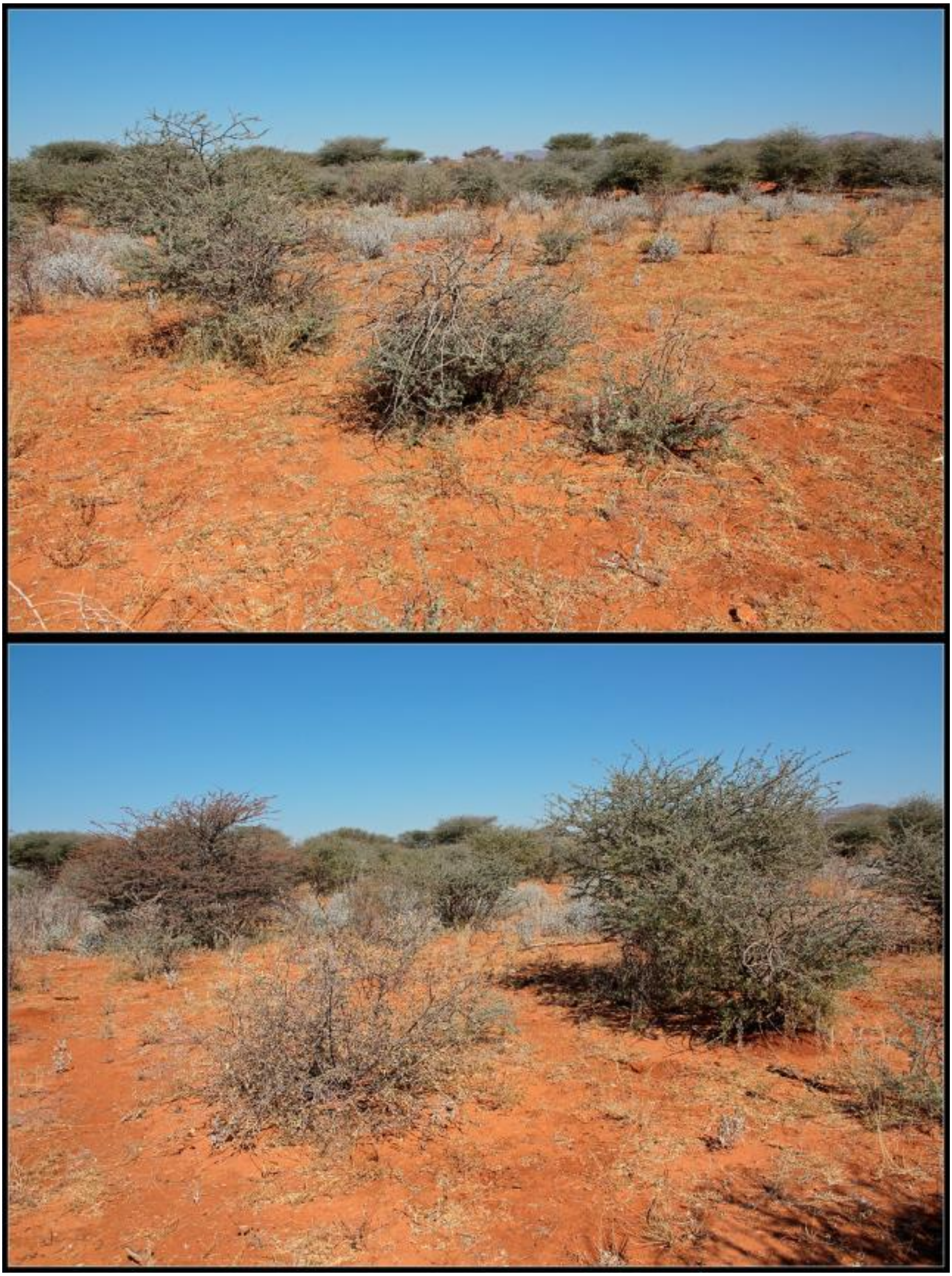


Figure 3.22 View of survey site RV3 (Randveld)

3.3.3.6 Farm Arcadia (320)

The farm Arcadia that includes the farm Paresis has a combined size of 10 000. The area is quite diverse in terms of soil and topography. It ranges from rugged terrain on granite of the Paresis Mountain to flat areas with deeper and heavier soil, as well as sandy sections. In the past the farm was heavily stocked with goats. Various attempts at bush control were applied at different times, and parts of the farm were used for charcoal production. The grazing on the farm is extremely limited and according to the farmer the cattle rely on the leaves of *Grewia flava* for survival. More information is presented in Appendix 2.

ARCADIA - PLOT 1 (AR1)

A comprehensive breakdown of the woody plant biomass of plot AR1 is presented in Table 3.20. The site is located on shallower soil with underlying limestone and is characterized by medium sized *A. reficiens* trees and *Grewia flava* (Figure 3.23). The area has never been treated with any arboricides. The tree density and ETTE/ha of the site are high (10 138 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 4.0 m can be harvested, which will render a total wood harvest of 4 750 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 4.3 m can be harvested, which will render a total wood harvest of 10 655 kg dry wood per hectare (41.3 % of the total wood mass). There is a very large number of seedlings (2 345 seedlings/ha) - notably *A. reficiens* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.20 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site AR1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		53	16	4	4	8	2	2	0
Acacia reficiens	1 973	638	6 411	1 511	22 324	23 835	2 196	5 476	14 652
Acacia senegal		106	166	38	94	132	28	51	15
Albizia anthelmintica	53	106	442	97	612	709	84	130	397
Boscia albitrunca		106	45	10	34	44	8	13	14
Commiphora pyracanthoides		53	11	2	6	9	2	3	2
Dicrostachys cinerea	53	319	274	55	143	198	49	80	14
Grewia flava	53	638	2 198	421	2 173	2 594	345	546	1 283
Grewia flavescens	213	426	576	103	410	514	74	120	216
Totals	**2 345**	**2 447**	**10 138**	**2 242**	**25 800**	**28 042**	**2 787**	**6 421**	**16 592**

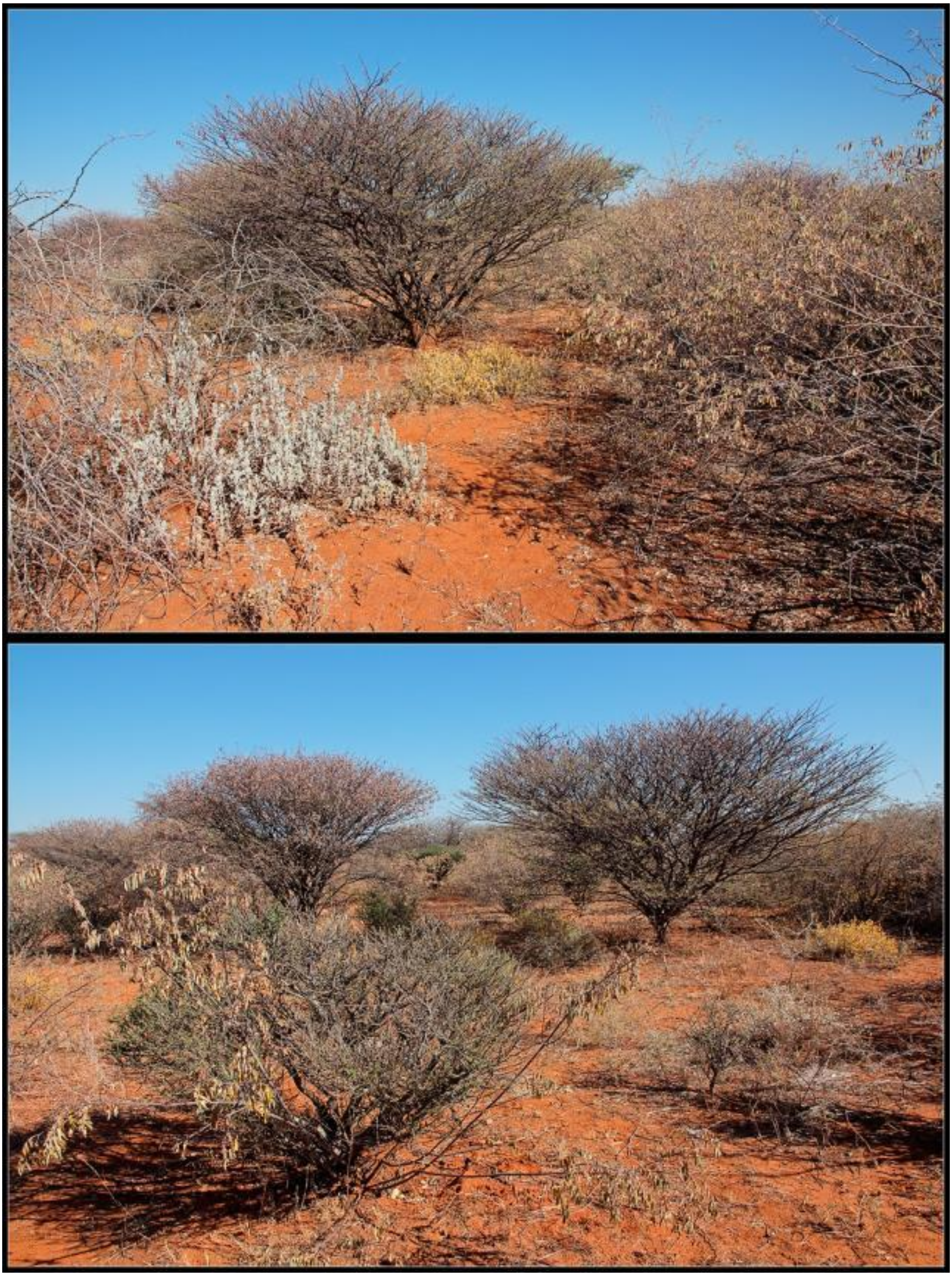


Figure 3.23 View of survey site AR1 (Arcadia)

ARCADIA - PLOT 2 (AR2)

A comprehensive breakdown of the woody plant biomass of plot AR2 is presented in Table 3.21. The site is located on shallower soil with underlying limestone and is similar to plot AR1. It has an interesting history as it is located in a fenced plot of 2 ha that was completely cleared during 1964 and then left untouched. It is now dominated by *A. mellifera* and *Grewia flava* (Figure 3.23). The tree density and ETTE/ha of the site are higher than plot AR1, but with a lower tree biomass (10 138 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 3.1 m can be harvested, which will render a total wood harvest of 5 545 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 3.6 m can be harvested, which will render a total wood harvest of 7 801 kg dry wood per hectare (40.0 % of the total wood mass). There is a small number of seedlings (400 seedlings/ha), but an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species is still recommended.

Table 3.21 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site AR2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		640	5 620	1 318	12 746	14 064	1 730	4 082	6 935
Acacia reficiens		160	927	216	1 575	1 791	255	574	747
Albizia anthelmintica	160	320	508	111	465	577	91	148	226
Commiphora pyracanthoides		240	54	12	34	45	9	16	9
Dicrostachys cinerea		560	854	177	732	909	189	347	196
Grewia flava	240	1 120	3 634	702	3 950	4 653	590	929	2 431
Totals	**400**	**3 040**	**11 598**	**2 537**	**19 503**	**22 040**	**2 863**	**6 096**	**10 544**

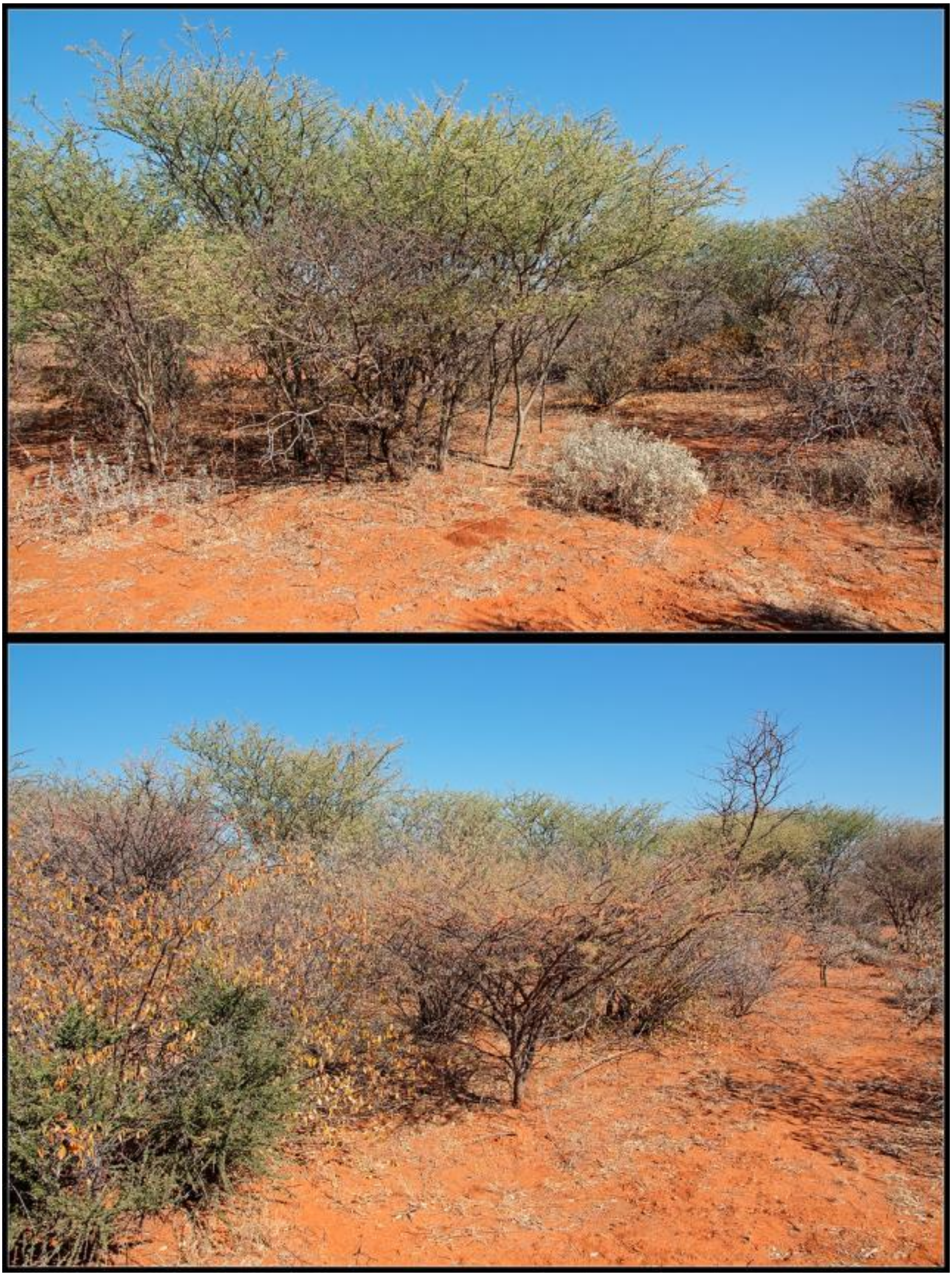


Figure 3.24 View of survey site AR2 (Arcadia)

ARCADIA - PLOT 3 (AR3)

A comprehensive breakdown of the woody plant biomass of plot AR3 is presented in Table 3.22. The site is located on shallow, rocky soil and is characterized by a dense stand of small *A. reficiens* and *A. senegal* trees of similar size, as well as *G. flava* (Figure 3.25). The area has never been treated with any arboricides. The tree density and ETTE/ha of the site are high (9 599 ETTE/ha), which present a problem density that will benefit from some thinning. Despite the high tree density, the wood biomass is comparatively low due to the small size of the trees.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 2.6 m can be harvested, which will render a total wood harvest of 3 725 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 3.0 m can be harvested, which will render a total wood harvest of 5 093 kg dry wood per hectare (46.4 % of the total wood mass). No seedlings were observed, but an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species is still recommended.

Table 3.22 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site AR3

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		80	136	31	77	108	23	42	12
Acacia reficiens		640	3 074	713	4 172	4 885	773	1 674	1 725
Acacia senegal		560	3 207	745	4 363	5 108	821	1 783	1 760
Ehretia alba		400	64	14	38	52	10	18	10
Grewia flava		1 200	2 359	424	1 553	1 976	298	486	768
Grewia flavescens		80	236	44	183	227	33	53	97
Grewia villosa		80	104	18	50	67	11	18	20
Terminalia prunoides		80	418	92	536	628	79	123	334
Totals	**0**	**3 120**	**9 599**	**2 080**	**10 972**	**13 051**	**2 049**	**4 198**	**4 726**

Figure 3.25 View of survey site AR3 (Arcadia)

ARCADIA - PLOT 4 (AR4)

A comprehensive breakdown of the woody plant biomass of plot AR4 is presented in Table 3.23. The site is located on granite at the foothill of the Paresis Mountain and is characterized by a dense stand of medium to large sized *A. erubescens* trees and *Grewia flava* (Figure 3.26). The area has never been treated with any arboricides. The tree density and ETTE/ha of the site are high (11 979 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 4.1 m can be harvested, which will render a total wood harvest of 7 192 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 4.5 m can be harvested, which will render a total wood harvest of 11 076 kg dry wood per hectare (43.0 % of the total wood mass). There is a large number of seedlings (1 440 seedlings/ha) - notably *A. erubescens* and *D. cinerea* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.23 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site AR4

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia erubescens	800	560	6 869	1 618	22 060	23 677	2 307	5 696	14 056
Boscia foetida	80								
Combretum apiculatum		240	32	7	24	30	8	12	3
Dicrostachys cinerea	560	160	712	151	813	965	183	361	268
Grewia flava		2 080	4 366	786	2 873	3 659	554	905	1 413
Totals	**1 440**	**3 040**	**11 979**	**2 562**	**25 769**	**28 331**	**3 053**	**6 974**	**15 741**

Figure 3.26 View of survey site AR4 (Arcadia)

ARCADIA - PLOT 5 (AR5)

A comprehensive breakdown of the woody plant biomass of plot AR5 is presented in Table 3.24. The site is located on heavier soil and is characterized by a dense stand of several *Acacia* and also *Grewia* species (Figure 3.27). The tree density and ETTE/ha of the site are very high (12 270 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 3.5 m can be harvested, which will render a total wood harvest of 5 989 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 4.5 m can be harvested, which will render a total wood harvest of 9 641 kg dry wood per hectare (34.2 % of the total wood mass). There is a small number of seedlings (480 seedlings/ha) - notably *A. reficiens* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.24 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site AR5

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia mellifera subsp. *mellifera*		800	6 028	1 417	20 375	21 792	1 992	4 935	13 448
Acacia reficiens	320	320	2 311	540	4 274	4 814	660	1 509	2 105
Albizia anthelmintica		160	275	60	294	355	50	80	164
Boscia albitrunca	80								
Boscia foetida		80	37	8	26	34	6	11	9
Dicrostachys cinerea	80	320	701	147	688	836	166	316	206
Grewia flava		480	1 958	377	1 900	2 277	308	489	1 103
Grewia flavescens		240	579	105	398	503	76	123	199
Lycium spp.		160	316	72	194	266	57	104	33
Terminalia prunoides		80	65	14	51	65	11	19	21
Totals	**480**	**2 640**	**12 270**	**2 741**	**28 201**	**30 942**	**3 327**	**7 587**	**17 287**

Figure 3.27 View of survey site AR5 (Arcadia)

3.3.3.7 *Farm Rusthof (353)*

Limited information on the history of the farm could be obtained, except that trees were harvested for charcoal production during the 1990's.

RUSTHOF - PLOT 1 (RH1)

A comprehensive breakdown of the woody plant biomass of plot RH1 is presented in Table 3.25. The site is located on sandy loam soil and is characterized by medium sized *A. luederitzii* trees and *Grewia* species (Figure 3.28). The tree density and ETTE/ha of the site are moderately high (6 038 ETTE/ha), which present a moderate problem density that will benefit from some thinning.

The total wood biomass is low due to the dominance of species such as *G. flava* and *G. flavescens* with a low biomass potential. Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 1.8 m can be harvested, which will render a total wood harvest of only 653 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha woody plants of the designated groups up to 2.4 m can be harvested, which will render a total wood harvest of only 2 615 kg dry wood per hectare (35.6 % of the total wood mass). There is a moderate number seedlings (690 seedlings/ha) - notably *G. flava* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.25 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site RH1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii		480	2 508	584	4 174	4 758	686	1 540	1 948
Acacia mellifera subsp. *mellifera*		80	595	138	884	1 022	159	352	373
Boscia albitrunca	80								
Grewia flava	480	640	1 558	285	1 142	1 427	210	339	593
Grewia flavescens	160	480	1 378	257	1 142	1 399	198	317	627
Totals	**690**	**1 680**	**6 038**	**1 265**	**7 341**	**8 606**	**1 252**	**2 547**	**3 541**

Figure 3.28 View of survey site RH1 (Rusthof)

RUSTHOF - PLOT 2 (RH2)

A comprehensive breakdown of the woody plant biomass of plot RH2 is presented in Table 3.26. The site is located on sandy soil and is characterized by *Philenoptera nelsii* and *T. sericea* trees of medium to large sizes (Figure 3.29). The tree density and ETTE/ha of the site are high (9 011 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 5.8 m can be harvested, which will render a total wood harvest of 2 975 kg dry wood per hectare (13.4 % of the total wood mass). Due to the species composition and size of the trees, it is not recommended to harvest beyond this target. There is a low number of seedlings (160 seedlings/ha) and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.26 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site RH2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii	80								
Boscia albitrunca		160	55	12	38	50	9	16	13
Commiphora pyracanthoides		560	346	76	270	345	60	100	110
Grewia flava		240	856	163	790	953	131	208	451
Grewia flavescens	80	480	1 749	339	1 819	2 157	283	446	1 089
Philenoptera nelsii		160	3 464	821	13 908	14 729	1 282	3 280	9 346
Tarchonanthus camphoratus		240	390	86	367	452	70	114	183
Terminalia sericea		80	2 150	476	4 947	5 423	437	643	3 867
Totals	**160**	**1 920**	**9 011**	**1 972**	**22 138**	**24 109**	**2 272**	**4 808**	**15 058**

Figure 3.29 View of survey site RH2 (Rusthof)

3.3.3.8 Omatjenne Research Station

The Omatjenne Research Station was included, primarily because these sites represented areas that had never been subjected to any prior form of bush control.

OMATJENNE - PLOT 1 (OM1)

A comprehensive breakdown of the woody plant biomass of plot OM1 is presented in Table 3.27. The site is located on heavier soil with a dominance of *Acacia* species. A characteristic feature of this plot is the presence of widely spaced, large *A. mellifera* trees (up to 6.0 m in height), which account for the high wood biomass (48 768 kg DM/ha) (Figure 3.30). The tree density and ETTE/ha of the site are high (10 633 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 5.0 m can be harvested, which will render a total wood harvest of 14 073 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha woody plants of the designated groups up to 6.0 m can be harvested, which will render a total wood harvest of 21 539 kg dry wood per hectare (44.2 % of the total wood mass). There is a low number of seedlings (160 seedlings/ha), but an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species is still recommended.

