Sustainable wood harvesting principles with the aim to restore rangeland in the Thornbush Savanna of Namibia

by

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I dedicate this PhD thesis to:

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LIST OF ACRONYMS

ACRONYM	MEANING
AEZ	Agro-Ecological Zones
BECVOL	Biomass Estimate from Canopy Volume
ETTE	Evapotranspiration Tree Equivalents
CO_2	Carbon dioxide
CV	Coefficient of Variation
CPL	Central Plateau
DM	Dry material/matter
GLM	General Linear Model
kg ha^{-1}	Kilogram per hectare
ha	Hectare
SD	Standard deviation
SE	Standard Error

ABSTRACT

Key terms: Bush-thickening, non-selective harvesting, selective thinning, coppice, sapling establishment, high wood-potential species, low wood-potential species, protected species, restoration

The savannas of northern Namibia are prone to woody plant thickening, and land owners, therefore, attempt to restore rangelands through the removal of some or all of the woody plants with a view to reduce the negative competition interactions with the herbaceous layer, allowing an increase in the grazing capacity for livestock. The utilization of the bush resource made available through these bush control programs has led to the development of a lucrative bush value-chain industry which often leads to the over-exploitation of the resource for short-term financial gains.

The effect of the most common harvesting practices such as non-selective and selective woody biomass harvesting was investigated over a three-year period in an area northwest of Otjiwarongo, described as the North-central plateau of Namibia and with vegetation classified as Thornbush Savanna. The dominant woody plant species were *Senegalia mellifera* and *Vachellia reficiens*. They are also the most sought-after species for charcoal production for their high wood yield potential, and for this reason they are also the species of interest in this study. The coppicing ability, survival, change in woody species composition, woody plant recruitment through coppice and/or sapling establishment, rate of biomass production, effect of annual total coppice defoliation on coppice regrowth survival of selected species, and growth rates and mortalities of woody plants were studied. The trail layout consisted of plots of 50 x 30 m (1 500 m^2) with at least two replications of each treatment.

The non-selective (bush-roller and chainsaw) harvesting showed no significant differences ($P>0.05$) in coppice regrowth of *Senegalia mellifera* and *Vachellia reficiens*. However, although not significant ($P>0.05$), the chainsaw harvested plots had higher coppice rates when considering all other woody species whereas, bush-roller harvested plots had a higher sapling establishment as compared to the chainsaw harvested plots. *Dichrostachys cinerea* was the only species that had a highly significant ($P=0.002$) increase in sapling establishment. There was a change in dominance from high wood-potential (mostly *S. mellifera, V. reficiens, Vachellia tortilis, V. hebeclada*) to low wood-potential (mostly all *Grewia* species, *D. cinerea, Catophractes alexandrii*) species. The ETTE ha^{-1} is projected to return to its original pre-

harvest state in less than 12 years, whereas the wood biomass did not show any signs of returning to its original pre-harvest state.

Annual total defoliation of coppice proved to be effective for the control of coppicing woody plants without the need for any chemical treatment (arboricide). There was a highly significant difference ($P<0.01$) in the rate of coppice between the two seasons (hot wet summer and cold dry winter) as treatments. Plants initially harvested in summer had a higher coppice and survival rate than plants harvested in winter. The summer harvested *S. mellifera* stumps coppiced more vigorously compared to *V. reficiens.* The winter harvested *V. reficiens* coppiced more vigorously compared to *S. mellifera.*

There were highly significant differences ($P<0.001$) in coppice amongst the selectively versus non-selectively harvested plots. Plants harvested selectively, while retaining 4 500 ETTE ha^{-1}, had lower coppicing rates than those where the whole area was harvested non-selectively. The high ETTE ha^{-1} before harvesting could not be matched three years after harvesting, whereas plants ha^{-1} in the selectively thinned plots significantly ($P<0.05$) exceeded the original plant density (plants ha^{-1}) before initial harvesting within three years. Mature *S. mellifera* woody plants had a significantly higher ($P<0.001$) mortality rate in the bush-thickened control plots. The mortality of *V. reficiens* was not as high as that of *S. mellifera.* Regarding shoot growth, the growth in shoot length was more pronounced than that of shoot diameter. *Vachellia reficiens* had a significantly higher ($P=0.001$) growth rate in shoot length compared to *S. mellifera.*

Allometric regression equations were also developed from harvested undamaged *Senegalia mellifera* and *Vachellia reficiens* plants for inclusion into the BECVOL-3 model. Highly significant relationships ($P<0.01$) were found between the spatial canopy volume and the dependent biomass variables predicted. There were negligible differences in percentage species composition of herbaceous plants amongst the different bush control treatment plots. Although surveys in all plots confirmed a state of bush thickening as per the general rule of thumb and thus the need for some form of bush thinning, the grass dry matter production did not improve, as generally assumed, with reduced woody plant competition. The herbaceous dry matter production showed a more pronounced positive response to increased rainfall rather than bush thinning during the study period. The first year of the study had a below-average annual rainfall and the rest of the years followed with above average annual rainfall.