Table 3.27 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site OM1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii		80	986	231	2 262	2 494	307	728	1 227
Acacia mellifera subsp. *mellifera*	80	640	9 573	2 268	46 476	48 744	3 588	9 330	33 558
Boscia albitrunca	80								
Grewia flava		80	74	12	29	41	7	12	10
Totals	**160**	**800**	**10 633**	**2 511**	**48 768**	**51 279**	**3 902**	**10 070**	**34 796**

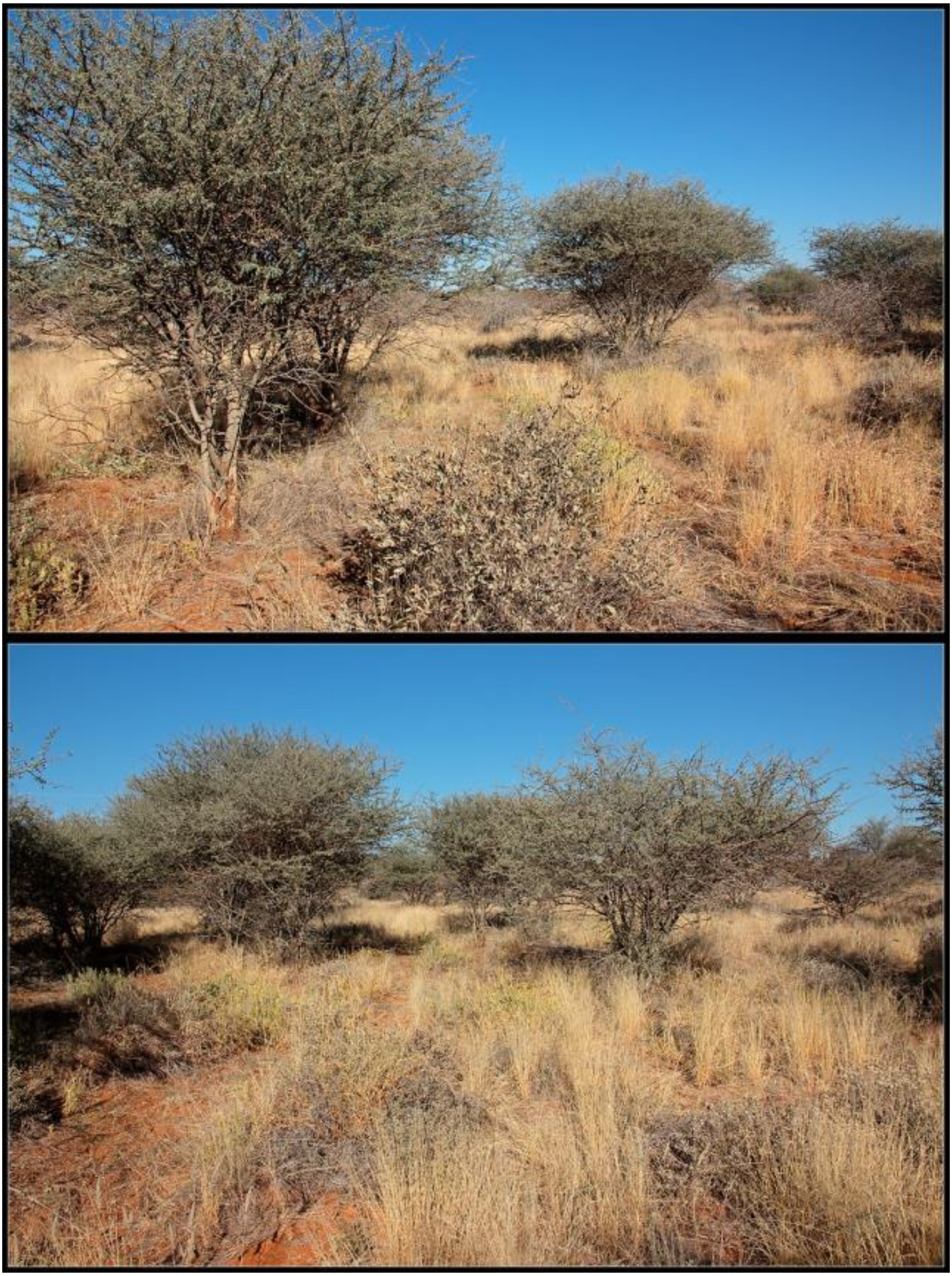


Figure 3.30 View of survey site OM1 (Omatjenne)

OMATJENNE - PLOT 2 (OM2)

A comprehensive breakdown of the woody plant biomass of plot OM2 is presented in Table 3.28. The site is located on heavier soil with a dominance of *Acacia* species A characteristic feature of this plot is the presence of widely spaced, large *A. mellifera* and *A. luederitzii* trees (up to 7.5 m in height), which account for the exceptionally high wood biomass (86 660 kg DM/ha) (Figure 3.31). The tree density and ETTE/ha of the site are high (13 019 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 6.0 m can be harvested, which will render a total wood harvest of 17 169 kg dry wood per hectare (19.81 % of the total wood mass). Due to the size of the trees, it is not recommended to harvest beyond this target. There is a high number of seedlings (1 200 seedlings/ha) - notably *G. flava* and *A. mellifera* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.28 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site OM2

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii		80	3 038	726	22 417	23 144	1 331	3 676	17 410
Acacia mellifera subsp. *mellifera*	480	480	9 347	2 224	63 855	66 080	3 815	10329	49 712
Boscia albitrunca	80	80	6	1	3	4	1	2	1
Catophractes alexandri		800	397	87	290	377	68	115	108
Commiphora pyracanthoides	80								
Grewia flava	240	160	182	31	82	113	19	31	32
Grewia retinervis	80	160	49	7	11	18	3	6	2
Lycium spp.	240								
Totals	1 200	1 760	13 019	3 076	86 660	89 736	5 236	14 158	67 265

Figure 3.31 View of survey site OM2 (Omatjenne)

OMATJENNE - PLOT 3 (OM3)

A comprehensive breakdown of the woody plant biomass of plot OM3 is presented in Table 3.29. The site is located on heavier soil with a dominance of *Acacia* species. A characteristic feature of this plot is the presence of widely spaced, medium sized *A. mellifera* and *A. luederitzii* trees (up to 5.0 m in height) (Figure 3.32). The tree density and ETTE/ha of the site are high (13 171 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 4.5m can be harvested, which will render a total wood harvest of 13 674 kg dry wood per hectare (36.4 % of the total wood mass). Due to the size of the trees, it is not recommended to harvest beyond this target. There is a low number of seedlings (240 seedlings/ha), but an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species is still recommended.

Table 3.29 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site OM3

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii	80	720	5 801	1 366	19 394	2 0759	1 948	4 831	12 614
Acacia mellifera subsp. *mellifera*		400	5 551	1 307	15 926	1 7233	1 832	4 465	9 628
Albizia anthelmintica		80	724	160	1 115	1 275	140	214	761
Grewia flavescens	80								
Lycium spp.	80	640	265	59	81	140	31	46	4
Maerua parvifolia		80	829	183	1 338	1 521	161	246	931
Totals	**240**	**1 920**	**13 171**	**3 074**	**37 854**	**40 927**	**4 113**	**9 803**	**23 938**

Figure 3.32 View of survey site OM3 (Omatjenne)

3.3.3.9 *Farm Ombarahewe (22)*

No information on the history of the farm could be obtained.

OMBARAHEWE - PLOT 1 (OB1)

A comprehensive breakdown of the woody plant biomass of plot OB1 is presented in Table 3.30. The site is located on sandy soil and is characterized by widely spaced, medium sized *A. luederitzii* trees and very few other species (Figure 3.33). The tree density and ETTE/ha of the site are medium high (5 756 ETTE/ha), which present a moderate problem density that will benefit slightly from thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 3.0 m can be harvested, which will render a total wood harvest of only 648 kg dry wood per hectare. Based on a target of 2 700 ETTE/ha, woody plants of the designated groups up to 3.5 m can be harvested, which will render a total wood harvest of only 1 833 kg dry wood per hectare (11.5 % of the total wood mass). There is a low number of seedlings (160 seedlings/ha) - notably *A. luedertzii* and *D. cinerea* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.30 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site OB1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia luederitzii	80	480	5 040	1 184	14 733	15 917	1 626	3 949	9 158
Acacia mellifera subsp. *mellifera*		80	699	163	1 185	1 349	196	443	546
Boscia albitrunca		80	17	4	11	14	3	5	3
Dicrostachys cinerea	80								
Totals	**160**	**640**	**5 756**	**1 351**	**15 929**	**17 280**	**1 825**	**4 398**	**9 707**

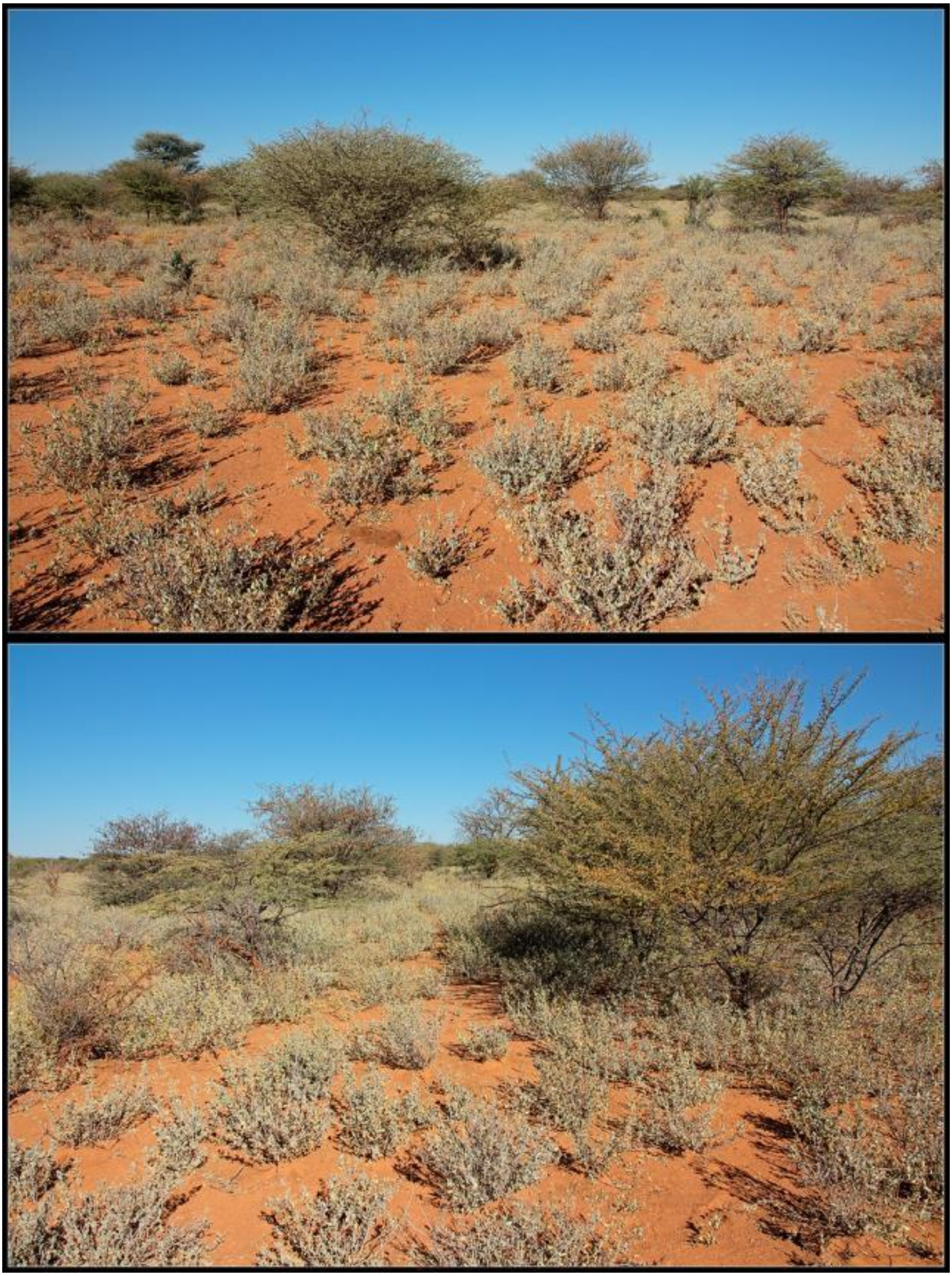


Figure 3.33 View of survey site OB1 (Ombarahewe)

3.3.3.10 Municipal land

The municipal land was included, primarily because these sites represented an area that had never been subjected to any prior form of bush control. It also has a history of severe grazing.

MUNICIPAL LAND - PLOT 1 (MM1)

A comprehensive breakdown of the woody plant biomass of plot MM1 is presented in Table 3.31. The site is located on sandy soil with quite a diverse species composistion. A characteristic feature of this plot is the presence of large *A. mellifera* and *A.fleckii* trees (up to 4.7 m in height) (Figure 3.34). The tree density and ETTE/ha of the site are high (14 264 ETTE/ha), which present a problem density that will benefit from some thinning.

Based on a target of 4 500 ETTE/ha (see section 3.3.2), woody plants of the designated groups (groups 2 & 3, see Table 3.3) up to 4.5 m can be harvested, which will render a total wood harvest of 15 073 kg dry wood per hectare (48.22 % of the total wood mass). Due to the size of the trees, it is not recommended to harvest beyond this target. There is a very high number of seedlings (2 640 seedlings/ha) - notably *D. cinerea* - and any harvesting will need to be followed by an aftercare programme to prevent rapid re-thickening by more aggressive and invasive woody species.

Table 3.31 Density of seedlings and established plants >0.5 m (plants/ha), Evapotranspiration Tree Equivalents (ETTE/ha) and Dry mass fractions (kg/ha) of all woody plants of site MM1

Species	Density Seedlings	Density >0.5 m	ETTE/ha	Leaf mass	Wood mass	Total biomass	Shoots 0-0.5 cm	Stems >0.5-2 cm	Wood >2 cm
Acacia fleckii		240	3 556	838	10 848	11 686	1 201	2 955	6 692
Acacia luederitzii		80	1 347	318	4 163	4 481	462	1 140	2 561
Acacia mellifera subsp. *mellifera*		800	7348	1719	15 034	16 753	2 170	5 031	7 833
Boscia albitrunca	80	560	188	41	129	170	32	54	44
Dicrostachys cinerea	2 160	480	368	74	176	250	63	99	14
Ehretia alba		80	11	2	6	9	2	3	1
Grewia flava	160	160	293	52	169	221	35	57	77
Grewia flavescens		80	30	5	8	12	2	4	2
Lycium spp.		80	46	10	16	26	6	9	1
Rhigozum brevispinosum	240	560	1076	245	694	939	196	366	132
Totals	**2 640**	**3 120**	**14 264**	**3 304**	**31 244**	**34 548**	**4 167**	**9 719**	**17 357**

Figure 3.34 View of survey site MM1 (Municipal land)

3.4 Views of key stakeholders on bush thickening, possible solutions and wood harvesting

3.4.1 Introduction

A total of 15 key stakeholders that included full-time commercial farmers and representatives of the Charcoal Producers Society, Agriculture Employers Association, Namibia National Farmers Union (NNFU), Ohorongo Cement Factory, Directorate Forestry (MAWF) and other role players were interviewed. A summary of their perception on the problem of bush thickening in Namibia, possible solutions and the willingness to participate in wood harvesting for electricity generation is presented below. Detailed information from the individual interviews is presented in Appendix 2.

In terms of the impact of bush thickening, farmers admitted that they have reached an irreversible situation where even the best rangeland management practices will not result in the restoration of the rangeland. Financially, farmers are not in a position to spend more money on efforts to counter the adverse impact of bush thickening. Most of the members belonging to the NNFU that include commercial farmers, farmers who own land under the Affirmative Action Scheme, resettled farmers as well as people making a living in communal land areas, are suffering from land degradation as a result of bush thickening.

The only solution would be to pursue a win-win strategy where the farmers and the environment will benefit by viable long-term solutions. To fulfill this objective, all possible opportunities should be investigated and explored. In general, the news of the envisaged power station that utilizes the biomass of locally harvested woody plants, was favourably received and for many it presented new hope for overcoming the devastating effect of bush thickening. The Namibia National Farmers Union as well as the Namibia Agricultural Union is in strong support of this project, provided that it is done in an environmentally responsible way.

3.4.2 Historical efforts to combat the problem of bush thickening

3.4.2.1 Charcoal and firewood production

Presently charcoal production and the production of firewood are the main source of income from excessive woody biomass on agricultural land in Namibia. Farmers sell charcoal for approximately N$ 1 500 per ton, while the net income is in the order of N$ 600-700 per ton. Depending on the quality of the wood, farmers produce on average one ton of charcoal from five tons of wood harvested (wet mass). Only wood thicker than 2.0 cm is utilized for this purpose. On average, interviewed farmers utilize only 50% of the available biomass for charcoal purposes.

The process of charcoal production is, however, very slow and with limited numbers of workers on a farm, only small areas of land can be cleared annually. Furthermore, there exists a strong resistance among farmers to allow too many people (harvesters) on their farms, mainly because of theft. The well-being of charcoal harvesters/workers on a farm is a very sensitive issue and for that purpose the Namibian Cabinet specified certain minimum requirements for workers which land owners must adhere to.

Land owners by law are not allowed to harvest woody plants indiscriminately. They must apply for a permit, which is issued by the Directorate Forestry (MAWF) and is valid for 3 months. This permit contains strict measures which harvesters must adhere to, i.e. no stems harvested should have a diameter of more than 15 cm. These environmental rules are generally accepted and supported by farmers.

There is a good national and international market for charcoal and opportunities for the export of this product are increasing. Despite these positive aspects farmers are hesitant to enter the charcoal industry, mainly because of their negative perception of charcoal production due to low profit margins, danger of veld fires and theft.

3.4.2.2 Methods used to combat bush thickening

Most of the farmers applied at some stage one or more methods being recommended for combating bush thickening. These included the use of a variety of arboricides (aerial spraying, foliar, stem absorbent and soil applied arboricides), as well as mechanical measures such as bulldozers and heavy rollers. Initial success in terms of increased grass production following the mortality of the woody plants was reported by all these farmers, but because of the removal of competition, new seedlings established themselves, while undesired smaller bushes filled the created vacuums. The main culprits were *D. cinerea*, *A. reficiens*, *A. mellifera* and various *Grewia* species on the more sandy soils. Presently they cannot afford to continue with control measures because it simply became too expensive.

They are of the opinion that the only viable approach to address the problem of bush thickening, is to find a way of utilizing the biomass of excess woody plants as a commodity with a monetary value. The possibility to harvest and sell biomass to Nampower or its contractor will definitely create favourable conditions for the farmer to apply aftercare, which in turn will ensure a more productive grass layer that is essential for sustainable extensive cattle farming. Without compensation for the harvesting of biomass, aftercare will not be affordable. The farmers stated clearly that if they do not receive compensation for the biomass, they will not allow any harvesting on their property.

Because labour intensive methods like felling and stumping are believed to be too time consuming and too expensive, they are not considered viable options. In addition, the farmers haven't experienced positive results with mechanical removal (bulldozing, bush rollers) either, since re-infestation was more severe and the areas were in a worse condition than before within only a few years after treatment.

According to the experience of farmers it will take in the order of 10 to15 years for regrowth to produce the same amount of biomass as before harvesting. Most farmers are convinced that regrowth is a serious threat to the environment as well as the productivity of the rangeland and that aftercare is, although unaffordable, still a necessity.

3.4.3 Economic considerations

Drastic increases in carrying capacity after bush thinning have been reported. On the farm of Hendrik Botha (Okahandja district) the carrying capacity increased from 25 kg/ha to 45 kg/ha within 4 years after chemical treatment. There was also a drastic increase from 9.5 to 18.5 kg live weight per hectare in meat production. The affordability of this exercise is only possible on farms in excess of 10 000 ha is size.

The average size of commercial farms is currently in the order of 5 000 ha and the average production cost of a cattle farm of this size is at least 50% of the net income, which is approximately N$300 000 per annum. From the remaining income, interest and capital repayments on farm-related debts, rent, taxes (income and land tax), as well as owners' remuneration must still be paid. During the period 2006 to 2014 the production cost on a cattle farm increased by 120%, while the beef price increased only by 73%. Subsequently, farmers without an additional source of income can simply not afford to apply sustainable bush control measures and will require a 100% subsidization.

Almost all the farmers indicated that they would like to be compensated for the removal of biomass. The estimated harvesting cost for the farmer is in the order of N$300-400 per ton. If a win-win situation is to be established, the price for biomass should be attractive enough for the stakeholders to ensure their continued participation.

3.4.4 Electricity supply in Namibia

3.4.4.1 Demand for electricity

Currently Namibia is facing serious challenges in terms of future electricity supply. Sixty percent of the electricity comes from imports, with the future supply from South Africa (Eskom) uncertain. In addition, the existing power supply infrastructure is ageing. The present generation capacity of Namibia is ± 487 MW of which approximately 70% is generated at Ruacana and 30% thermal. Planned power stations include Baynes (300 MW) and Kudu Gas (885 MW). Solar panels that can produce about 50 MW are also envisaged.

The bilateral agreement with Eskom (SA) will reach termination in 2017, while a new agreement (80 MW of which 50MW is fixed) with Zimbabwe started in April 2015 and will be effective for 10 years. The power agreement with Zambia (100 MW of which 50 MW is fixed) will last for another 6 years after which the agreement will have to be renewed. In the short term a critical additional supply of 250MW is required. What is extremely important for the biomass to energy project is that the ECB approved an increase of 9.53% in electricity tariffs. This implies that in the long run money via Namibian consumers should be available for repaying loans for all options.

If a biomass power plant appears to be economically feasible, it will also put various financial institutions such as Capricorn and Rand Mergent Bank - RMB in a position to attract many investors for such a project.

3.4.4.2 The value of biomass as a source of electricity

According to information provided (see Appendix 2 for more details) a wood-fired boiler generating high pressure steam to drive a 5.0 MWe turbine, would require approximately 4.5 metric tons per hour of dry biomass (@ <15% moisture content and > 16 GJ/t calorific value). For a 5.0 MWe biomass-to-energy power station running for 8 000 hours p.a. at near full load electrical output, would thus require biomass fuel at a tempo of 4.5 t/h x 8 000 h/p.a. = 36 000 tons p.a.

The above fuel consumption for each 5.0 MWe Power Station would translate into an encroacher bush clearing tempo of 36 000 t.p.a. + 10 t/ha = 3 600 ha p.a. A series of 5 x 10.0 MWe = 50 MWe output wood-fired power stations would thus result in an overall bush clearing area of 10 x 3 600 = 36 000 ha p.a.

All people interviewed are confident that there is more than enough biomass in the country for running several biomass power stations of 20 MW on a sustainable basis.

3.4.5 General conclusions of people interviewed

The future of a biomass related company will be dependent on three pillars:

- The reassurance of the long term operation of a biomass plant that is dependent on a constant supply of biomass at a reasonable price.
- Providing a competitive, yet affordable electricity rate for the consumer.
- The ability to operate on an environmentally sustainable basis.

Pending the availability of biomass, the intended power station at Gerus (Otjiwarongo district) can operate on a sustainable basis for as long as necessary. The Directorate of Forestry strongly supports the use of biomass for energy in future, provided that this happens within the framework of environmental principles. Presently this directorate is already positioning themselves in the following ways to support the project:

- Training of government officials (capacity building) within the Directorate of Forestry (DoF) and Directorate of Extension and Engineering Services (DEES) in all methods of bush control, environmental principles that should be adhered to and in exerting proper control over the harvesting process. The emphasis will also be on advisory services.

- Making the necessary budgetary provisions for the purchase of enough vehicles and operational costs to provide the necessary supportive services such as extension services and financial support to farmers. These needs should be properly investigated in advance.
- Attempting to change the perception that this is only a forestry problem to an understanding that it is also a problem of the livestock sector and therefore research and extension and the farming community should be actively involved.

3.5 Biomass potential yield and potential for investment

3.5.1 Observations from the field visit to Otjiwarongo

During the field visit to the study area in the Otjiwarongo district, the general poor condition of the rangelands of which bush thickening played a major role was very obvious. The desperate situation was aggravated by a below average rainfall of 300 mm of the previous season. During discussions with the various farm owners regarding the problem of bush thickening (see also section 3.4 and Appendix 2), three aspects became apparent: (i) the problem of bush thickening has now reached such a critical point that it threatens the continuation of profitable cattle farming in the area, (ii) the cost of bush control measures is a major obstacle, especially in view of the low return on capital that is typical of extensive cattle farming, and (iii) re-thickening of areas previously treated (mechanical, chemical or a combination of both) is a reality and a major problem.

These comments did not come as a surprise and support the realization that the causes of bush thickening, as well as the solutions to the problem are far more complex than generally anticipated. The simple approach of pursuing the most cost effective and quickest method of killing as many woody plants as possible is not always in the best interest of long-term solutions, and in many cases aggravated the problem almost beyond restoration. In general the farmers were well informed and aware of the potential pitfalls and requirements of maintaining an open savanna, but more often than not they simply don't have the resources to apply the required measures. Having said this, the research team also noted less effective measures that may not have been the most appropriate under the circumstances. These observations are valuable since it provide an opportunity to learn from the successes and also from the mistakes.

3.4.1.1 Aerial applications of arboricides

The active chemical ingredients of the most common arboricides sold in Namibia are tebuthiuron and bromacil and they can be applied selectively by manually applying them to the roots of target plants or alternatively, they can be applied from the air in a non-selective manner over large areas (Honsbein 2012). After application they remain inactive on the soil surface until rain carries the active ingredient into the soil, where it is taken up by the tree roots, inhibiting photosynthesis so that the leaves yellow and abscise and new leaves that are formed also abscise. This process continues until the tree no longer has reserves to initiate regrowth and dies (Smit *et al.* 1999). According to Honsbein (2012) caution must be taken when deploying pesticides on Namibian rangelands and it was recommended to established surveillance and monitoring systems to safeguard socio-economic interests and the environment.

Several examples of non-selective aerial applications of arboricides (mostly tebuthiuron) were observed in the study area of which some were fairly recently done (Figure 3.35). The normal outcome of these non-selective aerial applications is mortality of plants of a large number of species and size classes. A few species such as *Boscia albitrunca* are fairly resistant to tebuthiuron and survive.

Figure 3.35 A stand of dead trees after the aerial application of a non-selective arboricide.

Natural savanna ecosystems always tend to return to a point of relative stability (equilibrium) (Smith & Goodman 1986; Smit 2004). A dense bush thickened area represents a very stable environment. Killing some or all the woody plants in such a stable environment creates a vacuum that needs to be filled with other plants (Smit 2004). In applying this type of treatment it is hoped that this vacuum will be filled with grasses rather than other plants. In many cases this is indeed the case in the short-term, but unfortunately without further management this is seldom a permanent condition/state. Grasses are fast growing and respond very quickly to the removal of competition for soil water from the woody plants, as well as to the massive amounts of nutrients that are released from decaying roots of the dead plants. In time, with diminishing nutrients, combined with grazing, this vacuum may again become increasingly populated by woody plants (Ward & Esler 2011). Due to the limited distribution of the roots of seedlings and saplings of woody plants in the soil they often survive the initial application of the aerially applied arboricide and when the mature plants are killed, they flourish.

Potential invasive woody species are usually present in the environment as a natural component. These species are encouraged by disturbances where they act as pioneers and are able to colonize disturbed areas very rapidly, forming dominant stands, while excluding other more desirable species. A classic example of this is *Grewia flava* that appears to be the first woody species able to overcome the residual tebuthiuron that remain in the soil after an aerial application. It uses this ability to invade the open areas between the surviving *Boscia albitrunca* trees at the expense of other woody species and grasses (Figure 3.36). If left untreated the situation will develop in a state that is worse than before the treatment. The cost of a major follow-up treatment may equal or exceed the cost of the original treatment, with the result that these areas are often discarded to become unproductive rangeland.

Figure 3.36 Example of an area where an arboricide (tebuthiuron) was aerially applied and is now invaded by *Grewia flava* that appears to be the first woody species able to overcome the residual tebuthiuron remaining in the soil.

In some cases non-woody and non-grass plants species such as forbs may colonize disturbed areas. These forbs are almost without exception unpalatable, while still competing negatively with the grasses. An example of such a forb that can colonise disturbed areas is *Pechuel-Loeschea leubnitziae* (Wild sage or Stink bush) (Figure 3.37).

The biggest risk of the use of these non-selective arboricides in aerial applications is that the effect cannot be reversed in the short- or medium-term. Large trees that may be more than 50 years old and which are able to stabilize the environment by suppressing seedlings and saplings in their near vicinity (Smith & Goodman 1986; Grundy *et al.* 1994; Smit 2004) are killed, leaving behind an unstable environment that needs to be constantly battled to prevent re-infestation, often at considerable expense. Another disadvantage of this approach is that the dead trees remain standing for a long time and don't seem to break down and decay like trees that died of natural causes. The implication thereof is that the dead trees need to be physically removed, which adds to the cost factor.

Figure 3.37 A disturbed area invaded by *Pechuel-Loeschea leubnitziae* (Wild sage or Stink bush).

3.4.1.2 Mechanical treatments associated with soil disturbances

Mechanical clearing is usually undertaken with a heavy implement such as a bulldozer blade, which may also remove some of the roots of the trees. In cases where a heavy roller is used, the woody plants are often crushed, but not killed. Coppice regrowth from the collar region of woody plants is well documented (Smit 2003; Luoga *et al.* 2004) and is likely to occur (Figure 3.38).

Severe soil disturbance may often encourage the establishment of large numbers of seedlings of some woody plants such as *Dichrostachys cinerea* which has hard scaled seeds that can survive for long periods in the soil, just waiting for the right opportunity to germinate *en masse* and grow. Livestock and wildlife can also act as dispersal agents by consuming the seed pods and dispersing the seeds in their dung (Tjelele *et al*. 2012). In time this may result in a woody community which is denser than the original community (Figure 3.39). Thus, such mechanical methods are not generally recommended (Smit *et al.* 1999) and should rather be avoided.

Figure 3.38 An area invaded by *Dichrostachys cinerea* flattened with a heavy roller. Coppice regrowth is already visible and the area is likely to be overgrown again in a short time period.

Figure 3.39 An example of a severe infestation of *Dichrostachys cinerea* in an area with a history of mechanical disturbances.

3.4.1.3 Harvesting of trees for charcoal production

Presently charcoal production and the production of firewood are the main source of income from excessive woody biomass on agricultural land in Namibia. Only wood thicker than 2.0 cm is suitable for this purpose (Figure 3.4). In principle land owners are not allowed to harvest woody plants indiscriminately. They must apply for a permit, which is issued by the Directorate Forestry (MAWF) and is valid for 3 months. This permit contains strict measures which harvesters must adhere to, i.e. no stems harvested should have a diameter of more than 15 cm. Though these rules are generally accepted and supported by farmers, the reality is that they are difficult to enforce. Since workers are paid according to the weight of the wood they harvest, the incentive to cut large trees to maximise income is the main reason why more often than not large trees are being cut.

Since the smaller bushes with thin stems (low biomass) should primarily be targeted during bush control measures and some of the larger trees be retained (see section 3.3.2, Appendix 1), the opposite tends to happen in areas where woody plants are harvested for charcoal production. The consequence of this is that although a short-term income is being generated, it contributes very little to solving the bush thickening problem. In fact, areas where larger trees were selectively harvested for charcoal production have now been invaded by low biomass species such as *Grewia flava* and *G. flavescens* that form very dense, almost impenetrable, bush clumps with no benefit in terms of increased grass production (Figure 3.41). It is also unlikely that the woody biomass of these areas will ever again be suitable again for charcoal production due to their species composition and structure.

Figure 3.40 Bags of locally produced charcoal ready for transport.

Figure 3.41 An area where trees were selectively harvested for charcoal production and which has since been invaded by *Grewia flava* and *G. flavescens* that form very dense, almost impenetrable, bush clumps.

3.4.1.4 The need for an aftercare programme

As explained in the previous sections, removal of some or all of the woody plants creates a vacuum that will invariably be re-populated by woody plants, sometimes by more aggressive species. Natural defences against this phenomenon which have been documented and which can be utilized, include a healthy and strongly competitive grass layer (Ward & Esler 2011), and large trees that are able to suppress the re-establishment and survival of new tree seedlings (Smith & Goodman 1986; Grundy *et al.* 1994; Smit 2004) (Figure 3.42).

Despite these natural allies in the fight against re-infestation of aggressive woody species, an aftercare programme is absolutely essential to keep a thinned/harvested area open. This can be done in several ways such as mechanical slashing of new seedlings, localized (selective) chemical treatments of new growth, or even applying less popular management options such as controlled burning in combination with browsers. An efficient grazing management system that will ensure the maintenance of a healthy grass layer is also essential.

Figure 3.42 Natural defences against the rapid re-establishment of woody plants are a healthy and strongly competitive grass layer, and the protection of large trees that are able to suppress the establishment and survival of new tree seedlings.

The most important aspect of an aftercare programme is that it should not be viewed as a once-off operation, but should become a permanent component of the day-to-day management of the farm. Prior to any thinning/harvesting operation, careful consideration should be given to this aspect and it is essential that the cost implications of such an aftercare programme be realized and budgeted for. In general, the higher the intensity of thinning/clearing, the more aggressive the potential re-invasion and the more frequently actions need to be taken to keep such an area open.

Figure 3.43 illustrates an area subjected to a high intensity of clearing that is kept open and productive with a regular (almost annual) aftercare program to control the re-establishment of woody plants. Annual cutting of the grasses for hay will also assist in controlling new tree seedlings. Areas where the grass *Cenchrus cilliaris* is established can be considered a field/planted pasture and no longer a rangeland with natural grazing and should be managed accordingly. From the interviews (see section 3.4, Appendix 2) it is clear that many farmers understand the need of an aftercare programme, but few of them apply effective aftercare programs because of the high costs involved.

Figure 3.43 An example of an area virtually cleared of all woody plants, and which is kept open by a constant (almost annual) follow-up action to avoid re-establishment of woody plants.

3.5.2 Recommended tree harvesting for power generation

3.5.2.1 General considerations

From the information presented in the previous sections it has now been firmly established that if long-term restoration of the rangeland from bush thickening is an important objective, the most responsible ecological approach to wood harvesting should be selective thinning of the excess woody plants.

The next question relates to which trees should be removed and which trees should be retained, and the answer is clearly that the large trees (or largest trees available) should be retained at the cost of smaller trees and shrubs. The objective should be to reduce the leaf biomass (not wood biomass) of woody plants in affected areas in such a way that the suppressive effect of the woody plants on the grass layer is reduced to increase grass production. The presence of large trees, representing a structured savanna (see Appendix 1), will result in a more stable ecosystem. Such a structured ecosystem can be considered the most productive since all the benefits of woody plants are represented. These benefits include soil enrichment, which is a slow process and thus mainly associated with larger (and thus older) trees and increased stability as large trees may suppress the establishment and development of woody seedlings under their canopies and in their close proximity. The latter aspect is very important since it may in time reduce the frequency and cost of aftercare programs. However, restoration of bush thickened areas is not the only objective of this initiative. For the economically viablility of biomass harvesting for purposes of electricity generation, a certain minimum biomass harvest per hectare is required. The fact that the highest biomass yields reside in large trees, while these same trees are also the trees that needs to be retained, presents a potential conflict of interest. For this reason a realistic approach to the woody harvesting will invariably have to involve a compromise of harvesting as many trees as possible, while still retaining the benefits of some remaining trees. A considerable advantage of harvesting biomass for electricity generation is that all

biomass can be utilized, compared to harvesting for charcoal production where only stems thicker than 2.0 cm can be utilized.

3.5.2.2 Biomass resource in study area

All the values presented here are dry mass. Wet mass is highly variable and may differ between species, season or maturity of the plant. The water content of young, new season's shoots may be as high as 80% and as low as 20% in old, dense wood. It must also be noted that drying wood to determine the water content may take up to 2 weeks at a constant 70^{o}C for the wood to dry completely.

The total wood dry mass (all fractions) of the 28 plots varied from a low 7 291 kg/ha (plot RV3) to a high of 190 942 kg/ha (plot KN2) with an average of 36 222 kg/ha (Table 3.32). On average the wood >2.0 cm in diameter made up 70.1 % of the total wood mass, while the stems >0.5-2.0 cm and shoots <0.5 cm made up 20.8 and 9.1 % of the total wood mass respectively. Should the trees be harvested during the summer months when the trees have their full leaf carriage, the leaves on average would add another 6.8 % to the total tree dry mass. It can, however, be expected that most of the leaves will probably be lost during the harvesting and chipping process as they dry and fall from the branches.

From the data it is also clear that a high wood mass per hectare (such as plots KN2 and WV5) is without exception related to the presence of very large trees. Wood mass per hectare increased exponentially along an increase in the number of very large trees, while plots of predominantly small to medium sized trees - even at very high densities - yielded a much lower wood mass (Tables 3.33 and 3.34).

From the data presented in Table 3.32 it is evident that the potential woody biomass is extremely variable from area to area. The reason for this is partially due to environmental differences (soil type and depth, topography and drainage lines), but also due to past management activities such as mechanical and chemical bush control measures and wood harvesting for charcoal. This resulted in a mosaic pattern of high variability that complicated the extrapolation of the biomass estimations to larger areas. Ideally the best extrapolation of the data would require the subdivision of the whole study area in grid blocks where each grid block is allocated a biomass value based on the biomass of a comparable survey site. Unfortunately an extensive exercise like this was beyond the objectives, budged and time allocation of the project. Despite the limitation mentioned above it can be deducted that based on the average of 36 222 kg/ha the study area of 45 000 ha carries an estimated wood biomass of 1 629 990 metric tons (1.63 mil. metric tons).

3.5.2.3 Possible harvesting scenarios

Three possible harvesting scenarios are presented (Table 3.32):

i. Total biomass harvest. This is more of a theoretical option than something that should be considered. The purpose thereof is to assess the total biomass resource available in the study area that can also serve as a reference to the selective harvesting options.
ii. Selective harvesting with a conservative target - retaining 4 500 ETTE/ha (see section 3.3.2 for more details).
iii. Selective harvesting with an optimistic target - retaining 2 700 ETTE/ha that allows for the increased growth of the remaining trees (see section 3.3.2 for more details).

Table 3.32 Average wood biomass per hectare available in the study area based on three possible harvesting scenarios (see above).

Survey plot	Farm	Size (ha)	Wood biomass				
			Total available	Target 2 700 ETTE	% of Total	Target 4 500 ETTE	% of Total
BH1	Buffelhoek (342)	5 000	18 273	9 626	52.68	5 469	29.92
BH2			15 416	9 906	64.26	5 340	34.64
TK1	Tokai (348) + Knoll (201) + Randveld section1	12 000	10 200	2 809	27.54	936	9.18
TK2			70 376	28 522	40.52	28 522	40.52
TK3			18 903	5 867	31.03	3 492	18.47
TK4			9 890	9 561	96.67	9 561	96.67
KN1			10 583	1 556	14.70	50	0.47
KN2			190 942	53 760	28.16	53 760	28.16
WV1	Waverley (347)	7 000	12 048	4 269	35.43	1 887	15.66
WV2			12 797	6 010	46.96	2 542	19.86
WV3			30 275	10 516	34.73	10 516	34.73
WV4			11 210	1 519	13.55	0	0.00
WV5			119 585	47 468	39.69	47 468	39.69
RV1	Randveld (167)	4 000	97 675	30 571	31.30	30 571	31.30
RV2			18 581	10 588	56.98	10 588	56.98
RV3			7 291	2 475	33.95	451	6.19
AR1	Arcadia (320) + Paresis	10 000	25 800	10 655	41.30	4 750	18.41
AR2			19 503	7 801	40.00	5 545	28.43
AR3			10 972	5 093	46.42	3 725	33.95
AR4			25 769	11 076	42.98	7 192	27.91
AR5			28 201	9 641	34.19	5 989	21.24
RH1	Rusthof (353)	7 000	7 341	2 617	35.65	643	8.76
RH2			22 138	2 975	13.42	2 975	13.44
OM1	Omatjenne (21)	N/A	48 768	21 539	44.17	14 073	28.86
OM2			86 660	17 169	19.81	17 169	19.81
OM3			37 854	13 764	36.36	13 764	36.36
OB1	Ombarahewe (22)	N/A	15 929	1 833	11.51	648	4.07
MM1	Municipal land	N/A	31 244	15 073	48.24	15 073	48.24
Averages			**36 222**	**12 652**	**35**	**10 811**	**30**

Based on the conservative approach (target of 4 500 ETTE/ha), an average of 10 811 kg/ha wood can be harvested in the study area, which represents approximately 30 % of the total wood biomass (Table 3.32). Reducing the target to 2 700 ETTE/ha will increase the wood harvest with an additional 1 841 kg/ha to 12 653 kg/ha, which represents approximately 35 % of the total wood biomass (Table 3.32).

The suggestion of harvesting only 30-35 % of the available wood biomass may seem over conservative, but must be viewed in relation to the unique characteristics of each plot in terms of species composition, density and structure. The harvested wood may in fact vary from as high as 96 % of the available wood biomass (disturbed area with a dominance of invasive species of group 2) to a low of 4 % (plots with already a low biomass). Some plots with big trees may render a harvest of up to 53 000 kg/ha, but still at a low percentage (28.1 %) of the total wood biomass of that plot (e.g. plot KN2). Based on the information presented by Mr Matthys de Wet (see Appendix 2) it would appear that even the conservative wood

harvesting intensity (4 500 ETTE/ha remaining) will still meet the minimum requirement of 10 000 kg/ha for the viability of an electricity plant.

It is interesting to note that the survey plots with the highest wood biomass were those that have not been treated or harvested in any way in the past. Yet despite their high wood biomass they often score lower in terms of the severity of bush thickening. Other plots with a low harvestable wood biomass may score higher in terms of the severity of bush thickening. When assessing the severity of bush thickening, it is the amount of leaves that matter and not the amount of wood. The reason is that the leaves of the woody plants transpire water and the potential water use of woody plants (and thus competition with grasses) is directly correlated to leaf biomass and not wood biomass. In addition, large trees often have well developed root systems and a larger percentage of the water that they access may be sourced from deeper soil layers beyond the rooting zone of the grasses.

In addition, the ratio of leaves to wood, as well as the percentage that the leaves comprise of the total plant biomass, differ considerably between plants of different sizes, and also between species of different growth forms (Tables 3.36 and 3.37). Small trees and bushes have a high ratio of leaves : wood (1 : 2.245 and 1 : 1.769, respectively for the >0.5 – 1.0 m height class - Tables 3.36 and 3.37) and the leaves can comprise up to 56 % of the total plant biomass (Table 3.35). On the opposite end of the scale, very large trees have a very low ratio of leaves : wood (1 : 50.878 for trees >6.0 m) and the leaves as a percentage of the total plant biomass can be as low as 1.96 % (Table 3.34). Individual plant species of group 2 (see Table 3.3) will never achieve a high wood biomass because of their growth form (e.g. *Grewia flava*). The selective harvesting of plants from species group 3 (e.g. *Acacia* species) (see Table 3.3) may result in their replacement by species from group 2, resulting in a lowering of the biomass production potential of that area, which has also been observed in the study area (e.g. plot TK4).

Table 3.33 Summary of the average wood and leaf dry matter production per plant of trees and shrubs of group 2 (see Table 3.3), as well as the ratio leaves : wood and percentage that the leaves comprised of the total plant biomass.

Height class (m)	Wood DM/plant (kg)	Leaf DM/plant (kg)	Leaf : Wood ratio	Leaf %
>0.5 - 1.0	0.229	0.102	1 : 2.245	44.54
>1.0 – 2.0	1.398	0.306	1 : 4.569	21.89
>2.0 – 3.0	4.552	0.830	1 : 5.552	18.01
>3.0 – 4.0	5.504	0.979	1 : 5.622	17.78
>4.0 – 5.0	-	-	-	-
>5.0 – 6.0	-	-	-	-
>6.0	-	-	-	-

Table 3.34 Summary of the average wood and leaf dry matter production per plant of trees and shrubs of group 3 (see Table 3.3), as well as the ratio leaves : wood and percentage that the leaves comprised of the total plant biomass.

Height class (m)	Wood DM/plant	Leaf DM/plant	Leaf : Wood ratio	Leaf %
>0.5 - 1.0	0.184	0.104	1 : 1.769	56.52
>1.0 – 2.0	0.966	0.317	1 : 3.047	32.82
>2.0 – 3.0	6.557	1.147	1 : 5.716	17.50
>3.0 – 4.0	26.506	2.609	1 : 10.159	9.84
>4.0 – 5.0	60.341	3.909	1 : 15.436	6.78
>5.0 – 6.0	192.816	7.214	1 : 26.728	3.74
>6.0	579.353	11.387	1 : 50.878	1.97

It is recommended that trees be selectively harvested, starting with the smallest plants and progressively moving to larger plants until the target of retaining 4 500 ETTE/ha or 2 700 ETTE/ha has been reached. Harvesting should concentrate on the potential problem species (species from groups 2 and 3 - see Table 3.3) whereas non-problem species (species from group 1 - see Table 3.3) should be preserved.