While bush control measures are very costly, the knowledge gained from this research project will be of significant value to land owners and the scientific community by providing clear guidelines of what to expect from various bush harvesting programs. The results of the study emphasise the importance of distinguishing between restoration versus wood harvesting as the main objective, and provide clear guidelines for the sustainable utilization of the bush resource within the context of the ecological requirements for the long-term restoration of bush-thickened areas.

CHAPTER 1: INTRODUCTION

Namibia consists of three broad vegetation groups, namely; deserts, savannas and woodlands (Giess, 1998). Savannas cover the largest land surface area of Namibia and are further subdivided into eight vegetation types, namely: Mopane Savanna, Mountain Savanna and Thornveld, Thornbush Savanna, Highland Savanna, Camelthorn Savanna, Forest Savanna, Tree Savanna and Woodland, and the Dwarf Shrub Savanna (Giess, 1998). According to Scholes and Archer (1997), the term savanna is widely used but differs in how it is defined. The term savanna (or savannah), once restricted to describing central South American grasslands in Spanish, is now widely accepted as describing vegetation with a herbaceous layer dominated by graminoids, and an upper layer of woody plants, which can vary from widely spaced to a 75 % canopy (Edwards, 1983; Rutherford and Westfall, 1994). Khavhagali and Bond (2008) define a savanna as "*a tropical seasonal ecosystem with a continuous grass layer, mixed with forbs and sedges, with a variable cover of trees and shrubs."*

These savannas are prone to woody plant thickening, which involves indigenous woody species in their natural environment. Woody plant 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). Woody plant thickening has been a known problem in southern Africa for nearly a hundred years (Archer, 1995; van Auken, 2000; Roques *et al.,* 2001; O'Connor and Chamane, 2012; O'Connor *et al.,* 2014) and poses a major threat to nature conservation and livestock production as it alters the habitat structure and decreases herbaceous production (O'Connor and Crow, 1999). Woody plant thickening affects roughly 45 million hectares of farmland in Namibia alone (Nghikembua *et al.*, 2021). It is, therefore, a vegetation dynamic of global interest (O'Connor and Chamane, 2012).

Woody plant thickening is still not well understood at a fundamental level due to the poor understanding of the functioning of the savanna ecosystem and this needs to be dealt with in a practical manner (Smit, 2004; Joubert *et al.,* 2008). Thus, more case studies would contribute towards a broader foundation for improving the understanding of the underlying processes (O'Connor and Chamane, 2012). Another aspect that is also not well understood or ignored is the importance of major changes in the physical environment that directly affect the soil water balance (Pringle *et al.,* 2013). Woody plants are not only widely acknowledged for their ecological importance (Belsky 1994; Hagos and Smit 2005; Treydte *et al*. 2007), but also

provide feed for both domestic livestock and game species (Graz, 2003; Smit, 2004; Ward, 2005; Smit, 2014), fulfill multiple roles in farming systems (Geldenhuys, 1996; Leger, 1997; Graz, 2004; Smit, 2005; Abule *et al.*, 2007; Strohbach and Petersen, 2007; Mannheimer and Curtis, 2009) and are used for firewood, construction material, implements (Graz, 2003), medicine, mulch and soil conservation in semi-arid regions.

Smit (2001, 2004) argues that there are indications that bush thickening is not only detrimental to grazers but also to browsers, as the competition among woody plants for available soil water may result in a shortened period of leaf carriage in the case of winter deciduous species. In dense stands, deciduous woody species will drop their leaves much earlier during the dry season and delay budding at the onset of the new growing season. Wiegand *et al.* (2006) explain that woody plant species involved in bush thickening may often be unpalatable to domestic livestock. Therefore, woody plant thickening reduces the carrying capacity for domestic livestock in savannas and has physical barriers to livestock movement.