If for example only trees larger than 5 m are retained at a target value of 2 700 ETTE/ha an average of 90 trees/ha will remain (since 1 tree >5 m equals approximately 30 ETTE) (Table 3.35). Visualizing a density of 4 500 or 2 700 ETTE/ha may be difficult during practical bush harvesting. On the other hand, something like tree height is a much easier criterion to measure or visualize. For this purpose the mean equivalent ETTE-values of all woody plants combined were calculated in seven height classes and values of the four most abundant tree and shrub species were calculated as well (Table 3.35).

Table 3.35 Mean equivalent ETTE/plant-values of all woody species combined, *Acacia mellifera*, *A. luederitzii*, *A. reficiens* and *Grewia* species in seven height classes (all 28 plots combined).

Height class (m)	ETTE/plant All species	ETTE/plant *A. mellifera*	ETTE/plant *A. luederitzii*	ETTE/plant *A. reficiens*	ETTE/plant *Grewia* spp.
>0.5 - 1.0	0.43	0.43	0.64	0.43	0.79
>1.0 – 2.0	1.63	1.90	2.52	1.74	2.21
>2.0 – 3.0	4.58	5.57	5.10	5.13	4.45
>3.0 – 4.0	10.97	11.71	10.52	11.66	5.98
>4.0 – 5.0	16.53	15.97	19.20	19.68	-
>5.0 – 6.0	28.14	29.05	32.90	-	-
>6.0	44.58	53.46	41.63	-	-

The last issue that needs be addressed is whether the harvested plants be treated or allowed to regrow producing another biomass harvest after a number of years. It is suggested that the final decision on this aspect be left to the individual farmer. However, it is important to mention a few important considerations that may assist in the decision:

i. The majority of African savanna trees are able to coppice vigorously after mechanical damage, therefore cutting without treatment with a stem applied arboricide will result in coppice regrowth.
ii. A clear distinction must be made between existing plants that have been cut and that will regrow (coppice) from the collar region of the plant, versus new woody plants that will establish from seeds. Both these forms of regeneration are likely to occur after harvesting.
iii. Coppice regrowth will result in a plant that is structurally different from the original plant (multi-stemmed shrub vs. single-stemmed tree) and may probably never render the same wood biomass as the original plant. Because photosynthesis takes place in green leaves they are the factories of the plants, and after damage they will always prioritise the replacement of leaf biomass and not the replacement of wood biomass. It has been shown that trees that are cut and not treated, will regrow to their original leaf biomass within five years (Smit 2003), but with significantly lower wood biomass. They may continue to grow to a point where the leaf biomass (and thus competition with the grass layer) exceeds the original leaf biomass, while still having a much lower wood biomass.
iv. The species composition of the woody plants after tree harvesting is likely to differ/alter from what it used to be before the harvesting. Aggressive species such as *Dichrostachys cinerea*, *Grewia* species and *Catophractes alexandri* may invade and in time compete more severely with the grass layer, while producing less wood to harvest.

Where the decision is taken to treat the stumps of the harvested trees, it must be done with an ecologically safe arboricide as soon as possible after cutting without risk to the remaining trees. The soil applied arboricides (tebuthurion and bromasil) are not recommended because of their non-selective nature and they are also unsuitable for trees that were cut. The only treatment method recommended for the planned wood harvesting is to spray or paint the cut area of the stump with 2 % Access (picloram) + 2 % Actipron Super (wetting agent) mixed in water. Provision must be made for a follow-up treatment the next season to control coppice growth of plants not properly treated the first time. Access can again be used, but then as a leaf spray. As a leaf spray it should be sprayed at a concentration of 0.35 % Access (picloram) + 0.5 % Actipron Super (wetting agent) directly onto the leaves. An effective and continual aftercare program needs to be implemented to prevent/reduce the re-establishment and possible infestation of undesirable woody plants (re-thickening).

Where the decision is taken to allow the stumps to regrow for purposes of producing another biomass harvest after a number of years, it is recommended that an aftercare program still be implemented. For this purpose the re-establishment and possible infestation of undesirable group 2 species (low biomass species) should be controlled and where possible the number of stems of multi-stemmed coppice regrowth reduced to encourage the development of thicker stems that will produce biomass similar to the original harvested plants. The approach will also benefit the establishment of grasses during the interim period up to the next harvest.

3.6 Conclusion

Based on the average measured wood biomass available on the commercial farms in the close proximity of the Gerus electricity substation north-west of Otjiwarongo, the planned harvesting of biomass of indigenous woody plants for electricity generation that requires a minimum of 10 000 kg harvestable wood DM/ha appears to be ecologically viable. Based on the assumption that a 20 MW biomass power plant requires 150 000 tons biomass per annum and that such a power plant will have a life span of at least 15 years, it will require 2 250 000 tons biomass over this time period. Using the two proposed harvesting scenarios (leaving 4 500 ETTE/ha and 2 700 ETTE/ha, respectively) will require a total area of approximately 178 000 ha (leaving 2 700 ETTE/ha) to approximately 208 000 ha (leaving 4 500 ETTE/ha) to supply the required biomass to the power plant over this time period. This represents an area 3.9 to 4.6 times that of the study area (45 000 ha). This calculation, however, does not include the biomass of possible follow-up harvests of areas that were previously harvested and where the trees were allowed to regrow. The

assumption by some farmers that the trees will regrow to their original biomass prior to the harvesting in 10 to 15 years may be over optimistic. There is a general lack of scientific information on regrowth rates of woody plants, but based on what is currently known it is unlikely that harvested plots will regrowth to their original biomass in this time period, unless the harvested areas are specifically managed to encourage regrowth of woody species from group 3 (high biomass species), rather that group 2 (low biomass species) (Table 3.3). This aspect should be a priority for further research.

Based on the massive amount of biomass that is required for a 20 MW biomass power plant, it is clear to see that the incentive to harvest more trees than is ecologically desirable, is a definitive reality. For this reason, clear priorities need to be identified prior to the harvesting operation and realistic targets set. Responsibility and accountability are essential to avoid exploitation of natural resources for short-term financial gain at the cost of long-term sustainability.

The successful implementation of the project will largely depend on resolving challenges of logistics and financial constraints (cost of harvesting, chipping and transport and remuneration of farmers for harvested woody plants). Co-operation between all role players need to be obtained and training on all levels will be essential. It should also be realized that the harvesting cannot be considered a once-off operation. A continual aftercare program will need to be implemented following the harvesting, regardless of whether the stumps of the harvested plants are treated with an arboricide or allowed to regrow for purposes of producing another biomass harvest after a number of years.

References

Aucamp AJ. 1976. The role of the browser in the bushveld of the Eastern Cape. *Proceedings of the Grassland Society of southern Africa* 11: 135-138.

Abule E, Snyman HA, Smit GN. 2007. Rangeland evaluation in the middle Awash valley of Ethiopia: II. Woody vegetation. *Journal of Arid Environments* 70: 272-292.

Balehegn M, Eniang EA, Hassen A. 2012. Estimation of browse biomass of *Ficus thonningii*, an indigenous multipurpose fodder tree in northern Ethiopia. *African Journal of Range and Forage Science*. 29(1): 25-30.

Barac AS. 2004. EcoRestore - A decision support system for the restoration of degarded rangelands in southern Africa. M.Sc.-dissertation, North-West University, Potchefstroom, South Africa.

Barnes DL, Lloyd BV, McNeill L. 1976. The use of shoot dimensions to estimate the leaf mass or leaf area of certain indigenous trees in Rhodesia. *Proceedings of the Grassland Society of Southern Africa* 11: 47–50.

Barrett AS, Brown LR. 2012. A novel method for estimating tree demensions and calculating canopy volume using digital photography. *African Journal of Range and Forage Science*. 29(3): 153-156.

Bester FV. 1996. Bush encroachment: A thorny problem. *Namibia Environment* 1: 175-177.

Bester FV. 1999. Major problem: bush species and densities in Namibia. *Agricola* 10: 1-3.

Bothma J du P, van Rooyen N, van Rooyen MW. 2004. Using diet and plant resources to set wildlife stocking densities in African savannas. *Wildlife Society Bulletin* 32(3): 840-851.

Beauchamp JJ, Olson JS. 1973. Corrections for bias in regression estimates after logarithmic transformation. *Ecology* 54: 1403-1407.

Belsky AJ. 1994. Influences of trees on savanna productivity: tests of shade, nutrients and tree-grass competition. *Ecology* 75: 922-932.

Bond WJ. 2008. What limits trees in C_4 grasslands and savannas? *Annual Review of Ecology, Evolution and Systematics* 39: 641–59.

Bosch OJH, Gauch HG. 1991. The use of degradation gradients for the assessment and ecological interpretation of range condition. *Journal of the Grassland Society of southern Africa* 8(4): 138-146

Bosch OJH, Janse van Rensburg FP. 1987. Ecological status of species on grazing gradients on shallow soils of the western Grassland Biome in South Africa. *Journal of the Grassland Society of southern Africa* 4(4): 143-147.

Brown S. 1997. Estimating biomass and biomass change of tropical forests. A primer. FAO Forestry Paper 134.

Brown S, Gillespie AJ, Lugo AE. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science.* 35: 881−902.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riera B, Yamakura T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia.* 145: 87−99.

Cunningham PL. 1998. Potential wood biomass suitable for charcoal production in Namibia. Agri-Info 4(5): 4-8.

Dayton BR. 1978. Standing crops of dominant *Combretum* species at three browsing levels in the Kruger National Park. *Koedoe* 21: 67-76.

De Klerk JN. 2004. *Bush Encroachment in Namibia*. Report on Phase 1 of the Bush Encroachment Research, Monitoring and Management Project. Ministry of Environment and Tourism, Windhoek, Namibia.

Dye PJ, Spear PT. 1982. The effects of bush clearing and rainfall variability on grass yield and composition in south-west Zimbabwe. *Zimbabwe Journal of Agricultural Research.* 20: 103-118.

Ciais YP, Bombelli A, Williams M, Piao SL, Chave J, Ryan CM, Henry M, Brender P, Valentini R. 2011. The carbon balance of Africa: synthesis of recent research studies. *Phil. Trans. R. Soc. A.* 369: 2038-2057.

Cole TG, Ewel JJ. 2006. Allometric equations for four valuable tropical tree species. *Forest Ecology and Management* 229: 351−360.

Donaldson CH. 1980. *The extend of bush enchroachment in die bushveld areas of the Transvaal region*. In: Proceedings worksession: bush enchroachment and thickening. Department of Agriculture and Fisheries, Pretoria, South Africa.

Draper N, Smith H. 1981. *Applied regression analysis.* Wiley & Sons, New York.

Foroughbakhch R, Hernández-Piñero J, Alvarado-Vázquez M, Céspedes-Cabriales E, Rocha-Estrada A, Cárdenas-Avila M. 2009. Leaf biomass determination on woody shrub species in semiarid zones. *Journal of Agroforestry Systems*. 77: 181-192.

Friedel MH, Chewings VH. 1988. Comparison of crown cover estimates for woody vegetation in arid rangelands. *Australian Journal of Ecology* 13: 463-468.

Giess W. 1998. A preliminary vegetation map of South West Africa. *Dinteria* 4: 5-114.

Grote R. 2002. Foliage and branch biomass estimation of coniferous and deciduous tree species. *Journal of Silva Fennica* 36: 779-788.

Grundy IM, Campbell BM, Frost PG. 1994. Spatial pattern, regeneration and growth rates of *Brachystegia spiciformis* and *Julbenardia globiflora*. Vegetatio 115:101–107.

Hagos MG, Smit GN. 2005. Soil enrichment by *Acacia mellifera* subsp. *detinens* on nutient poor sandy soil in a semi-arid southern African savanna. *Journal of Arid Environments* 61: 47-55.

Hartnett DC, Ott JP, Sebes K, Ditlhogo MK. 2012. Coping with herbivory at the juvenile stage: responses to defoliation and stem browsing in the African savanna tree *Colophospermum mopane*. *Journal of Tropical Ecology* 28(2): 161-169.

Hoffmann WA, Schroeder W, Jackson RB, 2002. Positive feedbacks of fire, climate and vegetation and the conversion of tropical savanna. *Geophysical Research Letters*. 29: 2052.

Honsbein D. 2012. Evaluation on possible environmental effects of the generic arboricides Tebutuiron and Bromacil under Namibian conditions. Meat Board of Namibia, Windhoek.

Joubert DF. 1997. Grazing gradients in the Highland Savanna vegetation of Namibia. *Dinteria* 25: 69-86.

Joubert DF 2014. The dynamics of bush thickening by *Acacia mellifera* in the Highland Savanna of Namibia. PhD-thesis (Grasssland Science), University of the Free State, Bloemfontein, South Africa.

Joubert DF, Rothauge A, Smit GN. 2008. A conceptual model of vegetation dynamics in the semi-arid Highland savanna of Namibia, with particular reference to bush thickening by *Acacia mellifera*. *Journal of Arid Environments* 72(12): 2201-2210.

Joubert DF, Smit GN, Hoffman MT. 2012. The role of fire in preventing transitions from a grass dominated state to a bush thickened state in arid savannas. *Journal of Arid Environments* 87: 1-7.

Kalwu JM, de Boer WF, Mucina L, Prins HHT, Skarpe C, Winterbach C. 2010. Tree cover and biomass increase in a southern African savanna despite growing elephant population. Ecological Applications 20(1): 222-233.

Karekezi S, Kithyoma W. 2006. Bioenergy and the poor. *Bioenergy and Agriculture: Promises and Challenges.* International Food Policy Research Institute 2020 Focus No. 14, Washington D.C.

Kgosikoma OE, Harvie BA, Mojeremane W. 2012. Bush encroachment in relation to rangeland management systems and environmental conditions in Kalahari ecosystems of Botswana. *African Journal of Agricultural Research* 7(15): 2312-2319.

Knoop WT, Walker BH. 1985. Interactions of woody and herbaceous vegetation in a southern African savanna. *The Journal of Ecology* 73(1): 235-253.

Kohi EM, de Boer WF, Peel MJS, Rob Slotow, van der Waal C, Ignas MA. 2011. African elephants *Loxodonta africana* amplify browse heterogeneity in African savanna. *Biotropica* 43(6): 711-721.

Kyalangalilwa B., Boatwright JS , Daru BH, Maurin O, Van der Bank M. 2013. Phylogenetic position and revised classification of *Acacia* s.l. (Fabaceae: Mimosoideae) in Africa, including new combinations in *Vachellia* and *Senegalia*. *Botanical Journal of the Linnean Society*, 2013: 172: 500-523

Luoga EJ, Witkowski ETF, Balkwill K. 2000. Differential utilization and ethnobotany of trees in Kitulanghalo Forest Reserve and surrounding communal lands, eastern Tanzania. *Economic Botany.* 54(3): 328-343.

Luoga EJ, Witkowski ETF, Balkwill K. 2004. Regeneration by coppicing (resprouting) of miombo (African savanna) trees in relation to land use. *Forest Ecology and Management* 189(1): 23-35.

Mason LR, Hutchings SS. 1967. Estimating foliage yields on Utah Juniper from measurements of crown diameter. *Journal of Range Management* 20: 161–166.

Meilby, H, Puri, L. 2009. Features and allometric relationships characterising trees on farmland an example from Chainpur VDC, Chitwan. *Banko Janakari* 08: 19-26.

Mendelsohn J, el Obeid S. 2005. Forest and woodlands of Namibia. RAISON, Windhoek, Namibia.

Mendelsohn J, Javis A, Roberts C, Robertson T. 2002. Atlas of Namibia: A portrait of the land and its people. David Philip Publishers, Cape Town.

Mannheimer CA, Curtis BA (eds). 2009. Le Roux and Müller's Field guide to the Trees and Shrubs of Namibia. Windhoek: Macmillan Education Namibia.

Mucina L, Rutherford MC. 2006. *The vegetation of South Africa, Lesotho and Swaziland*. South African National Biodiversity Institute, Pretoria, South Africa.

Navar J. 2009. Biomass component equations for Latin American species and groups of species. *Annals of Forest Sciences* 66: 208−216.

Nghikembua MT. 2008. Quantifying farmers' perceptions and willingness as well as availability of encroaching aboveground Acacia bush biomass on CCF commercial farmlands in north central Namibia. MDS-dissertation, University of the Free State, Bloemfontein, South Africa.

O'Connor TG, Crow VRT. 1999. Rate and pattern of bush encroachment in Eastern Cape savanna and grassland. *African Journal of Range and Forage Science* 16: 26–31.

Picard N, Saint-André L, Henry M. 2012. Manual for building tree volume and biomass allometric equations: from field measurement to prediction. Food and Agricultural Organization of the United Nations, Rome, and *Centre de Coopération Internationale en Recherche Agronomique pour le Développement*, Montpellier, 215 pp.

Richter CGF, Snyman HA, Smit GN. 2001. The influence of tree density on the grass layer of three semi-arid savanna types of southern Africa. *African Journal of Range and Forage Science* 18: 1–7.

Roques KG, O'Connor TGO, Watkinson AR. 2001. Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. *Journal of Applied Ecology* 38: 268-280.

Rutherford MC. 1979. Plant-based techniques for determining available browse and browse utilization: a review. *Botanical Review* 45: 203-228.

Sawadogo L, Savadogo P, Tiveau D, Dayamba SD, Zida D, Nouvellet Y, Oden PC, Guinko S. 2010. Allometric prediction of above-ground biomass of eleven woody tree species in the Sudanian savanna-woodland of West Africa. *Journal of Forestry Research* 21(4): 475–481.

Shively GE, Zelek CA, Midmore DJ, Nissen TM. 2004. Carbon sequestration in a tropical landscape: an economic model to measure its incremental cost. *Agroforestry Systems* 60: 189–197.

Skinner JD, Chimimba CT. 2005. *The mammals of the southern African subregion* (third edition). Cambridge University Press, Cambridge.

Smit GN. 1989a. Quantitative description of woody plant communities: Part I. An approach. *Journal of the Grassland Society of southern Africa* 6: 186-191.

Smit GN. 1989b. Quantitative description of woody plant communities: Part II. Computerized calculation procedures. *Journal of the Grassland Society of southern Africa* 6: 192-194.

Smit GN. 1994. *The influence of intensity of tree thinning on Mopani veld*. Ph.D-thesis, University of Pretoria, Pretoria, South Africa.

Smit GN. 1996. BECVOL: Biomass Estimates from Canopy Volume (version 2) - users manual. Unpublished manual, University of the Free State, Bloemfontein, South Africa.

Smit GN. 1998. Management of rangeland in southern Africa with special reference to bush enchroachment. Unpublished paper presented at the Master Farmer day on the farm Waldorf, Otawi, Namibia, 15th April 1998.

Smit GN. 2001. The influence of tree thinning on the vegetative growth and browse production of *Colophospermum mopane. South African Journal of Wildlife Research* 31: 99-114.

Smit GN. 2003. The coppicing ability of *Acacia erubescens* and *Combretum apiculatum* subsp. *apiculatum* in response to cutting. *African Journal of Range and Forage Science* 20: 21-27.

Smit GN. 2004. An approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment. J*ournal of Environmental Management* 71(2): 179-191.

Smit GN. 2005. Tree thinning as an option to increase herbaceous yield of an encroached semi-arid savanna in South Africa. *BMC Ecology* 5:4

Smit GN. 2014. BECVOL 3 - an expansion of the above-ground biomass quantification model for trees and shrubs to include the wood component. *African Journal of Range and Forage Science* 31(2): 179-186.

Smit GN, Aucamp A, Richter CGF. 1999. *Bush encroachment: an approach to understanding and managing the problem*. In: Tainton, NM, (Ed.), Veld Management in Southern Africa, University of Natal Press, Pietermaritzburg.

Smit GN, Janse van Rensburg G, Deacon F. 2011. Final report: Estimation of the above ground biomass of woody plants on representative sites in the vicinity of the Ulco mine, Northern Cape (51 pages). Report commissioned by MBB Consulting Services South (Pty) Ltd, Stellenbosch.

Smit GN, Janse van Rensburg G, Deacon F. 2012. Final report: An assessment of the extend of bush encroachment on the property of the Sishen South (Kolomela) mine, Postmasburg (110 pages). Report commissioned by the Centre of Environmental Management, University of the Free State, Bloemfontein and Sishen Iron Ore Company (Kolomela), Postmasburg.

Smith TM, Goodman PS. 1986. The effect of competition on the structure and dynamics of *Acacia* savannas in southern Africa. *Journal of Ecology* 74: 1031–1044.

Statgraphics 1999. STSC Inc., USA.

Strohbach BJ. 1992. Loss of genetic diversity due to veld degradation - a case study in the northern Kalahari, Grootfontein district. *Dinteria* 23:102-115.

Strohbach BJ. 2000. Vegetation degradation trends in the northern Oshikoto Region: I. The *Hyphaene petersiana* plains. *Dinteria* 26: 45-62

Stromgaard P. 1985. Biomass estimation equations for miombo woodland, Zambia. *Agroforestry Systems* 3: 3−13.

Teague WR, Smit GN. 1992. Relations between woody and herbaceous components and the effect of bush-clearing in southern African savannas. *Journal of the Grassland Society of Southern Africa* 9: 60–71.

Teague WR, Trollope WSW, Aucamp AJ. 1981. Veld management in the semi-arid bush-grass communities of the eastern Cape. *Proceedings of the Grassland Society of southern Africa* 16: 23-28.

Ter-Mikaelian MT, Korzukhin MD. 1997. Biomass equations for 65 North American tree species. *Forest Ecology and Management* 97: 1−24.

Topps JH. 1997. Nutritive value of indigenous browse in Africa in relation to the needs of wild ungulates. *Animal Feed Science Technology* 69: 143-154.

Treydte AC, Heitkonig MA, Prins HHT, Ludwig F. 2007. Trees improve grass quality for herbivores in African savannas. *Perspectives in Plant Ecology, Evolution and Systematics* 8: 197-205.

Tjelele JT, Dziba LE, Pule HT. 2012. Recovery and germination of *Dichrostachys cinerea* seeds Fed to Goats (*Capra hircus*). *Rangeland Ecology & Management* 65: 105-108.

United Nations Department of Economic and Social Affairs. 2007. Small-Scale Production and Use of Liquid Biofuels in Sub-Saharan Africa: Perspectives for Sustainable Development. Commission on Sustainable Development, Background Paper No. 2, DESA/DSD/2007/2,51, New York.

Van der Meulen F, Werger MJA. 1984. Crown characteristics, leaf size and light throughfall of some savanna trees in southern Africa. *South African Journal of Botany* 3: 208-218.

Walter H. 1971. *Ecology of Tropical and Subtropical Vegetation*. Oliver and Boyd, Edinburgh, UK.

Ward D. 2005. Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science* 2005: 22(2): 101–105.

Ward D, Esler KJ. 2011. What are the effects of substrate and grass removal on recruitment of *Acacia mellifera*? *Plant Ecolog*y 212(2): 245-250.

Whittaker RH. 1968. Dimension and production relations of trees and shrubs in the Brookhaven forest, New York. *Journal of Ecology* 56: 1−25.

Willebrand E, Ledin S, Verwijst T. 1993. Willow coppice systems in short rotation forestry: effects of plant spacing, rotation length and clonal composition on biomass production. *Biomass and Energy* 4: 323−331.

Zimmermann I. 2009. *Causes and consequences of fenceline contrasts in Namibian rangeland*. PhD-thesis (Grasssland Science), University of the Free State, Bloemfontein, South Africa.

Zimmermann I, Joubert DF. 2002. A crude quantification of wood that is and can be harvested from bush thickening species in Namibia. Proceedings of the First National Forestry Research Workshop, 12-13 March 2002, Windhoek, Namibia. *Ministry of Environment and Tourism, Forestry Publication* 9: 56-66.

Appendix 1

ELSEVIER

Journal of Environmental Management 71 (2004) 179–191

Journal of Environmental Management

www.elsevier.com/locate/jenvman

An approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment

G.N. Smit*

Department of Animal, Wildlife and Grassland Sciences, University of the Free State, P.O. Box 339, Bloemfontein 9300, South Africa

Received 7 July 2003; revised 12 February 2004; accepted 19 February 2004

Abstract

Due to bush encroachment the grazing capacity of large areas of the southern African savanna has declined, often to such an extent that many previously economic livestock properties are now no longer economically viable. Attempts at restoring encroached areas by the removal of some or all of the woody plants will normally result in an increase of grass production and thus also the grazing capacity. However, the results of woody plant removal may differ between vegetation types, with the outcome determined by both negative and positive responses to tree removal. The rapid establishment of tree seedlings after the removal of some or all of the mature woody plants may reduce the effective time span of restoration measures. In many cases the resultant re-establishment of new woody seedlings may in time develop into a state that is worse than the original state. This paper is an attempt to summarize existing knowledge on the importance of woody plants in savanna and explore measures, based on ecosystem dynamics, which can be utilized to restore encroached areas more successfully. It is hypothesized that a more stable environment can be created by maintaining or restoring savanna structure (large trees). In a structured savanna, large trees are able to suppress the establishment of new seedlings, while maintaining the other benefits of woody plants like soil enrichment and the provision of food to browsing herbivore species. Effective restoration of encroached areas should not be considered a once-off event, but rather a long-term commitment.

Keywords: Competition; Ecosystem dynamics; Savanna structure; Soil enrichment; Tree thinning

1. Introduction

In southern Africa the phenomenon of increasing woody plant abundance is commonly referred to as bush encroachment (O'Connor and Crow, 1999). It involves indigenous woody species occurring in their natural environment and is thus mainly associated with the savanna biome. The term savanna (or savannah), once restricted to describe central South American grasslands in Spanish, is now widely accepted as describing vegetation with a herbaceous layer, dominated by graminoids, with an upper layer of woody plants which can vary from widely spaced to a 75% canopy (Edwards, 1983; Rutherford and Westfall, 1994). The savanna biome of southern Africa extends from north of 22°S into northern Namibia, Botswana, Mozambique and South Africa. The biome is large, comprising about 959,000 km^2 or 46.2% of southern Africa (Rutherford and Westfall, 1994).

Many savanna areas are water-limited ecosystems and bush encroachment is considered a major factor contributing towards the low occurrence or even total absence of herbaceous plants in severe cases (Smit et al., 1999). The grazing capacity of large areas of the southern African savanna is reported to have declined due to bush encroachment, often to such an extent that many previously economic livestock properties are now no longer economically viable (Donaldson, 1980). Removal of some or all of the woody plants will normally result in an increase of grass production and thus also in the grazing capacity. However, the results of woody plant removal may differ between vegetation types, with the outcome determined by both negative and positive responses to tree removal (Teague and Smit, 1992). Cognisance must thus be taken of the ecological importance of woody plants in savanna ecosystems.

It is a fact that bush encroachment is still not well understood at a fundamental level, both by scientists

* Tel.: +27-51-401-2125; fax: +27-51-401-2608.
E-mail address: smitgn.sci@mail.uovs.ac.za (G.N. Smit).

0301-4797/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2004.02.005

and land owners who have to deal with the problem in a practical manner. In view of the often poor understanding of savanna ecosystem functioning, finding solutions to the problem, especially long-term solutions, is often difficult. Restoration of bush encroached areas, and in particular chemical control measures, should comply with two important requirements before they can be considered successful (Smit, 1998). They should be ecologically responsible and economically justifiable. In southern Africa, judged on these two basic requirements, it is conceived that very few attempts at restoring bush encroached areas can be considered successful (Smit, 1998). This is either because the cost is too high or the wrong approach was followed with the loss of beneficial woody plants and re-encroachment, often resulting in a state that is worse than before. In this regard distinction should also be drawn to land use patterns and resources available to address the problem. The management of bush encroachment on communal land is quite different from that on land used for commercial agriculture, with restoration more commonly attempted on commercial farmland. This paper will thus be more applicable to the latter land use systems.

This paper is an attempt to summarize existing knowledge on the importance of woody plants in savanna and explore measures, based on ecosystem dynamics, which can be utilized to manage the bush encroachment problem more successfully. Management of woody plants can be divided into preventative and restoration measures. Answers to preventative measures can often be found within the causes of bush encroachment, which will also be discussed. In view of the massive scale of bush encroachment that already occurred in parts of southern Africa's semi-arid savannas, restoration of encroached areas is, however, of significant importance to land owners. The main focus of this paper will be on an approach, based on savanna structure theories, for the effective restoration of encroached areas, especially with a view to achieve benefits over the long-term.

2. Importance of woody plants in savanna

2.1. Direct uses of woody plants

Woody plants in southern African savannas are used for firewood, rough construction timber, the production of charcoal and wood carving. For many rural communities, wood is still the only source of fuel for cooking and heating. The wood of several savanna woody species is known for its excellent fuel properties, especially species with dense heartwood. These species also yield excellent charcoal. Branches from spiny woody species like *Acacia tortilis* and *Acacia erubescens* are used for the construction of fencing kraals where livestock can be protected from predators (Smit, 1999).

With the expansion of the tourism industry the market for woodcarving from indigenous tree species has become very popular. Subsequently, woodcarving has developed into a major industry in many southern African countries and the wood of a wide range of tree species is being used. In addition, woody plants are an important source of food for browser herbivore species, which include both domestic stock and game. With the recent expansion of the game ranching industry in southern Africa the latter aspect is of increasing importance. Game ranching is a recognised agricultural enterprise and is currently one of the fastest growing sectors in the agricultural industry of southern Africa (Van der Waal and Dekker, 2000). The presence of woody plants creates unique habitats that can thus support a greater diversity of species, including herbivore game species, than other ecosystems without woody plants. In addition cattle may utilize significant amounts of browse during the dry season (Moleele, 1998).

Contrary to common belief that bush encroachment is detrimental to grazers, but not browsers, there are indications that bush encroachment may also be detrimental to some browsers. While tree thinning will reduce the available browse at peak biomass, trees in low density stands often display a better distribution of browse, having leaves in comparatively younger phenological states over an extended period (Smit, 2001).

2.2. Soil enrichment

Nutrients, such as nitrates, phosphorus, a series of anions and cations and various trace elements, are essential to the nutrition of plants, and act as determinants of the composition, structure and productivity of vegetation. While the base-richness of the parent material is initially important in determining soil fertility, biological activities are important in the creation and maintenance of localised areas of enhanced soil fertility, often on base-poor substrates (Scholes, 1991). Trees may act as such a biological agent, creating islands that differ from those in the open.

Ample evidence in support of soil enrichment under tree canopies exists, notably with regard to % total N, % organic C and various exchangeable cations like Ca, K, Mg and Na. Due to the higher organic C content the soil bulk density is often lower in soil under tree canopies (Bosch and Van Wyk, 1970; Kennard and Walker, 1973; Tiedemann and Klemmedson, 1973; Kellman, 1979; Bernhard-Reversat, 1982; Belsky et al., 1989; Young, 1989; Smit, 1994; Smit and Swart, 1994; Hagos, 2001).

The question of source and mechanism of soil enrichment under tree canopies remains largely unexplained. Many theories have been presented. Leaf litter from leaf fall has been mentioned as a possible source (Bosch and Van Wyk, 1970; Stuart-Hill et al., 1987; Belsky et al., 1989). Stemflow and throughfall represent another source of mineral input to soil (Kellman, 1979; Williams et al., 1987; Potter, 1992). The occurrence of N-fixation due to microbial activities under leguminous trees is a possible source of N enrichment (Felker and Clark, 1982;

Högberg and Kvarnström, 1982; Virginia and Delwiche, 1982; Shearer et al., 1983; Högberg, 1986). The contributions of bird droppings and dung of large mammals spending time under trees have also been mentioned as a source of soil enrichment (Belsky et al., 1989; Teague and Smit, 1992). This is an example of what Scholes (1991) termed 'nutrient import'.

From this information it can be concluded that savanna woody plants are essential biological agents that contribute to areas of enhanced soil fertility, which will be lost over time by the complete removal of all woody plants. This is especially important on nutrient-poor sandy soils. Evidence exists that soil enrichment under tree canopies is a slow process. This is demonstrated by correlations between total C and N in soil under tree canopies and tree girth, an index of age (Bernhard-Reversat, 1982; Hagos, 2001). This implies that larger (older) trees are more important in terms of soil enrichment than newly established individuals.

2.3. Positive influences of trees on the herbaceous layer

Due to the afore-mentioned existence of soil enriched under canopy sub-habitats, trees may have positive effects on grass growth. Stuart-Hill et al. (1987) demonstrated a consistent pattern of grass production around isolated *Acacia karroo* trees in the false thornveld of the Eastern Cape, South Africa. High yields were recorded under and immediately to the south of the tree canopy, and low yields to the immediate north of the canopy. They attributed the former to the favourable influence of the trees on the micro-environment (e.g. deposition of leaf litter, shading) and the latter to the reduced water input associated with the physical redistribution of rainfall by the trees.

In Kenya, Belsky et al. (1989) recorded significantly higher production of herbaceous plants under the canopies of both *A. tortilis* and *Adansonia digitata* than outside their canopies. In another study in South Africa, higher DM yields have been recorded under the canopies of leguminous trees (*A. erubescens*) in comparison with yields under either non-leguminous trees (*Combretum apiculatum*) or between the tree canopies, mainly due to the occurrence of the grass *Panicum maximum* under tree canopies (Smit and Swart, 1994). They concluded that contrary to most other grass species, the yield of *P. maximum*, a palatable and potentially very productive species, increased with an increase in tree density, up to a point whereafter the yield of this species was also suppressed through competition from the trees.

The association between *P. maximum*, and tree canopies is also documented in numerous other studies (Bosch and Van Wyk, 1970; Kennard and Walker, 1973; Belsky et al., 1989; Smit and Rethman, 1992; Smit and Van Romburg, 1993; Smit and Swart, 1994; Kinyamario et al., 1995; Schmidt et al., 1995; Durr and Rangel, 2000). *P. maximum* exhibited less water stress, had lower stomatal conductance and transpiration, and had a higher water use efficiency than, for example, *Themeda triandra*, which do not grow under tree canopies (Kinyamario et al., 1995). The association of *P. maximum* on tree canopies imply that total clearing of all woody plants will be detrimental to the long-term persistence of this species (Schmidt et al., 1995).

In contrast to the previous studies, Grossman et al. (1980) measured significantly greater biomass in open grassland than under *Burkea africana* and *Ochna pulchra* trees, although the canopied habitats did yield better quality forage. The relatively high nutrient status of soil under, compared to between, tree canopies, would be expected to lead to a relatively higher nutrient content of the grass growing under the tree canopy. However, reported results are variable. Grossman et al. (1980) reported no difference in the in vitro digestible organic matter content but a higher protein content of forage growing under *B. africana* trees that are growing in open savanna. In Mopane savanna, Smit (1994) reported that subhabitat differentiation by Mopane trees did provide some qualitative benefits. Some good forage grass species, which typically have high crude protein and in vitro digestibility values, prefer the canopied sub-habitat to the open sub-habitat and would probably be lost with the removal of all the Mopane trees. Pieterse and Grunow (1985) reported, however, that clearing all woody plants in *Combretum* veld in the Limpopo Province of South Africa had no effect on forage quality. In addition, Muoghalu and Isichei (1991) could find no significant difference between the crude protein, lignin and fibre content of forb species growing in the open and under tree canopies in Nigerian savanna.

2.4. Negative influences of trees on herbaceous plants and their response to tree thinning

The botanical composition and productivity of any mature stand of vegetation is largely determined by competition (Wilson, 1988). Competitive interactions between the woody and herbaceous components of savannas, involving mainly available soil water as the primary determinant of production, have been reported worldwide (Australia: Walker et al., 1986, 1989; Harrington and Johns, 1990; Scanlan and Burrows, 1990; North America: Scifres et al., 1982; Scifres, 1987; Archer et al., 1988; Bozzo et al., 1992; Haworth and McPherson, 1994; southern and east Africa: Donaldson and Kelk, 1970; Dye and Spear, 1982; Scholes, 1987; Belsky et al., 1989; Smit, 1994; Smit and Swart, 1994; Smit and Rethman, 1999; 2000; Richter et al., 2001).

The roots of woody plants are fundamental in their competitive interactions with herbaceous plants and other woody plants. Roots determine the spatial distribution of water and nutrient uptake and can cause an increase or a decrease in resource availability (Wu et al., 1985).

The roots of savanna woody plants extend well beyond their projected crown radius (Wu et al., 1985). In *Burkea savanna*, for example, the lateral roots of some species commonly extend linearly up to seven times the extent of

the canopy (Rutherford, 1980). The roots of *Colophospermum mopane* trees have been shown to extend horizontally to a distance of approximately 7.6 times their height and 12.5 times the extent of their canopies (Smit, 1994). In addition, a large proportion of the roots are concentrated at a shallow depth (Kellman, 1979; Muthana and Amora, 1980; Rutherford, 1983; Knoop and Walker, 1985; Castellanos et al., 1991; Smit and Rethman, 1998b), where they would actively compete with the shallow rooted herbaceous plants.

Smit and Rethman (2000) presented evidence that the roots of some drought adapted woody species, like *C. mopane*, are able to utilise soil water at a matric potential lower than that of grasses ($\psi < -1500$ kPa). This feature, combined with high rainwater runoff losses due to a lack of a herbaceous cover, resulted in a dramatic reduction in the amount of plant available water with an increase in tree density.

Moore et al. (1985) reported reduced production of the herbaceous layer with increasing tree abundance in Kalahari Thornveld and Shrub Bushveld of the Molopo area in South Africa. In another study Moore and Odendaal (1987) found no reduction in grass production up to a density of 200 tree equivalents (1 TE = a single stemmed tree 1.5 m high) per hectare in the Molopo area, but grass production declined linearly with further increases in tree density. A density of 2000 TE ha^{-1} almost completely suppressed grass growth. Richter (1991) and Richter et al. (2001) reported similar results from other parts of the Molopo area of the Northern Cape Province of South Africa. However, clearing woody plants in mixed savanna dominated by *C. apiculatum* and *A. tortilis* resulted in only a small improvement in grazing capacity (Donaldson, 1978).

Notwithstanding the references to higher grass DM production at low tree densities than in open savanna, much work has shown that the complete removal of trees leads to substantial increases in grass production (Donaldson and Kelk, 1970; Louw and Van der Merwe, 1973; Dye and Spear, 1982; Walker et al., 1986; Harrington and Johns, 1990; Scanlan and Burrows, 1990; Richter, 1991). Donaldson and Kelk (1970) found that grass yields did not decline linearly with increasing tree density. Yields declined rapidly as tree density increased to 350 mature *Acacia mellifera* trees per hectare, after which yields declined more slowly. Similar results were recorded in the Northern Cape Province of South Africa (Richter, 1991; Richter et al., 2001) and in the Mopane savanna of the Limpopo Province of South Africa (Smit, 1994).

These differences in the response to tree thinning or clearing may be ascribed to differences in soil type and soil fertility, both of which are important determinants of the magnitude of the response to tree thinning (Dye and Spear, 1982). In the years of high rainfall, higher yield responses have been attained in thornveld on relatively fertile clay soil than on nutrient poor sandy soil. Scholes (1987) estimated an absolute increase in herbaceous production with clearing of 300–500 kg ha^{-1} in *Combretum* savanna, 300–2500 kg ha^{-1} in *Acacia* savanna and 300–350 kg ha^{-1} in *C. mopane* savanna. During a period of prolonged water stress he noted increased grass tuft mortality in uncleared plots, especially on soils with a fine texture (*Acacia* and *C. mopane* sites). Different components of the herbaceous layer may also react differently to tree thinning. It was demonstrated by Smit (1994), for example, that in *C. mopane* savanna the DM yield of the grass component reacted positively to thinning but that the yield of forbs declined.

The reaction of the herbaceous component to tree removal will, however, depend on rainfall. Harrington and Johns (1990) concluded that increased herbaceous biomass following clearing of all trees of a *Eucalyptus* savanna in Australia would be obtained in any month only if rainfall exceeded 10 days' potential evapotranspiration and that herbaceous biomass would accrue at a rate of 0.5 g m^{-2} for each mm of monthly rainfall over this threshold. The total clearing of all woody plants resulted in a herbaceous biomass increase of 430–670%. In Mopane savanna, grass yields of thinned plots were considerably higher than those of densely wooded plots, especially during years of below average rainfall, while grass yields at high tree densities differed little between seasons of varying rainfall (Smit, 1994).

The aim of tree thinning or tree clearing is usually to achieve increased herbaceous production, but the species composition of herbaceous plants is also important as species may vary significantly in their acceptability to grazing herbivores. Other considerations include long-term stability as influenced by the state of plant succession (e.g. predominance of climax grasses, mainly perennials, as opposed to the predominance of pioneer grasses, mainly annuals), ground cover for prevention of soil erosion and water runoff (Snyman and Van Rensburg, 1986), and the maintenance of soil fertility (Hook et al., 1991).

The effect of bush encroachment on herbaceous cover differs between mesic and arid savannas. In mesic savannas herbaceous plants still co-exist with relatively high tree densities. Under these conditions changes in the composition of the herbaceous layer may occur following tree thinning as a result of changing regimes like shade, soil temperatures, soil water and soil nutrients. Depending on the situation, the advantage of increased production of herbaceous plants following tree thinning may, from an agricultural point of view, be offset by unfavourable species changes (e.g. whereby palatable, low fibre 'sweet' grasses are being out-competed and replaced by more unpalatable, high fibre 'sour' grasses; Smit and Rethman, 1999).

In arid savannas the herbaceous layer largely disappears under high tree densities, leaving large areas of bare ground. Crust formations will often form and these crust formations are known to reduce infiltration and cause substantial losses due to rainfall runoff (Hillel and Gardner, 1970; Agassi et al., 1981; Ralph, 1989; Harmse and Nel, 1990).

3. Causes of bush encroachment

An increase in woody plant abundance is primarily brought about by two processes. The first is by an increase in the biomass of already established plants (vegetative growth) and the second is by an increase in tree density, mainly from the establishment of seedlings (reproduction). Some influences may inhibit vegetative growth and/or reproduction, resulting in the decreased biomass of woody plants. The reasons for an increase in the abundance of woody plants in any vegetation type are diverse and complex. In most situations, the determinants of savanna systems were modified by man, either directly or indirectly. These determinants may either be primary (such as climate and soil) or secondary (such as fire and the impact of herbivores) (Teague and Smit, 1992; Roques et al., 2001; Ringrose et al., 2002). The latter are of particular interest since, although they act within the constraints imposed by the primary determinants, they can often be directly modified by management. Examples are the exclusion of occasional hot fires, the replacement of most of the indigenous browsers and grazers by domestic (largely grazing) livestock often at extremely high stocking rates, the restriction of movement of herbivores by the erection of fences, poor grazing management practice, and the provision of artificial watering points (Smit et al., 1999).

African savannas have an evolutionary history of high levels of browsing ungulate herbivory, capable of significantly modifying the structure and composition of woody plants (Owen-Smith, 1989). Browsing herbivores may include small herbivores (Belsky, 1984) and mega-herbivores, notably elephants (Jarman, 1971; Guy, 1981; Barnes, 1985; Okula and Sise, 1986; Kalemera, 1989; Ben-Shahar, 1991a; Lewis, 1991; Styles, 1993). Removal of browsing ungulate game species may have contributed to the bush encroachment problem.

The impact of poor grazing practices would seem to be particularly severe during dry seasons because of the greater negative effect of such management on grass growth than on the tree growth during periods of severe water stress (Britton and Sneva, 1981). The warmer and drier climate, which is reported to have been experienced over the past 100 or so years may also have favoured the woody component of the savannas over the grass component (Smeims, 1983). Biological interactions may be further complicating factors since they can modify the impact of the various determinants. For example, Lewis (1991) found that although a high percentage of coppiced *C. mopane* trees were browsed by elephants in Zambia, a mean mortality of only 0.5% was recorded. However, an incident of intense browsing followed by a below-average rainfall reportedly led to a 100% mortality of damaged trees.

It is generally conceded that high grazing pressure reduces the growth rate and reproductive potential of individual plants and in doing so influences the competitive relationships among the different species. Conversely, with an intact African mammal fauna, grazer-maintained, very short 'grazing lawns' occur in parts of East and southern Africa and these grasses maintain high productivity under intense grazing pressure (Bond, 2003). The fact that herbivores can keep grasses very short for prolonged periods can also have an indirect influence of woody plants by way of influencing the occurrence of fire (intensity and frequency). In this regard, Roques et al. (2001) reported that in the lowveld savanna of north-east Swaziland, high grazing pressures through their effect on fire frequency, was critical in promoting bush encroachment. The effect of fire on woody plants will be discussed in more detail later in the paper.

Grasses are fast-growing plants with roots in the upper layer of the soil and it is generally conceded that they can compete out woody plants for water and nutrients (Walter, 1939). Walker et al. (1981) hypothesised that below the grass root zone (called the subsoil), the woody vegetation has nearly exclusive use of any water that infiltrates to this soil depth. With overgrazing the grasses are removed, freeing up water and soil resources for the woody plants to exploit. Van Vegten (1983) also identified overgrazing of grasses as the main cause of the increased woody plant density in the eastern areas of Botswana. Skarpe (1990) showed that in non-grazed and moderately grazed areas, shrub densities showed no consistent trend, but increased where grazing was heavy. The tree species whose abundance increased were shallow rooted (*A. mellifera* and *Grewia flava*) which, according to Skarpe (1990), suggests that they were favoured by an increase in water availability in the surface soil following overgrazing of the grass layer. It is generally conceded, however, that trees are able to make more effective use of deep water than can the grasses (Walker and Noy-Meir, 1979; Stuart-Hill, 1985) so that any management actions which increase water penetration to depth in the soil profile should stimulate growth in already established trees.