Wood harvesting for firewood and charcoal production is the main use of wood for energy in Namibia (Cunningham, 1998; Nghikembua, 2008) and has become an increasingly popular practice in Namibia. This is done in an attempt to alleviate the woody plant thickening problem, with an opportunity to generate an extra income. Woody plants tend to regrow after harvesting, especially if no specific woody plant control measures are in place to maintain the rangeland in an "open state". However, the regrowth of these harvested woody plants often becomes a bigger problem as harvested woody plants coppice into multi-stemmed shrubby plants with a high leaf and low wood biomass that is not suitable for a repeat wood harvest (Smit, *et al*. 2015).

Bush thickening is difficult and expensive to combat and requires a long-term commitment (Smit, *et al*. 2015). The use of woody plants as a secondary source of income is a major source of annoyance for the majority of Namibian farmers and is more motivated by necessity than by personal preference (Boys and Smit, 2020). The effects of the specific harvesting method and the consequent regrowth patterns of the woody plants are not well understood and greatly affect the initial purpose of wood harvesting, which is normally intended to improve the productivity of the land for meat production. The use of wood harvesting for the sustainable restoration of rangelands, therefore, becomes an important aspect to be studied. Depending on whether the method of harvesting involved any soil disturbance or not, the main objectives of the study were to determine - after the initial harvesting of various species of woody plants - if:

1. Woody plants would coppice, and seedlings of more aggressive (pioneer) woody plants would establish following non-selective wood harvesting,

2. Early, continuous, heavy defoliation of coppice would lead to some die-off of woody plants over time following non-selective wood harvesting,

3. Season (dormant or actively growing) of cutting would affect the vigour of the regrowth of woody plants following non-selective wood harvesting,

4. Coppice of those woody plants selectively harvested through gradual thinning over time would differ from those where once-off thinning took place and/or all woody plants were cut, due to differences in inter-tree competition, and

5. Woody plants suitable for wood harvesting would continue to develop and grow (shoot length and diameter) in a bush-thickened environment.

The above objectives were investigated by testing the following hypotheses:

1. Woody plants will coppice, and seedlings of more aggressive (pioneer) woody plants will establish following non-selective wood harvesting,

2. Early continuous heavy defoliation of coppice will lead to some die-off of woody plants over time,

3. All species will coppice after cutting, but those cut in the dormant season (winter) will coppice less vigorously than those cut in the actively growing season (summer),

4. Coppice of those woody plants selectively harvested through gradual thinning over time will be less than those where plants were thinned once-off and/or all woody plants were cut, due to severe competition from the undamaged plants, and

5. Woody plants suitable for wood harvesting will have little growth activity (shoot length and diameter) in a bush-thickened environment due to severe competition from neighbouring plants.

In addition,

1. Regression equations relating spatial canopy volume and above-ground biomass (leaf and wood fractions) were developed from harvested *Senegalia mellifera* and *Vachellia reficiens* plants (undamaged plants) for inclusion in the BECVOL-3 model (Smit 2014).
2. The effect of the different bush-control treatments on the herbaceous layer on parameters such as above-ground biomass yield and species composition were determined.

CHAPTER 2: LITERATURE REVIEW

2.1. The functioning of savanna ecosystems

The dominant plant types in any savanna ecosystem are woody and herbaceous plants (Kelly, 1977), and woody plants are a very important component of savannas in Namibia. According to Scholes and Archer (1997), the woody and herbaceous plants within a savanna ecosystem can interact through numerous mechanisms, which include both positive (facilitation) and negative (competition) interactions.

Woody plants play an important ecological role in any savanna ecosystem, such as improving the soil to enhance the sustained production of the herbaceous layer and maintaining the right balance in the ecosystem. Woody plant species enrich the soil under their canopies through numerous processes (Dubeux Jr. *et al.,* 2014; Ward *et al*. 2018). Because of the symbiotic relationship between nitrogen (N) fixing bacteria (*Rhizobium*) and the roots of woody plants, the soil under woody plants - especially under leguminous woody plants - has a higher nutritive value than the soil between woody plants (Vetaas, 1992; Smit and Swart, 1994; Hagos and Smit, 2005). Woody plants are also able to extract nutrients from the soil below the root zone of grasses (Tiedeman and Klemmedson, 1973; Vetaas, 1992), reduce nutrient losses due to erosion and leaching, and increase soil nutrient availability due to greater soil organic matter mineralization (Grossman *et al.,* 1980; Dubeux Jr. *et al.,* 2014). Additionally to nitrogen fixation, soils under woody plant canopies are enriched in several ways, which include: animals gathering under woody plants for shelter and excreting wastes that fertilize the soil (Belsky *et al.,* 1989); plant leaves accumulating under woody plant canopies, which adds to the organic matter (Bosch and van Wyk, 1970; Belsky *et al.,* 1989; Vetaas, 1992); and stem-flow (Smit & Swart 1994; Hagos & Smit 2004; Ward *et al.* 2018). Soil water is also retained for a longer time under woody plant canopies due to lower evaporation, enabling a higher rate of decomposition (Vetaas, 1992).