Knoop (1982) observed that on a site dominated by *Acacia* species, large numbers of seedlings germinated and survived in an area cleared of vegetation, but that few were found in an uncleared area. Thompson (1960) reported that *C. mopane* seedlings could not establish where the grass cover was dense. In contrast to these reports, Brown and Archer (1989) recorded high rates of emergence and establishment of *Prosopis* on long-term protected plots, which carried a good grass cover. Similarly, in the eastern Cape, sparing veld did not prevent the establishment of *A. karroo* seedlings after the eradication of mature trees (Du Toit, 1972).

These reports are therefore at variance with the widespread and general view that long-term or heavy grazing is a requisite for increased rates of woody plant establishment. This invariably contributed to the conclusion by Ward (2000) that the conventional model of bush encroachment (Walter, 1939) that heavy grazing removes dominant grasses from competing with woody plants in the upper

soil layer has been found to be inappropriate or even wrong in many situations. However, this view does not unconditionally rule out the potential role of heavy grazing as a contributing factor to the process of bush encroachment. For example, Smit and Rethman (1992) reported that woody plants increased over a period of 52 years on a site in the Limpopo Province of South Africa, regardless of grazing treatment, but that the rate of increase was much faster in areas which had been severely grazed annually during the growing season. It was also shown by them that woody plants were positively correlated with Increaser IIb herbaceous species (species that increase under moderate overgrazing) and the latter were found to be negatively correlated with grass production.

In Botswana, Moleele and Perkins (1998) established that cattle density explained most of the variation in the density of encroacher woody species around boreholes. It was also demonstrated by Friedel (1987) that the increase of *A. karroo* in South African rangelands following disturbance was correlated with pasture condition, but this relationship was not linear. Friedel (1987) argued that this indicated a threshold in condition below which a dramatic increase in tree density is likely, but that there was evidence of a second threshold where soil compaction inhibits establishment of *A. karroo* seedlings.

It has been suggested that rainfall amount and frequency may play a key role in the occurrence of bush encroachment because trees require more rain to germinate than do grasses and may germinate in large numbers with or without grazing in rare, high rainfall years (Ward and Rohner, 1997).

The role of fire as a determinant of woody plant density has received considerable attention in the literature (Trollope, 1980; Rutherford, 1981; Belsky, 1984; Sweet and Mphinyane, 1986; Trollope and Tainton, 1986; Sabiiti and Wein, 1988; Higgins et al., 2000; Bond et al., 2003). Fire is widely used, ostensibly to control woody plants, in spite of it now having been repeatedly established that fire alone is not effective in killing woody components of the savannas of southern Africa (Rutherford, 1981; Belsky, 1984; Sweet and Mphinyane, 1986; Trollope and Tainton, 1986). This is, indeed, not surprising since the vegetation of Africa has for long been subjected to regular fires and the woody species which now occupy these regions are well able to survive in its presence. Veld fires may, however, be used to modify the structure of the woody layer and it is for this purpose that they are most useful. The total exclusion of fire or, conversely, the frequent occurrence of fire under conditions different from the above-mentioned fire regime, may benefit the establishment of woody plants (Smit et al., 1999).

Climate change and increased atmospheric CO_2 concentrations may also have an effect on the different floristic components of savanna ecosystems. According to Ringrose et al. (2002), with reference to Botswana rangelands, the expected increased aridity of the area will result in the degradation of vegetation stands from tree and shrub savanna to shrub and bush savanna. Increases in atmospheric CO_2 improve water-use efficiency and increased carbon uptake in C_3 plants (Polley et al., 1992) and in recent times may have favoured C_3 woody plants at the cost of C_4 grasses. Bond et al. (2003) tested the possible importance of CO_2/fire interactions. They suggested that the slow recovery of trees after fire, rather than differential photosynthetic efficiencies in C_3 and C_4 plants, might have been the significant factor in the Late Tertiary spread of flammable grasslands under low CO_2. This is because open, high light environments would have been a prerequisite for the spread of C_4 grasses. Their simulation further suggest that low CO_2 could have been a significant factor in the reduction of trees during glacial times, because of their slower regrowth after disturbance, with fire favouring the spread of grasses.

4. Ecosystem dynamics important for the effective restoration of encroached savanna

4.1. The importance of tree-on-tree competition and savanna structure

Where tree densities are very high the first operation which may be required will be the thinning of trees to some predetermined density, after which a post-thinning management programme will be required to keep an area open (Smit et al., 1999). Tree thinning or clearing by means of mechanical or chemical methods will result in immediate changes in competition between woody and herbaceous plants, which often determines the growth and structure of savannas. The resulting gaps will lead either to increased growth of neighbouring individuals or to the establishment of new individuals (Teague and Smit, 1992).

Thinning *C. mopane* stands has been shown to stimulate vegetative growth, flowering and seed bearing in the remaining trees (Smit, 1994; Smit and Rethman, 1998a). Over a three-year period the leaf DM yield of the trees increased by 64.9% in plots cleared to 10% of the original density, compared to an increase of 22.2% in uncleared plots. Scholes (1990) estimated that, through seedling establishment, recovery of cleared *C. mopane* thicket in the eastern lowveld to its pre-cleared competitive ability would occur within 14 years. This recovery period would be shortened by high rainfall and lengthened by drought. He estimated that the *C. mopane* trees would grow to their original pre-cleared state within 40 years.

In Botswana, stem basal area increased by 11–21% and tree height by 1.2–3.9% in thinned plots compared to increases of 3.5 and 1.1%, respectively, in uncleared plots (Coe, 1991). Smith and Goodman (1986) found a significant increase in both stem diameter and shoot extension of *A. nilotica* trees whose neighbours had been removed within a radius of 5 m. In time, therefore, the competitive ability of the remaining trees will gradually increase and so reduce

the impact of the initial thinning, even without seedling establishment.

An important determinant of woody seedling establishment is competition from other plants, either from other woody plants or herbaceous plants (Smith and Walker, 1983; Smith and Goodman, 1986; Schmitt et al., 1987; Smith and Goodman, 1987; Smith and Shackleton, 1988; Ben-Shahar, 1991b; Grundy et al., 1994). Ben-Shahar (1991b) has demonstrated that tree species of communities dominated by *Acacia senegal–A. tortilis* and *Euclea divinorum–A. nilotica* have characteristic dispersal strategies. These were manifested through intra- and inter-specific competition among the dominant tree species. *A. senegal* became dominant in areas previously dominated by *A. tortilis*, while *E. divinorum* was replacing previous dominance by *A. nilotica*.

Tree-on-tree competition appears to be species specific (Smith and Goodman, 1986) or related to the shade tolerance of the seedlings (Smith and Shackleton, 1988; O'Connor, 1995). In some, seedling establishment is unaffected by a tree canopy while in others, establishment is limited to between-canopy environments (Smith and Goodman, 1986; Grundy et al., 1994). In the Eastern Cape Province of South Africa, shading increased the density of surviving *A. karroo* seedlings (O'Connor, 1995), while at Nylsvley in the Limpopo Province of South Africa shading decreased the density of surviving *A. tortilis* seedlings (Smith and Shackleton, 1988). In another study it was established that *E. divinorum* does have the ability to establish under canopies, while seedlings of several *Acacia* species are distinctive as they fail to establish under the canopy of any established individual, regardless of species (Smith and Goodman, 1986). Both *A. nilotica* and *E. divinorum* were found to be regularly dispersed, but there was no significant correlation between nearest-neighbour distance and combined size for mixed-species nearest-neighbour pairs of *A. nilotica* and *E. divinorum* (Smith and Goodman, 1987).

Significant positive correlations between the size of a tree and the distance to its nearest neighbour were reported for large individuals of *Brachystegia spiciformis* and *Julbernardia globiflora* in Zimbabwe (Grundy et al., 1994). However, they did not observe the same regular dispersion pattern in stands of immature trees. They ascribe this to the fact that young plants often grow in under-canopy environments and that positive correlations between tree size and distance to nearest neighbour only develop through a thinning process as the trees mature.

4.2. The concept of stability and equilibrium in savanna ecosystems

Walker (1980) defined three concepts that have to do with system dynamics, viz. stability, resilience and a system's domain of attraction. He describes a stable system as one which when subjected to outside stress (e.g. drought or grazing) changes little in composition and production. A resilient system may or may not be stable, but remains attracted towards its equilibrium. A domain of attraction is described as that region of a system's state-space within which the system is attracted towards an equilibrium. According to Walker (1980), in a resilient system the domain of attraction is usually large. If a stable system changes to such an extent that it falls outside the domain of attraction, the amounts of the variables will then either change to a different equilibrium, or they will go to zero (extinction). Walker and Noy-Meir (1981) have explored this hypothesis further and have shown that in some conditions a single, stable equilibrium of woody vegetation and grasses exist. This concept follows the state-and-transition approach later described by Westoby et al. (1989) and implemented in various models (Plant et al., 1999).

The terms equilibrium and non-equilibrium as used in rangelands, are points of strong debate among scientists. The central aspect of this debate is the definition of the degree to which climate or consumers (herbivores) influence vegetation. One view is that consumers reach densities that degrade environments from a previous condition of equilibrium and the other view is that the dynamics of pastoral systems are non-equilibrial and primarily dictated by variability in rainfall (Ellis and Swift, 1988). Illius and O'Connor (1999) argued that the view that herbivory has little impact in climatically variable systems is unjustified. They proposed an alternative model in which it is assumed that despite the apparent lack of an equilibrium, animal numbers are regulated in a density-dependent manner by the limited forage available in key resource areas, which are utilized in the dry season. Their model asserts that strong equilibrial forces exist over a limited part of the system, with the animal population virtually uncoupled from resources elsewhere in the system.

Higgins et al. (2000) suggested a non-equilibrium mechanism of coexistence for savanna ecosystems. According to their model, grasses and trees coexist for a wide range of environmental conditions, and exhibit long periods of slow decline in adult tree numbers interspersed with relative infrequent recruitment events. Recruitment is controlled by rainfall, which limits seedling establishment, and fire, which prevents recruitment into adult size classes.

From the literature it would thus appear if ecosystems can display both equilibrial and non-equilibrial trends. In this regard the degree of aridity is important, with arid ecosystems that are less stable (non-equilibrial), while mesic ecosystems are often more stable (equilibrial).

5. Restoring encroached savanna with the correct approach to tree thinning

5.1. Utilizing the principle of relative stability of savanna ecosystems

The principle of stability, resilience and domain of attraction is shown in Fig. 1. The *x*-axis represents

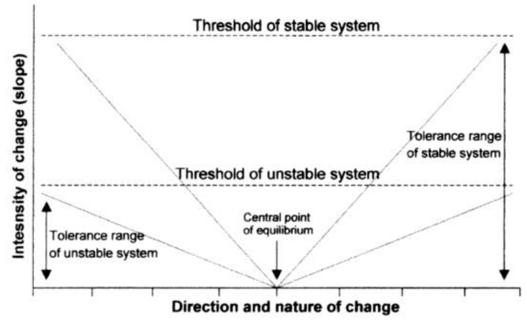


Fig. 1. Illustration of the principle of stability, resilience and domain of attraction (see text).

the direction and the nature of possible changes in the ecosystem. These changes can be due to a number of factors like drought and grazing. The *y*-axis represents the intensity or slope of the changes. Each specific ecological environment has a threshold above which further change will cause the system to go to another state or go extinct. In an ecosystem with a large domain of attraction the tolerance to change will be large (stable), while still able to return to the central point of equilibrium. The opposite is true for an ecosystem with a small domain of attraction (Fig. 1).

A simplified approach to the principle of stability, resilience and domain of attraction, as applied to bush encroachment, is shown in Fig. 2. Position 1 illustrates a state that is not encroached and which is productive and fairly stable. In this state, changes in response to determinants like drought or grazing may occur (depending on its resilience), but as the influence of these changes is removed it will still be attracted towards its original state. For it to return to its original state the changes must be within the limits of the ecosystem's domain of attraction. Should the intensity and duration of the influence of a determinant or determinants be such that the changes exceed the ecosystem's domain of attraction (threshold) the ecosystem will then change to another state (position 2, Fig. 2), which can also be fairly stable. Such a new state will then represent an encroached situation, which is unproductive.

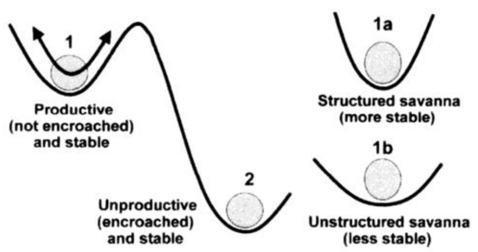


Fig. 2. Illustration of a simplified approach to the principle of stability, resilience and domain of attraction as applied to bush encroachment, illustrating the importance of savanna structure (see text).

Bush control measures usually attempt to restore the ecosystem to its former position (position 1, Fig. 2). However if for example, it is done in such a way that large trees are lost (unstructured) the resultant state will be productive (increased herbaceous yield), but stability will be low and such a state may return to an encroached state very quickly (1b, Fig. 2). This instability is due to the ecosystem's small domain of attraction. Preferably tree thinning should be conducted in such a way that larger trees are retained or encouraged to develop (structured), which will result in a more stable ecosystem with a large domain of attraction that is less prone to re-encroachment (1a, Fig. 2).

5.2. Maintaining or restoring savanna structure as a measure to increase stability

From the former discussion it is apparent that the presence of large trees, representing a structured savanna, may result in a more stable ecosystem. Such a structured ecosystem can be considered the most productive since all the benefits of woody plants are represented: soil enrichment, which is a slow process and thus mainly associated with larger (and thus older) trees; favourable sub-habitats for the maintenance of positive grass-tree associations (e.g. *P. maximum*) and increased stability as large trees may suppress the establishment and development of woody seedlings under their canopies or in their close proximity.

It is perceived that the loss of large trees from savanna ecosystems through indiscriminate, non-selective bush control measures is one of the major reasons why long-term solutions to the restoration of bush encroached areas are not achieved. Restoring savanna structure in cases where it is lost is a slow process. This will entail a highly selective approach where woody plants are thinned in such a way that the remaining trees will benefit from the reduced competition from other woody plants, resulting in increased growth and thus an increasing sphere of influence on newly establishing seedlings.

Due to environmental and ecological limitations the development of a highly structured woody vegetation may differ between different environments. This is also related to specific species, which are affected by gradients in precipitation, soils and relief. In some ecosystems the limitations may be such that a structured savanna will never develop. Any attempts at utilizing the principle of a structured savanna to create more stability against bush encroachment will thus be of little use in such environments. In Fig. 3 the most important determinants that influence the potential in which structure can develop, are illustrated. These determinants can influence the structure potential on their own or in combination with one or more of the other determinants. In a stable ecosystem the element, essential for plant growth, which is present in the most critical quantities will determine the growth of the plants, regardless of the quantities of other essential elements that are present.

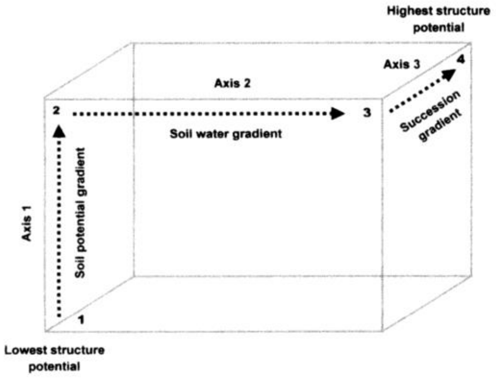


Fig. 3. Schematic illustration of the most important determinants that will influence the potential of a savanna area to develop structure (see text).

The first important determinant is soil. According to Campbell et al. (1995) much of the spatial heterogeneity in woody vegetation is correlated with various physical and chemical soil properties. For example a shallow, gravelly soil with a low soil nutrient status will limit the size and species of woody plants that can grow there (position 1, Fig. 3). An increase in rainfall on such soils will not improve the potential for a structured savanna vegetation to develop. As the soil potential improves (axis 1, Fig. 3) the potential for a structured woody vegetation to develop will also improve (position 2, Fig. 3). Over such a soil potential gradient the available soil water will play an increasingly important role. On a deep, fertile soil, rainfall will invariably become the next element (axis 2, Fig. 3) that will determine the potential to which a structured savanna will develop. A high structure potential will exist in areas with a deep, fertile soil and high soil water potential (position 3, Fig. 3).

In some savanna vegetation types the woody vegetation may develop from the dominance of more pioneer woody species, usually xerophytic spinescent microphyllous species, to a more stable savanna consisting of longer-lived broad-leaved species (axis 3, Fig. 3). This is facilitated by the ability of some broad-leaved woody species that are able to germinate and develop under the canopies of spinescent species like some *Acacia* species. In time the spinescent species may succumb to natural causes, where after the broad-leaved species predominate, since the spinescent species is unable to establish under the canopies of any established individual. Such a state, in combination with a high soil nutrient and soil water potential, represents the most stable condition with the highest structure potential (position 4, Fig. 3).

6. Conclusions

From this review it is clear that the presence of woody plants in savanna is associated with both positive and negative aspects, which are closely related to tree density or tree abundance. In view of this it can be concluded that any restoration program (chemical, mechanical or biological) of encroached areas should focus on tree thinning rather than on clearing of all woody plants. In making decisions on the intensity of tree thinning, the sizes of the trees which should be removed, and the species to be thinned, cognisance should thus be taken of the importance to achieve a balanced compromise between the reduction of the competitive effect of the trees on the herbaceous layer and the preservation of the positive influences which the trees may have.

The aridity of the area also needs to be borne in mind since more woody plants can be retained at wet than at dry sites without affecting herbaceous yields. It is also important to realise that there is no single optimum tree density and that even within a vegetation type, the optimum density falls within a range rather than being represented by a single value.

The rapid establishment of tree seedlings after the removal of some or all of the mature woody plants may reduce the effective time span of restoration measures. In many cases the resultant re-establishment of new seedlings may in time develop into a state that is worse than the original state. It is hypothesized that a more stable environment can be created, which is not as prone to the rapid regeneration of new woody plants, by making use of system dynamics. Here, the natural functioning of the savanna system is allowed to stimulate the development of an open savanna comprised mainly of large trees. It is based on the principle that the distance between a tree and its nearest neighbour of the same species is not determined purely by chance, but that tree spacing is normally distributed. The larger the individual, the greater is the distance between it and the nearest individual of the same species. This is particularly noticeable with *Acacia* species.

It has been shown that if a tree is killed, the reduced competition afforded to the remaining individuals results in an increase in their growth rate. Competition between individuals in a community can result in the stagnation of growth in a tree population. If, in such a community, low intensity thinning is applied, the growth rate of individuals adjacent to the thinned individuals will increase and this will lead to a suppression of the growth of other woody species within the area thinned. The key here is low intensity thinning. If thinning is too intensive, the remaining trees will provide insufficient competition to prevent woody plants from regenerating in the cleared area. In time this approach can assist in the creation of a more stable and structured savanna that is more resistant to bush encroachment, especially in areas where all the larger trees were lost through previous non-selective control measures.

It is important for any land manager to realize that there is no quick solution to the problem of bush encroachment. Effective management of bush encroachment should not be considered a once-off event, but rather a long-term

commitment. This may involve alternative approaches that are not necessarily the simplest or cheapest. The least expensive method of killing trees is invariably not the most economical approach in the long term. Once the established matured trees are lost from the ecosystem, land owners may discover that they now have to manage a much more unstable system that requires frequent and repeated efforts in dealing with a high rate of re-encroachment, often from other, more threatening woody species. It is also important to avoid or minimize other direct or indirect causes of bush encroachment. Of these, sound grazing management practices, especially during wet seasons, which will ensure a vigorous and competitive herbaceous layer are of critical importance.

References

Agassi, M., Shainberg, I., Morin, J., 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Science Society of America Journal 45, 848–851.

Archer, S., Scifes, C., Bassham, C.R., 1988. Autogenic succession in a sub-tropical savanna: conversion of grassland to thorn woodland. Ecological Monographs 58, 111–127.

Barnes, R.F.W., 1985. Woodland changes in Ruaha National Park (Tanzania) between 1976 and 1982. African Journal of Ecology 23, 215–221.

Belsky, A.J., 1984. Role of small browsing mammals in preventing woodland regeneration in the Serengeti National Park, Tanzania. African Journal of Ecology 22, 271–279.

Belsky, A.J., Amundson, R.G., Duxbury, J.M., 1989. The effects of trees on their physical, chemical and biological environments in a semi-arid savanna in Kenya. Journal of Applied Ecology 26, 1005–1024.

Ben-Shahar, R., 1991a. Selectivity in large generalist herbivores: feeding patterns of African ungulates in a semi-arid habitat. African Journal of Ecology 29, 302–315.

Ben-Shahar, R., 1991b. Successional patterns of woody plants in catchment areas in a semi-arid region. Vegetatio 93, 19–27.

Bernhard-Reversat, F., 1982. Biogeochemical cycles of nitrogen in a semi-arid savanna. Oikos 38, 321–332.

Bond, W.J., 2003. Top-down control of grassy ecosystems. Proceedings of the VII International Rangeland Congress, Durban, South Africa. Page 4.

Bond, W.J., Midgley, F.G., Woodward, F.I., 2003. The importance of low atmospheric CO_2 and fire in promoting the spread of grasslands and savannas. Global Change Biology 9(7), 973–982.

Bosch, O.J.H., Van Wyk, J.J.P., 1970. The influence of bushveld trees on the productivity of *Panicum maximum*: a preliminary report. Proceedings of the Grassland Society of southern Africa 5, 69–74.

Bozzo, J.A., Beasom, S.L., Fulbright, T.E., 1992. Vegetation responses to 2 brush management practices in south Texas. Journal of Range Management 45, 170–175.

Britton, C.M., Sneva, F.A., 1981. Effects of Tebuthiuron on western Juniper. Journal of Range Management 34, 30–32.

Brown, J.R., Archer, S., 1989. Woody plant invasion of grasslands: establishment of honey mesquite (*Prosopis glandilosa* var. *glandilosa*) on sites differing in herbaceous biomass and grazing history. Oecologia 80, 19–26.

Campbell, B.M., Cunliffe, R.N., Gambiza, J., 1995. Vegetation structure and small-scale pattern in Miombo woodland, Marondera, Zimbabwe. Bothalia 25, 121–126.

Castellanos, J., Maass, M., Kummerow, J., 1991. Root biomass of a dry deciduous tropical forest in Mexico. Plant and Soil 131, 225–228.

Coe, K.H., 1991. Effects of thinning on *Colophospermum mopane* in an indigenous woodland setting. Journal of the Forestry Association of Botswanna. 47–57.

Donaldson, C.H., 1978. Evaluation of *Cenchrus ciliaris*. II. A comparison of bushveld, debushed veld and bushveld combined with *Cenchrus pastures*. Proceedings of the Grassland Society of southern Africa 13, 45–48.

Donaldson, C.H., 1980. The extend of bush enchroachment in die bushveld areas of the Transvaal region. In: Proceedings worksession: bush enchroach-ment and thickening. Department of Agriculture and Fisheries, Pretoria, South Africa.

Donaldson, C.H., Kelk, D.M., 1970. An investigation of the veld problems of the Molopo area. I. Early findings. Proceedings of the Grassland Society of southern Africa 5, 50–57.

Durr, P.A., Rangel, J., 2000. The response of *Panicum maximum* to a simulated subcanopy environment. 1. Soil × shade interaction. Tropical Grasslands 34, 110–117.

Du Toit, P.F., 1972. *Acacia karroo* intrusion: the effect of burning and sparing. Proceedings of the Grassland Society of southern Africa 7, 23–27.

Dye, P.J., Spear, P.T., 1982. The effects of bush clearing and rainfall variability on grass yield and composition in south-west Zimbabwe. Zimbabwe Journal of Agricultural Research 20, 103–118.

Edwards, D., 1983. A broad-scale structural classification of vegetation for practical purposes. Bothalia 14, 705–712.

Ellis, J.E., Swift, D.M., 1988. Stability of African pastoral ecosystems: alternative paradigms and implications for development. Journal of Range Management 41, 458–459.

Felker, P., Clark, P.R., 1982. Position of mesquite (*Prosopis* spp) nodulation and nitrogen fixation (acetylene reduction) in 3-m long phraetophytically simulated soil columns. Plant and Soil 64, 297–305.

Friedel, M.H., 1987. A preliminary investigation of woody plant increase in the western Transvaal and implications for veld assessment. Journal of the Grassland Society of southern Africa 4, 25–30.

Grossman, D., Grunow, J.O., Theron, G.K., 1980. Biomass cycles, accumulation rates and nutritional characteristics of grass layer plants in canopied and uncanopied subhabitats of *Burkea savanna*. Proceedings of the Grassland Society of southern Africa 15, 157–161.

Grundy, I.M., Campbell, B.M., Frost, P.G., 1994. Spatial pattern, regeneration and growth rates of *Brachystegia spiciformis* and *Julbenardia globiflora*. Vegetatio 115, 101–107.

Guy, P.R., 1981. Changes in the biomass and productivity of woodlands in the Sengwa Wildlife Research area, Zimbabwe. Journal of Applied Ecology 18, 507–519.

Hagos, M.G., 2001. The influence of tree thinning and subhabitat differentiation on the reproductive dynamics of *Acacia mellifera* subsp. detinens. M.Sc. Agricultural Thesis, University of the Free State, Bloemfontein.

Harmse, H.J.von M., Nel, D.J., 1990. Chemical amelioration of a Swartland soil with prominent crusting. Applied Plant Science 4, 62–66.

Harrington, G.N., Johns, G.G., 1990. Herbaceous biomass in a *Eucalyptus* savanna wood land after removing trees and/or shrubs. Journal of Applied Ecology 27, 775–787.

Haworth, K., McPherson, G.R., 1994. Effexts of *Quercus emoryi* on herbaceous vegetation in a semi-arid savanna. Vegetatio 112, 153–159.

Higgins, S.I., Bond, W.J., Trollope, W.S.W., 2000. Fire, reprouting and variability: a recipe for grass-tree coexistence in savanna. Journal of Ecology 88, 213–229.

Hillel, D., Gardner, W.R., 1970. Transient infiltration into crust-topped profiles. Soil Science 109, 69–76.

Högberg, P., 1986. Nitrogen-fixation and nutrient relations in savanna woodland trees (Tanzania). Journal of Applied Ecology 23, 675–688.

Högberg, P., Kvarnström, M., 1982. Nitrogen fixation by the woody legume *Leucaena leucocephala* in Tanzania. Plant and Soil 66, 21–28.

Hook, P.B., Burke, I.C., Lauenroth, W.K., 1991. Heterogeneity of soil and plant N and C associated with individual plants and openings in North American shortgrass steppe. Plant and Soil 138, 247–256.

Illius, A.W., O'Connor, T.G., 1999. On the relevance of non-equilibrium concepts to arid and semi-arid grazing systems. Ecological Applications 9(3), 798–813.

Jarman, P.J., 1971. Diets of large mammals in the woodlands around Lake Kariba, Rhodesia. Oecologia (Berlin) 8, 157–178.

Kalemera, M.C., 1989. Observations on feeding preference of elephants in the *Acacia tortilis* woodland of Lake Manyara National Park, Tanzania. African Journal of Ecology 27, 325–333.

Kellman, M., 1979. Soil enrichment by neotropical savanna trees. Journal of Ecology 67, 565–577.

Kennard, D.G., Walker, B.H., 1973. Relationship between tree canopy cover and *Panicum maximum* in the vicinity of Fort Victoria. Rhodesia Journal of Agricultural Research 11, 145–153.

Kinyamario, J.I., Trlica, M.J., Njoka, T.J., 1995. Influence of tree shade on plant water status, gas exchange, and water use efficiency of *Panicum maximum* Jacq. and *Themeda triandra* Forsk. in a Kenya savanna. African Journal of Ecology 33, 114–123.

Knoop, W.T., 1982. Interactions of woody and herbaceous vegetation in two savannacommunities at Nylsvley. M.Sc. Thesis, University of the Witwatersrand, Johannesburg.

Knoop, W.T., Walker, B.H., 1985. Interactions of woody and herbaceous vegetation in a southern African savanna. Journal of Ecology 73, 235–253.

Lewis, D.M., 1991. Observations of tree growth, woodland structure and elephant damage on *Colophospermum mopane* in Luangwa Valley, Zambia. African Journal of Ecology 29, 207–221.

Louw, A.J., Van der Merwe, J.J., 1973. Influence of tree clearing of mixed veld on red clayey soil of the Springbok flats on veld composition and animal production. Technical Communication 110, Department of Agricultural Technical Services, Pretoria.

Moleele, N.M., 1998. Encroacher woody plant browse as feed for cattle. Cattle diet composition for three seasons at Olifants Drift, south-east Botswana. Journal of Arid Environments 40, 255–268.

Moleele, N.M., Perkins, J.S., 1998. Encroaching woody plants species and boreholes: is cattle density the main driving factor in the Olifants Drift communal grazing lands, south-eastern Botswana. Journal of Arid Environments 40, 245–253.

Moore, A., Odendaal, A., 1987. Die ekonomiese implikasies van bosverdigting en bosbeheer soos van toepassing op 'n speenkalfproduksiestelsel in die doringbosveld van die Molopo-gebied. Journal of the Grassland Society of southern Africa 4, 139–142.

Moore, A., Van Niekerk, J.P., Knight, I.W., Wessels, H., 1985. The effect of Tebuthiuron on the vegetation of the thorn bushveld of the northern Cape: a preliminary report. Journal of the Grassland Society of southern Africa 2, 7–10.

Muoghalu, J.I., Isichei, A.O., 1991. Effect of tree canopy cover on the yield, crude protein and fibre content of forb species in Nigerian Guinea savanna. Vegetatio 95, 167–175.

Muthana, K.D., Amora, G.D., 1980. Performance of *Acacia tortilis* (Forsk) under different habitats of the Indian arid zone. Annals of Arid Zones 19, 110–118.

O'Connor, T.G., 1995. *Acacia karroo* invasion of grassland: environmental and biotic effects influencing seedling emergence and establishment. Oecologia 103, 214–223.

O'Connor, T.G., Crow, V.R.T., 1999. Rate and pattern of bush encroachment in Eastern Cape savanna and grassland. African Journal of Range and Forage Science 16, 26–31.

Okula, J.P., Sise, W.R., 1986. Effects of elephant browsing on *Acacia seyal* in Waza National Park, Cameroon. African Journal of Ecology 24, 1–6.

Owen-Smith, N., 1989. Megaherbivores: The Influence of Very Large Body Size on Ecology, Cambridge University Press, Cambridge.

Pieterse, P.A., Grunow, J.O., 1985. Production and quality of a number of grass species in the *Combretum*-veld of Northern Transvaal. Journal of the Grassland Society of Southern Africa 2, 26–30.

Plant, R.E., Vayssiéres, M.P., Greco, S.E., George, M.R., Adams, T.E., 1999. A qualitative spatial model of hardwood rangeland state-and-transition dynamics. Journal of Range Management 52, 51–59.

Polley, H.W., Johnson, H.B., Mayeux, H.S., 1992. Carbon dioxide and water fluxes of C_3 annuals and C_3 and C_4 perennials at subambient CO_2 concentrations. Functional Ecology 6, 693–703.

Potter, C.S., 1992. Stemflow nutrient inputs to soil in a successional hardwood forest. Plant and Soil 140, 249–254.

Ralph, W., 1989. Water-ponding reclaims inland soils. Rural Research 144, 9–12.

Richter, C.F.G., 1991. Grass-shrub interactions in the bushveld areas of the Northern Cape. M.Sc. Agricultural Thesis, University of the Free State, Bloemfontein.

Richter, C.G.F., Snyman, H.A., Smit, G.N., 2001. The influence of tree density on the grass layer of three semi-arid savanna types of southern Africa. African Journal of Range and Forage Science 18, 1–7.

Ringrose, S., Chipanshi, A.C., Chanda, A.C., Matheson, R., Motoma, L., Magole, I., Jellema, A., 2002. Climate-and human-induced woody vegetation changes in Botswana and their implications for human adaptation. Environmental Management 30(1), 98–109.

Roques, K.G., O'Connor, T.G., Watkinson, A.R., 2001. Dynamics of shrub encroachment in an African savanna: relative influence of fire, herbivory, rainfall and density dependence. Journal of Applied Ecology 38, 268–280.

Rutherford, M.C., 1980. Field identification of roots of woody plants of the savanna ecosystem study area, Nylsvley. Bothalia 13, 171–184.

Rutherford, M.C., 1981. Survival, regeneration and leaf biomass changes in woody plants following spring burns in *Burkea africana–Ochna pulchra* savanna. Bothalia 13, 531–552.

Rutherford, M.C., 1983. Growth rates, biomass and distribution of selected woody plant roots in *Burkea africana–Ochna pulchra* savanna. Vegetatio 52, 45–63.

Rutherford, M.C., Westfall, R.H., 1994. Biomes of southern Africa: an objective categorization. Memoirs of the Botanical Survey of South Africa, 63.

Sabiiti, E.N., Wein, R.W., 1988. Fire behaviour and the invasion of *Acacia sieberiana* into savanna grassland openings. African Journal of Ecology 26, 301–313.

Scanlan, J.C., Burrows, W.H., 1990. Woody overstory impact on herbaceous understory in *Eucalyptus* spp. communities in central Queensland. Australian Journal of Ecology 15, 191–197.

Schmitt, J., Eccleston, J., Ehrhardt, D.W., 1987. Dominance and suppression, size-dependent growth and self-thinning in a natural *Impatiens capensis* population. Journal of Ecology 75, 651–665.

Schmidt, A.G., Theron, G.K., Van Hoven, W., 1995. Herbaceous phytomass and composition changes in relation to woody plant density in the Mixed Bushveld of the Northern Province, South Africa. South African Journal of Botany 61, 278–280.

Scholes, R.J., 1987. Response of three semi-arid savannas on contrasting soils to the removal of the woody component. Ph.D Thesis, University of the Witwatersrand, Johannesburg.

Scholes, R.J., 1990. The regrowth of *Colophospermum mopane* following clearing. Journal of the Grassland Society of southern Africa 7, 147–151.

Scholes, R.J., 1991. The influence of soil fertility on the ecology of south African dry savannas. In: Werner, P.A., (Ed.), Savanna Ecology and Management. Australian Perspectives and Intercontinental Comparisons, Blackwell, London, pp. 71–76.

Scifres, C.J., 1987. Economic assessment of tebuthiuron-fire systems for brush management. Weed Technology 1, 22–28.

Scifres, C.J., Mutz, J.L., Whitson, R.E., Drawe, D.L., 1982. Interrelationships of huisache canopy cover with range forage on the coastal prairie. Journal of Range Mangement 35, 558–562.

Shearer, G., Kohl, D.H., Virginia, R.A., Bryan, B.A., Skeeters, J.L., Nilsen, E.T., Sharifi, M.R., Rundel, P.W., 1983. Estimates of N_2-fixation from variation in the natural abundance of 15N in Sonoran desert ecosystems. Oecologia (Berlin) 56, 365–373.

Skarpe, C., 1990. Shrub layer dynamics under different herbivore densities in an arid savanna, Botswanna. Journal of Applied Ecology 27, 873–885.

Smeims, F.E., 1983. Origin of the bush problem-a geological and ecological perspective of contemporary distributions. In: Proceedings of the Bush Management Symposium, Society of Range Management, Albuquerque, New Mexico.

Smit, G.N., 1994. The influence of intensity of tree thinning on Mopani veld. Ph.D Thesis, University of Pretoria, Pretoria.

Smit, G.N., 1998. Management of rangeland in southern Africa with special reference to bush enchroachment. Unpublished paper presented at the Master Farmer day on the farm Waldorf, Otawi, Namibia, 15th April 1998.

Smit, G.N., 1999. Guide to the Acacias of South Africa, Briza Publications, Pretoria, 224 pp.

Smit, G.N., 2001. The influence of tree thinning on the vegetative growth and browse production of *Colophospermum mopane*. South African Journal of Wildlife Research 31, 99–114.

Smit, G.N., Rethman, N.F.G., 1992. Inter-related floristic changes associated with different long-term grazing treatments in Sourish Mixed Bushveld. Journal of the Grassland Society of southern Africa 9, 76–82.

Smit, G.N., Rethman, N.F.G., 1998a. The influence of tree thinning on the reproductive dynamics of *Colophospermum mopane*. South African Journal of Botany 64, 25–29.

Smit, G.N., Rethman, N.F.G., 1998b. Root biomass, depth distribution and relations with leaf biomass of *Colophospermum mopane*. South African Journal of Botany 64, 38–43.

Smit, G.N., Rethman, N.F.G., 1999. The influence of tree thinning on the establishment of herbaceous plants in a semi-arid savanna of southern Africa. African Journal of Range and Forage Science 16, 9–18.

Smit, G.N., Rethman, N.F.G., 2000. The influence of tree thinning on the soil water in a semi-arid savanna of southern Africa. Journal of Arid Environments 44, 41–59.

Smit, G.N., Swart, J.S., 1994. The influence of leguminous and non-leguminous woody plants on the herbaceous layer and soil under varying competition regimes in Mixed Bushveld. African Journal of Range and Forage Science 11, 27–33.

Smit, G.N., Van Romburgh, K.S.K., 1993. Relations between tree height and the associated occurrence of *Panicum maximum* Jacq. in Sourish Mixed Bushveld. African Journal of Range and Forage Science 10, 151–153.

Smit, G.N., Aucamp, A., Richter, C.G.F., 1999. Bush encroachment: an approach to understanding and managing the problem. In: Tainton, N.M., (Ed.), Veld Management in Southern Africa, University of Natal Press, Pietermaritzburg.

Smith, T.M., 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.

Smith, T.M., Goodman, P.S., 1987. Successional dynamics in an *Acacia nilotica–Euclea divinorum* savannah in southern Africa. Journal of Ecology 75, 603–610.

Smith, T.M., Shackleton, S.E., 1988. The effect of shading on the establishment and growth of *Acacia tortilis* seedlings. South African Journal of Botany 54, 375–379.

Smith, T.M., Walker, B.H., 1983. The role of competition in the spacing of savanna trees. Proceedings of the Grassland Society of Southern Africa 18, 159–164.

Snyman, H.A., Van Rensburg, W.L.J., 1986. Effect of slope and plant cover on run-off and water use efficiency of natural veld. Journal of the Grassland Society of Southern Africa 3, 153–158.

Stuart-Hill, G.C., 1985. Competitive interactions between herbaceous and woody vegetation in semi-arid Acacia savanna in the Eastern Cape. M.Sc. Agricultural Thesis, University of Natal, Pietermaritzburg.

Stuart-Hill, G.C., Tainton, N.N., Barnard, H.J., 1987. The influence of an *Acacia karroo* tree on grass production in its vicinity. Journal of the Grassland Society of southern Africa 4, 83–88.

Styles, C.V., 1993. Relationships between herbivores and *Colophospermum mopane* of the northern Tuli Game Reserve. M.Sc. Thesis, University of Pretoria, Pretoria.

Sweet, R.J., Mphinyane, W., 1986. Preliminary observations on the ability of goats to control post-burning regrowth in *Acacia nigrescens/Combretum apiculatum* savanna in Botswanna. Journal of the Grassland Society of southern Africa 3, 79–84.

Teague, W.R., Smit, G.N., 1992. Relations between woody and herbaceous components and the effect of bush-clearing in southern African savannas. Journal of the Grassland Society of Southern Africa 9, 60–71.

Thompson, J.G., 1960. A description of the growth habits of mopani in relations to soil and climatic conditions. In: Proceedings of the first Federal Science Congress, Salisbury, southern Rhodesia.

Tiedemann, A.R., Klemmedson, J.O., 1973. Effect of Mesquite on physical and chemical properties of the soil. Journal of Range Management 26, 27–29.

Trollope, W.S.W., 1980. Controlling bush encroachment with fire in the savanna areas of South Africa. Proceedings of the Grassland Society of southern Africa 15, 173–177.

Trollope, W.S.W., Tainton, N.M., 1986. Effect of fire intensity on the grass and bush components of the eastern Cape Thornveld. Journal of the Grassland Society of southern Africa 2, 27–42.

Van der Waal, C., Dekker, B., 2000. Game ranching in the Northern Province of South Africa. South African Journal of Wildlife Research 30, 151–156.

Van Vegten, J.A., 1983. Thornbush invasion in a savanna ecosystem in eastern Botswana. Vegetatio 56, 3–7.

Virginia, R.A., Delwiche, C.C., 1982. Natural 15N abundance of presumed N_2-fixing and non-N_2-fixing plants from selected ecosystems. Oecologia (Berlin) 54, 317–325.

Walker, B.H., 1980. Stable production versus resilience: a grazing management conflict. Proceedings of the Grassland Society of southern Africa 15, 79–83.

Walker, B.H., Noy-Meir, I., 1979. Aspects of stability and resilience of savanna ecosystems. Proceedings of the Symposium on Dynamic Changes in Savanna Ecosystems. CSIR, Pretoria, South Africa.

Walker, B.H., Noy-Meir, I., 1981. Aspects of the Stability and Resilience of Savanna Ecosystems. In: Huntley, B.J., Walker, B.H. (Eds.), Ecology of Tropical Savannas, Springer, Berlin.

Walker, B.H., Ludwig, D., Holling, C.S., Peterman, R.M., 1981. Stability of semi-arid grazing systems. Journal of Ecology 69, 473–498.

Walker, J., Robertson, J.A., Penridge, L.K., Sharpe, P.J.H., 1986. Herbage response to tree thinning in a *Eucalyptus creba* woodland. Australian Journal of Ecology 11, 135–140.

Walter, H., 1939. Grassland, savanne und busch der ariden teile Afrikas in ihrer ökologischen. Bedingtheit Jaarboek Wissenschaftliche Botanie 87, 750–860.

Ward, D., 2000. The effects of grazing on plant biodiversity in arid ecosystems. In: Waide, R., Gosz, J., Shachak, M. (Eds.), Dryland Biodiversity, Oxford University Press, Oxford.

Ward, D., Rohner, C., 1997. Anthropogenic causes causes of high mortality and low recruitment in three Acacia tree taxa in the Negev desert, Israel. Biodiversity and Conservation 6, 877–893.

Westoby, M., Walker, B., Noy-Meir, I., 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42, 266–274.

Williams, A.G., Kent, M., Ternan, J.L., 1987. Quantity and quality of bracken throughfall, steamflow and litterflow in a Dartmoor catchment. Journal of Applied Ecology 24, 217–230.

Wilson, J.B., 1988. Shoot competition and root competition. Journal of Applied Ecology 25, 279–296.

Winter, W.H., Mott, J.J., McLean, R.W., 1989. Evaluation of management options for increasing the productivity of tropical savanna pastures 3. Trees. Australian Journal of Experimental Agriculture 29, 631–634.

Wu, H., Sharp, P.J.H., Walker, J., Penridge, L.K., 1985. Ecological field theory: a spatial analysis of resource interference among plants. Ecological Modelling 29, 215–243.

Young, A., 1989. Agroforestry for Soil Conservation, CAB International, Wallingford, 276 pp.

Appendix 2 Views and experience of key stakeholders in biomass harvesting

1 Representatives of the farming community

Interview: Mr Danie van Vuuren: Namibia Agricultural Union
Principle: Agriculture Employers Association
Tel No: 0811126119

As a member of the Namibia Agricultural Union Mr van Vuuren represents more than 500 charcoal producers in Namibia, though a substantial number are currently inactive.

Presently there is a huge national as well as international market for charcoal.

A permit which stipulates strict harvesting conditions is required before any land owner can utilize any undesired bushes or trees for charcoal or any other wood product. This permit is valid for only three months wher after it must be renewed.
Under the Principles and Criteria of the Forest Stewartship Council certification is also required for the export of charcoal. These Principles and Criteria are not specific to any particular country or region as they are applicable worldwide and are relevant to forest areas and different ecosystems, as well as cultural, political and legal systems.
All ten FSC principles and criteria must be applied in any forest management unit before it can receive FSC certification. They also apply to all forest types and areas within the management unit included in the scope of the certificate.
The ten FSC Principles require the following of the forest owner or manager:

Principle 1: Compliance with laws and FSC Principles – to comply with all laws, regulations, treaties, conventions and agreements, together with all FSC Principles and Criteria.
Principle 2: Tenure and use rights and responsibilities - to define, document and legally establish long-term tenure and use rights.
Principle 3: Indigenous peoples' rights - to identify and uphold indigenous peoples' rights of ownership and use of land and resources.
Principle 4: Community relations and worker's rights - to maintain or enhance forest workers' and local communities' social and economic well-being.
Principle 5: Benefits from the forest - to maintain or enhance long term economic, social and environmental benefits from the forest.
Principle 6: Environmental impact - to maintain or restore the ecosystem, its biodiversity, resources and landscapes.
Principle 7: Management plan - to have a management plan implemented, monitored and documented.
Principle 8: Monitoring and assessment - to demonstrate progress towards management objectives.
Principle 9: Maintenance of high conservation value forests - to maintain or enhance the attributes which define such forests.
Principle 10: Plantations - to plan and manage plantations in accordance with FSC Principles and Criteria.

The well being of charcoal harvesters/workers on a farm is a very sensitive issue and for that purpose principle 4 can cause the refusal of such certification. For this purpose the Namibian Cabinet also specified certain minimum requirements for workers which land owners must adhere to.
In practice the Labour Act does not serve as a stumbling block for charcoal production or biomass harvesting. The availability of workers for this purpose is, however, a huge problem.
Although these principles are in place, there are certain countries which do not require FSC certification and therefore charcoal can be exported/shipped to them. For many farmers these procedures are very

frustrating and an alternative way of utilizing the existing biomass without endangering the environment would be preferable.