In addition to improving the soil, woody plants are also widely acknowledged for other ecological and economic importance (Belsky 1994; Hagos and Smit 2005; Treydte *et al*. 2007). They provide feed for both domestic livestock and game species (Graz, 2003; Smit, 2015) and serve as a valuable resource in farming systems (Geldenhuys, 1996; Leger, 1997; Graz, 2004; Smit, 2005; Abule *et al.,* 2007; Strohbach and Petersen, 2007; Mannheimer and Curtis, 2009) such as being used for firewood, charcoal production, construction materials, implements (Graz, 2003), medicine, mulch, and soil conservation in semi-arid regions.

Apart from the positive influences of woody plants, there are also negative effects on the savanna ecosystem. The most important of these is thickening to undesirable densities and involves indigenous woody species in their natural environment (Smit, 2004; Ward, 2005; Britz and Ward, 2007; Scogings and Mopipi, 2008; Hare *et al.*, 2021). Bush thickening poses threats to the ecosystem, of which a reduction in the grazing capacity is the most problematic (Curtis and Mannheimer, 2005; Hare *et al.*, 2021). Palatable grasses and herbs are suppressed by the increase in density of indigenous woody plant species that are often unpalatable to domestic livestock (Dye and Spear, 1982; O'Connor, 1991; Smit *et al.*, 1996; Smit and Rethman, 1999; Ward, 2005). This leads to a reduction in the grazing capacity of the affected area for livestock (Curtis and Mannheimer, 2005). Although a healthy grass layer may out-compete woody species for water in the upper soil surface (Tefera *et al.*, 2007), shallow-rooted woody plant species such as *Senegalia mellifera* and *Grewia flava* may increase in abundance following overgrazing of the grass layer as they are favoured by an increase in available water in the soil surface (Skarpe, 1990; Smit *et al.*, 1999).

Globally, soils and plants contain around twice and three times the amount of carbon in the atmosphere, respectively (Ghosh and Mahanta, 2014). The plants are the carbon sequesterers of atmospheric carbon, which is then supplied to the soil. This establishes the soil as both a carbon source and a carbon sink (Gosh and Mahanta, 2014). A recent study in the Otjiwarongo district in Namibia indicates that woody plants in areas considered bush thickened sequester significantly more carbon than in areas where the woody plants are controlled (Musekiwa *et al.*, 2022). Moreover, areas where all woody plants are cleared experience a loss in overall soil fertility over time (Zimmerman *et al.* 2017). Musekiwa *et al.* (2022) further found that mechanically controlled areas sequestered 7.5% more carbon dioxide than chemically controlled areas. Other than woody plants, natural grasslands also play a significant, but poorly recognized, role in the global carbon cycle (Scurlock and Hall, 1998). Based on Musekiwa *et al.* (2022), thickened savannas may be better carbon sequesterers. Still, it is not natural and, therefore, a rangeland management approach that is holistic to climate change mitigation and forage improvement should be practiced. Amongst other causes, thickened savannas should rather be seen as driven by atmospheric carbon dioxide levels and may be regarded as favourable in terms of carbon sequestration (Stehn, 2020).

2.2. Bush thickening

Bush thickening is best defined as the excessive increase in the density and cover of one or more indigenous woody species that exploit disruptions of the grass/woody plant balance at the

expense of grasses (Smit *et al.* 1999; Tefera *et al.* 2007; Joubert, 2014; Harmse *et al.* 2016). Bush thickening is a global phenomenon and is mostly associated with savanna and grassland biomes (O'Connor *et al.*, 2014).