Interview: Mr Mushohabanje Immanuel Mwilima
Acting Executive Director: Namibia National Farmers Union (NNFU)
Tel no: 26461271117
Cell: 264811499036

The opinions expressed here represent the views of the Namibia National Farmers Union.

Bush encroachment is a serious problem and contributes to the process of desertification. Most of the members belonging to the NNFU are suffering from land degradation as a result of bush encroachment and these include commercial farmers, farmers who own land under the Affirmative Action Scheme, resettled farmers as well as people making a living in certain bush encroached communal land areas.

Combatting invader bushes will require a lot of capacity building - no only for farmers but especially those (extension officers/technicians) who must train and advise farmers. A project where invader bushes are going to be harvested for the purpose of establishing an electric power plant will benefit farmers enormously in terms of improved grazing. Therefore the NNFU strongly support this project, provided that is done in an environmentally responsible way.

Farmers participating in such a project should be well informed and trained in advance so that they can assist the Government in exerting proper control over the harvesting process. The primary responsibility remains with the Government. The principles laid down in Policies and Acts should be implemented and for this purpose the capacity to implement these principles should be built among extension/forestry personnel.

After care is regarded as an integral part of the whole project. Government should support farmers in various ways which could include subsidies on interest rates and herbicides. For resettled farmers a 100% subsidy will be required on herbicides/interest rates. This assistance should only apply for 5 years after which the farmer must reach a stage where s/he must become independent.
Charcoal production should also be supported by government as an alternative way of earning money.

Whatever is intended to be done, a proper balance in the ecosystem should be maintained.

Interview: Mr Pieter Potgieter
Chairman Charcoal Producers Society
Tel No: 0814873785

Mr Potgieter is a business entrepreneur producing charcoal on private farms. In most cases he is responsible for harvesting the necessary biomass without paying the owner for the biomass. There are however, certain farms where he is responsible for the aftercare by means of providing arboricides.

It takes the six labourers 6 months to clear 200 ha and produce charcoal from the harvested biomass (farm situated 20 km east of Otjiwarongo). The charcoal yield from this area is 180 tons at a rate of 1 ton per 5 tons biomass, therefore a total of 900 tons biomass = 4.5 tons/ha. The total amount of biomass/ha (according to his experience) is 2.5 times the harvested amount = 11.2 tons/ha.

The ratio of Mopane trees is one ton charcoal per four tons biomass. In order to adhere to environmental principles, trees that should not be harvested are identified and clearly marked beforehand. He is of the

opinion that the biomass yield in the vicinity of the intended biomass power plant is adequate and that it will meet the minimum requirements.

However, there is a strong resistance among farmers to allow people (harvesters) on their farms, mainly because of theft.

The price for unsifted charcoal varies between N$1400 and N$1650 per ton. On average 60% of the total weight consists of large coals (Price N$1850/ton) and 40% of fine coals at a price of N$700 to N$900/ton. The labour cost is N$700 per ton.

A permit for harvesting is issued by the Directorate Forestry (MAWF) and is valid for 3 months. This permit contains strict measures which harvesters must adhere. i.e. no stems harvested should have a diameter of more than 15 cm.

According to his experience, regrowth will take about 10 years to produce the same amount of biomass. If the timing of the intended harvesting on a farm is too far in the future he is of the opinion that farmers will be very reluctant to sign a fuel supply agreement unless it makes provision for a price which allows for inflation.

Interview: Mr Roelie Venter
Project Manager: Implementation of National Rangeland Management Policy and Strategy Policy and Strategy and Farmer

Drastic increases in carrying capacity are achieved by means of bush thinning. On the farm of Hendrik Botha (Okahandja district) the carrying capacity increased from 25 kg/ha to 45 kg/ha within four years after chemical treatment. There was also a drastic increase from 9.5 kg to 18.5 kg live weight per hectare in meat production. The affordability of this exercise is only possible on farms of more than 10 000 ha.

Currently the average size of farms is in the order of 5 000 ha and at an average production cost of at least 50 % the net income per farm is approximately N$300 000 per annum. From this income rent, interest and capital repayments on farm-related debts, as well as taxes like income and land tax, as well as owners' remuneration must still be paid. Subsequently farmers cannot afford to pay for de-bushing with an unaffordable increase in additional indebtedness.

Since 2006 to 2014 the production cost on a farm increased by 120 %, while the beef price increased only by 73 %. Therefore, in general, farmers are not able to pay for de-bushing and will require a 100 % subsidization.

The only way to enable them to do de-bushing is to get an income from the biomass on the farm. This amount should be negotiated with the agricultural sector in general. The income from charcoal production could serve as an indication of what farmers should be paid.

2 Stakeholders farming community

Interview: Mr Tinus Pretorius
Farm: Phantom No 490
Size: 5 176 ha
Farmer and Business man: Utilization of biomass
Tel No: 0811282429

Mr Pretorius has many years of intensive experience in the utilization of invader bushes for various purposes as well as bush thinning to restore the initial carrying capacity of the rangelands on his farm. In his experience severe re-infestation of bushes occurred where the land has been chemically cleared and chemical treatment had to be applied again to kill them. Fire as an aftercare did not deliver any positive results. Where *Dichrostachys cinerea* (Sickle bush), occurred the situation became much worse.

He is of the opinion that no aftercare should be allowed where bushes are harvested for an electricity plant. According to him it will take 10 years before regrowth will result in the same biomass yield/ha, during which excellent grazing will be available for the first 7 years. Therefore a combination of "bush farming" and cattle farming will be much more lucrative.

Water run-off to dams will also increase after bush harvesting/clearing without a detrimental effect on the grazing.

Farmers should benefit from the establishment of such a power plant. Therefore Nampower or the appointed contractor should pay a certain amount per ton biomass delivered by the farmer. To ensure participation of farmers, such a power plant should be established in the form of a company in which farmers can buy shares.

In the harvesting process special care must be taken to use horizontal grinders to chip the wood. This procedure will be more effective and cheaper. To be environmentally more effective and efficient, large trees should be avoided and the softer material of invader species should be targeted only. It is predicted that during the re-harvesting, the production costs will even be lower because of the softer biomass.

Based on his experience, a harvestable biomass of 10t/ha is within easy reach in the intended power plant area. This will still allow for a variation in desired trees and bushes per hectare. The radius around such a power plant should not be more than 30 km.

Even if the delivery of biomass is contracted out, individual farmers should be allowed to harvest and deliver to the power plant at their own cost at a reasonable price (in the order of N$ 700/ton).

Financing at reasonable interest rates should be made available by financial institutions (such as the Development Bank of Namibia, Agribank etc.) as well as repayment conditions for purchasing suitable equipment and initial input costs.

Interview: Mr Timo Bredenhan
Farm: Buffelshoek
Size: 5 000 ha

The soil types on this farm vary from fairly heavy sandy loam to loamy in the western side to sandy in the east.

Since the early nineties this farmer has been involved in combating invader bushes. The main problem species were *A. mellifera, A. reficiens, A. luderitzii* and *D. cinerea*. In some areas the latter became very dominant. A variety of methods to clear large areas has been used which included:

- Selective to aerial application of various types of arboricides (roots, foliar and stem).
- Selective manual removal of bushes by stumping/felling and using these bushes for charcoal production.
- Use of caterpillar rollers.
- Use of browsers to a lesser extent.

The results on this farm were very disappointing. In almost all cases the treatments ended up in severe re-infestation. Although aftercare was done after a few years, various bush species (mainly pioneers) started to thicken again. Today the problem in some areas is even worse. With a total rainfall in the order of 300 mm during the previous rainy season, it is clear that the present densities of invader species are suppressing the growth of grasses. Perennial grasses are very scarce in general the soils are almost totally denuded. Newly established bush seedlings are present in alarming numbers.

All these efforts were very expensive. Financially, he took a serious knock and presently he has reached a stage where despondency is obvious. The prospect of establishing a biomass power plant fills him with optimism that such a project could drasically improve his farming situation, provided that farmers are remunerated for the biomass in such a way that they can do the necessary aftercare.

Based on his experience of the current regrowth rate there will be the same amount of biomass after 10 to 15 years. An area was pointed out to the visiting team where *D. cinerea* has thickened within 15 years to the extent that no animals are able to penetrate these camps.

He is willing to enter into an agreement provided that they will be fairly compensated for the biomass. The income generated from charcoal production should serve as the minimum payment. Such an amount should be enough to cover the cost for aftercare.

The number of workers entering the farm should be restricted and there must be proper control over the workers themselves as well as the kind of trees to be harvested. According to his experience the total biomass is between 12 and 15 tons per hectare.

Interview: Mr JL Botha
Farm Tokai (Tokai, Randveld and Knoll)
Size: 12 000 ha
Tel no 0812900625

- Farmers will only commit themselves if they are paid for the biomass that is removed from the farm.
- The minimum price should equal the income per ton charcoal that they are earning presently. Price of charcoal is N$ 1500/ton and the price paid to the harvesters is in the order of N$700 excluding transport.
- On average 5 tons of biomass are needed to produce one ton of charcoal.
- The production rate is at 9 tons charcoal per 6 weeks, which equals one charcoal month. Thereafter the charcoal must still be bagged.
- The small size drums are used for charcoal production since the large kilns are impractical in that they are difficult and expensive to move them from one location to another.
- Large areas have already been de-bushed over a period of 35 years. Methods varied from manual to aerial application of arboricides and the use of rollers and caterpillars. On average all these cleared areas became re-encroached again between 10 and 15 years despite after care measures and the present bush population consists mainly of *D. cinerea, A. mellifera, A. reficiens, A luederitzii, Grewia flavescens* and *Grewia flava.* On the farm Knoll very high densities of *A. reficiens, A. luederitzii* and *A. mellifera* occured. The soils on this farm vary from sandy to loamy soils.
- The regrowth was enough to harvest more or less the same amount of biomass as before the initial bush clearing took place.
- Bush clearing as well as after care is too expensive and the owner cannot afford to do it. The only way in which after care will be feasible is when farmers are paid for the biomass. This should at least be based on the net income that is derived from charcoal production.
- If the envisaged power plant is not going to be established, there is no hope for farmers to win this battle.

Interview: Mr Jaque Swart
Farm: Randveld No 167
Size: 3 949 ha

The soil on this farm varies from sandy loam to loam on the eastern side of the farm with the largest area consisting of ridges where dolomite, limestone and quartzite dominate. Presently he is farming with cattle in combination with game. He also runs a butchery on his farm to add value to the meat that is produced.

Since bush encroachment became a huge problem, bushes were cleared by means of a bulldozer from 1991 to 1998. All these treated areas were afterwards well covered with desired grass species, but these favourable conditions lasted for approximately 10 years. Re-infestation by mainly *A. mellifera, A. luederitzii* and *A. reficiens* resulted in a heavily bush encroached farm within 15 years of clearing.

The owner has already geared himself to start with the production of charcoal and he is able to produce about 9 tons per month (Which equals a nett income of approximately N$ 6 300/month). When possible, he will expand the rate of charcoal production. He is not willing to allow harvesting of bushes without remunerated. In principle he is looking forward to the opportunity being offered by the biomass project. Therefore, he will certainly participate in making biomass available to Nampower.

From his own experience the establishment of seedlings were much less in areas where not all bushes/trees were removed and for this reason he will not allow total removal of bushes and trees.

Interview: Mr Pieter Krohne
Farm Arcadia No 320
Size 10 000 ha

Four years ago Mr Krohne took the farming business over from his father. Up until that stage he served as an extension technician within the Ministry of Agriculture, Forestry and Water for about 18 years.

If this project is focussing on the harvesting of biomass for energy purposes, he is very much in support of it and would welcome such an opportunity. Certain conditions should however be in place, namely:

- The harvesting should be done in an environmentally friendly way.
- There should be proper control over the people entering the farm – not only in terms of which bushes/trees should be cut/left but also to prevent theft. Should this happen, the contract will be cancelled (he produced charcoal for a while but stopped the process because of theft).
- He should receive remuneration for the biomass. This income will be used for aftercare. Without remuneration he will not be able to do the inevitable aftercare. The price for biomass should at least equal the income generated from charcoal production.

Various efforts - chemical and felling - were made in the past by his father, to eradicate encroacher species such as *A. mellifera, A reficiens, A. erubescens* and *Dichrostachys cinerea.* All these areas were heavily re-encroached after 10 to 15 years. Large numbers of goats were introduced to fight bush encroachment and to prevent re-infestation, but to no avail. The restoration of the veld by means of rangeland management is presently impossible. There is a huge potential for biomass harvesting.

The soil types vary from dolomite, limestone, shale, quartzite and schist. The topography varies from mountaineous (small percentage) in the south to fairly flat hills (but still accessible). The largest part of this farm is relatively flat.

Interview: Mr Hartmut Kretzschmar
Farm: Waverley No 347
Size: 7 500 ha

The soil types on this farm vary from sandy to sandy loam. Bush encroachment has been a serious problem over many years. Various efforts were made to address the problem and even with aftercare it became a serious problem again. The main culprits were *A. reficiens, A. mellifera, A. luedritzii*, *Grewia flavescens* and *Terminalia sericea.* According to him the regrowth and re-infestation after seven to ten years was just as severe as before. He is not sure whether the present total biomass per hectare is the same as before as he did not measure it.

In his experience the problem increased where arboricides were used. Selective felling was also done, but afterwards new seedlings established themselves and over the years became dominant again to such an extent that cattle cannot freely graze in camps anymore. To solve this problem, bulldozer rollers were used to clear various broad strips across these camps. Various areas were cleared for cutting grass. Even in these camps regular aftercare is inevitable.

3 Relevant stakeholders in the use of biomass

Interview: Anonymous

Economic indicators in Namibia:

- Stable economy and political environment
- GDP growth 5.13% (2013); 5.3% (2014)
- GDP forecast for 2015: 5.6%
- Average inflation for 2014 was 4.6% and prediction for 2015 is 5.4%

Currently Namibia is facing certain challenges in terms of future electricity:

- Present reliance on imports: 60%
- Possible absence of power supply from Escom
- Ageing power supply infrastructure

The present generation capacity of Namibia is ± 487 MW of which approximately 70% is generated at Ruacana and 30% thermal.

Planned power stations:

Baynes: 300 MW
Kudu Gas: 885 MW
Solar panels to produce about 50 MW is also envisaged

The bilateral agreement with Eskom (SA) comes to an end in 2017 while a new agreement (80 MW of which 50 MW is firm) with Zimbabwe kicked off in April 2015 and will be effective for 10 years. The power agreement with Zambia (100 MW of which 50 MW is firm) will last for another 6 years after which the agreement will have to be renewed. In the short term a critical supply of 250 MW is required. What is extremely important for the biomass to energy project is that the ECB approved an increase of 9.53% in electricity tariffs. This means that money should be available through Namibian consumers to repay loans for all options in the long run.

If a biomass power plant seems to be economically feasible various financial institutions are also in a position to attract many investors for such a project (Both Capricorn and Rand Mergent Bank- RMB). Unfortunately they cannot compete with the Development Bank of Namibia in terms of interest rates.

Interview: Mr Reiner Jagau
Officer Power System Development (Nampower)
Cell no: 0811245270

It is confirmed that Namibia will experience a shortage of 250 MW per annum from 2016. Plans are in place to address this problem which include the Kudu Power project (more than 880 MW) and 3 x 10 MW solar PV to be implemented by Nampower and 9 x 10 MW solar power stations to be implemented by private companies. The Kudu power plant will take 15 years to be operational, but further investigations on the feasibility of this project must still be done.

Nampower will still manage power stations (including possible biomass plants) in future, but they will not be involved in any logistics. Feasibility studies on biomass power plants have not been launched, but this will be done in the near future. Whenever contracts with farmers for the supply of biomass are to be signed it will have to be on a long term basis (at least 15 years). According to him it is doubtful whether farmers will commit themselves for such a long period.

The recent 9.53% increase in the tariffs of electricity (as approved by the ECB) is not meant for new power station development, but for the increasing maintenance/operational costs of Nampower.

On average, 16 to 17 MJe can be produced from one kilogram biomass, while the corresponding figure for coal is 25 MJe. To produce one KWh, 0.9 kg coal is needed vs. 1.5 kg biomass. The harvesting cost of biomass, according to him, is in the order of N$700 per ton. That is approximately N$1.05/KWh (1.5 kg biomass for 1 KWh), which is too expensive and it is unlikely that this amount per ton can be paid to farmers.

Presently the price (including all costs + profit to produce electricity) which the consumer is paying is in the order of N$ 1.30/KWh (inserted JN de Klerk). The price of charcoal during 2013 and 2014 was N$1517/ton (received from M Schneider). The corresponding price for 1 KWh from coal is therefore N$1.36. Will it therefore be cheaper to produce electricity from biomass? A price of N$700/ton means that farmers will make no profit on biomass sales if they have to harvest themselves. The harvesting cost is thus a critical factor and cheaper ways of harvesting will have to be explored.

Interview: Mr Matthys J de Wet Pr Eng
Email: matthysdewet@nrgen.com.za
Cell: +27836265761

The following information provided by Mr De Wet is very relevant to the total amount of biomass available/needed for a biomass power station (Quoted from a study submitted to GIZ dated 27 April 2015).

- The smallest economical high pressure steam turbine available for typical application in a biomass-fired power station = 5.0 MWe (continuous output).
- A wood-fired boiler generating high pressure steam to drive the above 5.0 MWe turbine, would require approximately 4.5 metric tonnes per hour of dry biomass (@ <15% moisture content and> 16 GJ/t calorific value).
- For a 5.0 MWe biomass-to-energy power station running for 8 000 hours p.a. at near full load electrical output, would thus require biomass fuel at a tempo of 4.5 t/h x 8 000 h/p.a. = 36 000 tonnes p.a.
- The above fuel consumption for each 5.0 MWe Power Station would translate into an encroacher bush clearing tempo of 36 000 t.p.a. + 10 t/ha = 3 600 ha p.a.

- A series of 5 x 10.0 MWe = 50 MWe output wood-fired power stations would thus lead an overall bush clearing area of: 10 x 3 600 = 36 000 ha p.a.

- If the above 5 x 10.0 MWe power stations could perform continuously for 50 years, a total supply base area (assuming zero regrowth) of: 50 x 36 000 = 1.8 million ha would be cleared, translating into 1.8 x 10^6 -:- 26 x 10^6 = 7% of the current infested area.

- If the total current shortage of generating capacity in Namibia of 300 MWe (2015, NamPower Presentation) would be forthcoming from local biomass resources, with immediate effect for the next 50 years, assuming no regrowth, approximately: 300 -:- 50 x 1.8 X 10^6 = 11 million hectares or 40% of the total bush encroached area area would be cleared by 2065.

It is safe to assume that sufficient biomass exists in Namibia to fuel 100 MWe wood-fired boilers for a long time, as is conservatively calculated below:

- Biomass required to fuel a total of 100 MWe power plants for >8 000 hours p.a. on a continuous basis @ 900 kg/h of biomass required per 1.0 Mwe.

- 100 MWe x 0.9 t/h x 8 000 ha.p.a. = 720 000 t.p.a.

- Encroacher bush area required for the above consumption, assuming 9 tonne/ha of dry biomass available is: 720 000/9 = 80 000 ha.p.a.

Interview: Mr Raino Bauer
Manager Cenored, Otjiwarongo

Cenored Otjiwarongo is not interested in a 20 MW power station in the vicinity of Otjiwarongo. A 2 to 5 MW station could possibly be considered, but it is very unlikely. They would rather receive additional power from Nampower.

Interview: Mr Thomas Konzmann (Ohorongo Cement)
Date 9 July 2015

The experience shared by Mr Konzmann was very encouraging. Ohorongo Cement is doing very well with biomass as a major source of energy for the cement factory. In addition to the biomass, the entire business still makes use of an additional 15 MW per annum. An additional constant supply of electricity is therefore crucial to their daily/long term operations.

According to him the average biomass yield in the vicinity of Ohorongo Cement is 15 tons per hectare. It could also be as much as 40 tons/ha. Only 50% of the total biomass is harvestable, however, in some areas it could be as much as 70%. The moisture content of wood varies during the year between 5 and 15%.

The future of a biomass related company will be dependent on three pillars:
- The reassurance of the long term operation of a biomass plant that is dependent on a constant supply of biomass at a reasonable price.
- Providing a competitive, yet affordable electricity rate for the consumer.
- The ability to operate on an environmentally sustainable basis.

The harvesting of biomass at Ohorongo Cement will be contracted out to a private company/ companies to ensure constant supply. SME's will also be seriously considered, and there will still be ample opportunity for individual farmers to provide biomass to the factory.

The use of solar panels have also been considered, but the fact that biomass can be used on a 24/24 hour basis gives it a huge advantage above solar energy. According to their experience 10% of a farm should be harvested which means that the farm could be bush-thinned over a period of ten years. In this way camps can be harvested every tenth year which will ensure a high percentage of grass production on a farm/each camp before re-infestation takes place.

4 Government institutions

Interview: Mr Joseph Hailwa
Director Forestry; MAWF

The Directorate of Forestry support the use of biomass as energy in future provided that this happen within the framework of environmental principles.

Presently this directorate is already preparing themselves to support this project in the following ways:

- Training of government officials (capacity building) within the Directorate of Forestry (DoF) and Directorate of Extension and Engineering Services (DEES) in all methods of bush control, environmental principles that should be adhered to and in exerting proper control over the harvesting process.The emphasis will also be on advisory services. All foresters in Otjiwarongo, Outjo, Otavi, Omaruru and Okahandja will be involved in this process.
- Making the necessary budgetary provisions for the purchase of enough vehicles and operational costs to provide the necessary supportive services such as extension services and financial support to farmers. These needs should be properly investigated in advance.
- Attempting to change the perception that this is only a forestry problem to an understanding that it is also a problem of the livestock sector and therefore research and extension and the farming community should be actively involved.

Detailed Assessment of The Biomass Resource and Potential Yield in a Selected Bush Encroached Area of Namibia

Very few attempts at restoring bush thickened areas can be considered successful. Results are the loss of beneficial woody plants and re-encroachment, often worse than before treatment.

The authors studied 45,000 hectares of bush encroached areas on eight commercial farms. They find that natural savannah ecosystems always tend to return to a point of relative stability. Removing some or all the woody plants creates a vacuum that will be filled. In time, with diminishing nutrients, and combined with grazing, this vacuum may again become densely populated by woody plants. As large trees support stability of the savannah ecosystem they should be retained at the cost of smaller trees and shrubs.

A considerable advantage of harvesting biomass for electricity generation is that all biomass can be utilised, even smaller bush. The authors find that in the area studied even a conservative wood harvesting intensity will meet the minimum requirement for the viability of an electricity plant.