Bush thickening is a relatively slow process that develops over time as more pressure is exerted on the herbaceous component of the rangeland (Trollope, 1980). Smit (2004) explains that the thickening of woody plants takes place in two forms, namely: (a) the increase in the biomass of already established woody plants; and (b) the increase in woody plant density, mainly from newly established seedlings. Smit (2004; 2005) also mentions that man had an influence - whether directly or indirectly - by modifying the determinants of savanna ecosystems. These determinants can be primary, which includes the climate and the soil, or secondary, which can include fire and the impact of herbivores on the rangeland. Being financially driven, the management of rangelands often changed in such a way that it did not benefit all vegetation components (Kelly, 1977; Smit 2004). Some of these management modifications include the exclusion of occasional hot fires (Trollope, 1974; Trollope, 1980; Belsky, 1984; Sweet and Mphinyane, 1986; Trollope and Tainton, 1986; O'Connor *et al.* 2014); the replacement of adapted indigenous animals with less adapted, high producing livestock at sometimes high stocking rates (Smit, 1999); the erection of fences that restrict the natural movement patterns of the herbivores; poor grazing management and the provision of artificial water points (Smit, 2004).

As a result of prolonged overgrazing, there is lower competition from the less competitive grass layer, and woody plants can flourish (Smit, 2004; 2005; Cutis and Mannheimer, 2005; O'Connor *et al.*, 2014). Chirara *et al.* (1998) found that *Vachellia karroo* seedlings growing in heavily clipped grass plots under greenhouse conditions had a higher biomass production than those competing with moderately clipped grass. However, Ward (2005) believes that overgrazing or fire is not the sole cause of bush thickening. It has been reported by Skarpe (1990) and Smit (1999; 2004; 2005) that ungrazed and moderately grazed areas showed no consistent trend regarding the abundance of the woody component, but the woody plants increased at a higher rate where the grazing was heavy, especially during the growing season. Smit *et al.* (1999), Smit (2004), as well as Britz and Ward (2007), also found that grasses are generally more severely affected by droughts compared to woody plants. This is because woody species have a better-developed root system that enables them to access soil water from a larger volume of soil.

Grasses are fast-growing plants that can generally out-compete woody plants because of their roots situated in the upper soil levels (Smit, 2004) of about 15-20 cm. However, Joubert *et al*. (2008) found that grass swards in low rainfall areas were unable to compete with woody seedlings. In addition, low densities of *Senegalia mellifera* and a lack of an increase in plant densities in areas that are grazed or browsed by game, do not suggest that browsing and or grazing by game can prevent thickening (Britz and Ward, 2007). It has been observed by Smit (2004) that in rangeland dominated by *Senegalia* and *Vachellia* species, large numbers of woody seedlings germinated and survived on bare areas, while the germination and survival of woody seedlings were very low in areas where the rangeland was in good condition.

According to Hoffman and Todd (2000) and Burke (2006), the increase in the ratio of grazers to browsers amongst herbivores and the resulting impact on vegetation have been postulated to contribute to the development of bush thickening in semi-arid southern African savannas, as well as the main rangeland degradation process in these areas.

Several other factors can contribute to bush thickening, most notably elevated atmospheric carbon dioxide concentrations; nitrogen pollution; fire suppression; loss of mega-herbivores; inherent soil and climatic conditions; overgrazing; and poor rangeland management practices (de Klerk, 2004; Sankey, 2012; Nghikembua, 2021). Climate change and the role of increasing CO_2 emissions due to human activity are a growing concern. There are indications that increased levels of atmospheric CO_2 benefit woody plants as they increase the growth rate and survival of juvenile plants (Bond and Midgley, 2012), contributing to the conversion of open savannas to shrublands. As a result, woody plants have increased in many savannas throughout the world, while some humid savannas are being converted to forests (Bond and Midgley, 2012).

2.3. Coppicing and seedling establishment of woody plants after wood harvesting

Cutting of woody plants has become common practice, either for direct use as firewood or to control bush thickening (Strohbach, 1999; Smit, 2002; De Klerk, 2004; Cunningham and Detering, 2017; Nghikembua *et al.*, 2020). It is well documented that cut plants in African savannas will coppice readily after cutting (Milton, 1988; Mushove and Makoni 1993; Smit, 2004; Cunningham and Detering, 2017; Nghikembua *et al.*, 2020). It is also known that coppice regrowth is structurally altered and prioritizes leaf as opposed to wood production (Smit, 2003). Coppice regrowth is therefore undesirable from both a wood production and bush control point

of view, unless the regrowth is managed through pruning. Gessesse *et al*. (2015) argues that coppice pruned back to two or three stems yielded good results in wood production in less time.

Wood harvesting is done either manually or mechanically. According to Nghikembua *et al.* (2021), mechanical harvesting involves self-propelled powered machines fitted with cutting equipment such as cutting shears or other mechanisms such as rollers and blades that damage the plant near the stem base either through breaking or uprooting. Semi-mechanical harvesting involves the use of small hand-held powered tools, whereas manual harvesting involves the use of axes and pangas. Several wood harvesting machines are used in the wood harvesting industry, especially in Namibia. Amongst these, the bulldozer is known to cause severe soil disturbance during the wood harvesting process.

The soil disturbance caused by heavy machinery can lead to soil erosion (Joubert and Zimmerman, 2002), loss of soil structure. Joubert and Zimmerman (2002) argue that heavy machinery used for mechanical wood harvesting causes severe soil disturbance and should be avoided. According to casual observations, young, flexible-stemmed woody plants are often not effectively killed by machinery, particularly bush rollers, and have an immediate competitive advantage over other plants after harvesting. Along with the young, flexible-stemmed plants, the soil disturbance also leads to a higher germination rate of seeds of species with existing soil seed banks, such as *Dicrostachys cinerea* (Joubert and Zimmerman, 2002). Mechanical wood harvesting is fast and is often used for large-scale wood harvesting in Namibia due to its high productivity (2.48 ha/day) (Leinonen, 2007). Most self-propelled machines fitted with rollers or blades are large in dimensions and make it difficult for selective thinning of woody plants (Trede and Patt, 2015; Birch *et al.*, 2016).

Woody plants have evolved over thousands of years and have been exposed to various forms of physical damage by large herbivores and fire. To ensure their existence, especially through damage by large herbivores, they have developed the strategy of coppicing and re-growing. Coppice refers to the vegetative regrowth of woody plants from the stem base after the plant has been cut off or otherwise damaged. Coppicing after physical damage is supported by the use of carbohydrates that are stored in the roots and used for growth and respiration (Schultz *et al.* 2011). These carbohydrates are produced during the active growing phase and stored for regrowth when needed. Along with carbohydrate availability, other factors such as moisture availability and the plant's phenological state explain the variability in the coppicing ability of woody plants (Milton, 1998). The season in which the disturbance factor is applied also plays

an important role in the ability to coppice (Strohbach, 1998; Luoga *et al.*, 2004; Schutz *et al.*, 2011). Furthermore, it was found that carbohydrate reserves are important in the regrowth of *Vachellia karroo,* but growth is inhibited under certain circumstances where carbohydrate supplies appear to be adequate, notably as a result of a deficiency of plant hormones (Teague, 1983).

Another survival strategy is the ability of mature woody plants to flower and produce large quantities of viable seeds (Smit *et al.,* 1996). These seeds need to get dispersed, germinate, and survive (Smit *et al.*, 1996). Good rainfall seasons normally enable the survival of seedlings (Joubert *et al,* 2013; Joubert *et al.,* 2017). Apart from the fact that these woody plants produce large numbers of seeds, another survival strategy is hard, permeable seed coats that can go through an animal's digestive tract without being digested (Leistner, 1961; Gwynne, 1969; Hoffman *et al*., 1989; Miller, 1995). The small seeds often escape mastication, and their germination ability is improved by scarification by digestive fluids and rumen contents and easily germinate after excretion (Coughenour & Detling, 1986; Coe & Coe, 1987). It was also reported by Smit *et al.* (1996) that seeds of some woody plants can survive in the soil for long periods of time. The long survival periods of seeds are possible through hard, permeable seed coats or allelochemicals that can prevent them from germinating (Warag, 1994), or seasonal dormancy (Zietsman and Botha, 1987; Meyer and Monsen 1992).

2.4. The effect of early total defoliation of coppice on some woody plants

Damaging woody plants by fire and cutting, and combinations of these, is a common practice in southern African savannas and is normally followed by a strong coppicing response by these plants (Du Toit, 1972; van Niekerk and Kotze, 1977; Teague and Walker, 1988; Teague, 1983; Adejumo, 1992; Strohbach, 1996; Smit, 2003; Cuningham and Detering, 2017; Hoveka, 2019). Some additional control measures are then needed to control the coppice, of which defoliation by browsers such as goats is one such option. However, Teague (1988) found that leaf growth on the plants defoliated by goats at moderate levels was approximately three-fold that of plants defoliated moderately by hand. Teague (1988) also found that defoliation, in general, does stimulate plant regrowth in the growing season. The method, season, and intensity of defoliation, therefore, become crucial depending on the outcome required from the defoliation of woody plants.

Teaque and Walker (1988) found that defoliation of *V. karroo* by goats during growing phenophases results in considerable stimulation of leaf and shoot growth as compared to non-

defoliated plants. This is largely dependent on the intensity and the phenophase of the plant at defoliation (Teague and Walker, 1988). Sweet and Mphinyane (1986) also found similar results after burning at different browsing intensities. During the early spring flush, plants normally use carbohydrates stored from the previous season for regrowth (van Niekerk and Kotze, 1977; Teague and Walker, 1988). It then becomes critical that this growth from the stored reserves is not wasted through defoliation, as the vegetative growth is needed to boost photosynthesis until a point where carbohydrates produced from photosynthesis exceed the energy needed for growth. Teague (1983) emphasizes the need for moisture and adequate carbohydrate levels for regrowth survival. During the rest of the growing season, carbohydrate levels are high, and growth is less affected by defoliation and may even stimulate leaf and shoot growth. Teague and Walker (1988) found that moderate to high defoliation of *V. karroo* during the growing season leads to increased leaf and shoot growth.

Continued total defoliation of the coppice after initial woody plant removal (Du Toit, 1972) and defoliation through browsing herbivores during the early spring flush when carbohydrate levels are low (Teague and Walker, 1988) has proved effective in controlling the plants and avoiding re-thickening. This can lead to a significant improvement in the cover, composition, and vigour of grass plants (Du Toit, 1972), especially in areas utilized by goats. Drastic hand defoliation early in the season through the removal of coppice sprouts and leaves is still to be investigated.

2.5. The effect of the season of cutting on the coppice and the growth vigour of woody plants

Not all woody plants coppice after cutting, and not all plants that initially coppiced may survive. According to Cunningham and Detering (2017), some factors that affect the ability of woody plants to coppice after cutting are the season of harvest, species, the method of harvest, size of the tree harvested, rainfall, soil type and browsing impact. These same factors also affect the survival of the plants that initially coppiced. These findings are supported by Adejumo (1992) and Strohbach (1996), who found that the season of cutting and the type of species rank the highest as determining factors for the coppice of woody plants after felling for wood harvesting. However, rainfall is the most limiting factor in these arid to semi-arid savannas and should therefore rank amongst the highest factors determining coppice ability and survival. Adejumo (1992) found that *Gliricidia sepium* in southern Nigeria had the highest coppice when plants were cut in the early dry season. However, Hoveka (2019) found that *S. mellifera* had the best coppicing ability when plants were cut in the hot, wet season, although there were no significant

differences in coppicing ability between the different seasons of woody plant felling. Cunningham and Detering (2017), as well as Hoveka (2019), found that woody plants with smaller basal stem diameters had higher coppicing ability as compared to the larger trees.

Woody plants are season-dependent in their growth cycle (Curtis and Mannheimer, 2005), during which rainfall is crucial (Joubert, 2014). Seed germination takes place in the hot, wet season (Joubert, 2014), followed by vegetative growth and the formation of fruits and/or pods (Curtis and Mannheimer, 2005). The photosynthates of the deciduous woody plants are then translocated to the roots at the end of the growing season to be used as growth reserves for the next season's growth.

The only work done in Namibia on the effect of the season of cutting on the coppicing of woody plants, especially *S. mellifera*, is that of Hoveka (2019), where, although the results were not significant, the plants cut during the hot-wet season produced more coppicing sprouts as opposed to those cut during the cold-dry and hot-dry seasons. The plants cut during the cold-dry season also produced more coppice sprouts than in the hot-dry season. In another study with limited data, Cunningham and Detering (2017) found that after a harvest, the mean rate at which stumps coppiced varied between 45% for *Vachellia reficiens* subsp. *reficiens* and 92.8% for *Dichrostachys cinerea* subsp. *africana* in north-central Namibia.

These findings certainly need to be investigated in more detail to determine the rate of survival of these plants after coppicing. The overall vegetation change in a harvested area will also have to be monitored for an extended period to assess the complete effect of wood harvesting in an area.

2.6. Selective woody plant thinning as a means of woody plant control

The removal of woody plants in a bush-thickened rangeland is primarily undertaken in an attempt to restore the savanna state of the rangeland where trees, shrubs and the herbaceous component are in equilibrium. After the removal of woody plants, there is usually a drastic increase in herbaceous plants, especially grass and herbs. This drastic increase in herbaceous plants is a result of the reduction in the suppressive effect of woody plants on the herbaceous layer and the release of large quantities of nutrients (Smit *et al.,* 1996). The suppressive effect of the woody plants on the herbaceous layer is primarily due to competition for soil water (Richter *et al.,* 2001). This re-establishment of woody plants will take place in the form of coppice and seedling germination (Smit *et al.,* 1996). This re-establishment of woody plants

will continue for years and, if not controlled regularly, will result in re-thickening of the bush, in some instances, to a state worse than before the thinning operation.

Smit (2004; 2005) advocates for thinning as opposed to clearing woody plants for the long-term restoration of bush thickened rangeland. Positive results on bush thinning for increased grass production and minimal woody re-infestation were also achieved by Nghikembua *et al.* (2021) and Hare *et al.* (2021). The ideal number of woody plants 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 areas than in dry areas without affecting herbaceous yields. In general, the average long-term rainfall is a deciding factor. Based on research elsewhere (Dye and Spear, 1982; Richter *et al.*, 2001; Smit, 2005), a "general rule of thumb" stipulates that the median number of Evapotranspiration Tree Equivalents (ETTE)/ha that can be supported in a specific rainfall region without adversely affecting the grass layer should not exceed 10 times the mean annual rainfall of the area.

The removal of woody plants to a predetermined density ("the general rule of thumb") based on aridity, in order to restore the rangelands, will increase herbaceous production, but with possible re-thickening by woody plants over time. Studies by Teague and Smit (1992) and Smit (2004; 2005) indicate that, in time, the competitive ability of the woody plants remaining after thinning will gradually increase and reduce the impact of the initial thinning, even without seedling establishment. Both herbaceous and woody species diversity is likely to be increased by thinning, since the dominance of the thickening species will be reduced, allowing other species to thrive (Joubert and Zimmerman, 2002).

Rangeland restoration studies have been done on once-off thinning of woody plants to a predetermined density (Smit, 2004; 2005). The effect of thinning woody plants to a predetermined density over time is not clear. It is expected that, if thinning of woody plants takes place gradually over time, the rangeland may become more resilient (i.e., may or may not be stable, but remain attracted towards its equilibrium) without sudden changes that might react towards "negative stability" (reverting to woody thickening as opposed to higher grass production).

2.7. Growth rate of woody plants in a bush-thickened environment

The growth rate of woody plants in African savannas is mainly dependent on rainfall and is further influenced by soil type, fire and browse impact by herbivores (Sebata, 2017). The

importance of rainfall on the growth of woody plants is also reported by Joubert *et al.* (2017). According to Joubert *et al.* (2017), woody plants, especially *Senegalia mellifera*, grow slowly, contrary to current popular perceptions of the species being an "aggressive invader". Therefore, mature thickets of savanna woody plants are assumed to be much older than previously thought. Growth of woody plants in open savannas with minimal competition was recorded at just above 7 cm per annum (Joubert *et al.*, 2017). Joubert (2007) also found that mature *S. mellifera* shrubs grow at a stem lengthening rate of 3.2 cm per annum in dense thickets. Cunningham and Detering (2017) found a stem diameter growth rate of 3.79 mm and 3.40 mm per annum for *S. mellifera* and *V. reficiens*, respectively. Mature woody plants also grow faster than those at seedling and/or sapling stage (Joubert, 2007). This is mainly because of the extensive root system of these mature plants being able to utilize water from a broader soil spectrum.

Competition between savanna plants does play a role in the growth rate of these plants (Smit and Rethman, 1999; Smit, 2004; 2005; 2014). Although several studies have investigated competition between trees and grasses, little is known about tree–tree interactions (Meyer *et al.*, 2008). According to Meyer *et al.* (2008), competitor removal experiments did not lead to increased shrub sizes. Such experiments should be done long-term as a limited duration experiment may not yield the expected results. Furthermore, competition-induced mortality only becomes obvious when analyzing the shift towards less aggregated spatial patterns when shrubs become reproductively mature (Meyer *et al.*, 2008). Most studies were done on *S. mellifera*, and very little is known about *V. reficiens.*

It becomes particularly important to measure the growth rates of existing species of interest to determine how they react to management and environmental factors. The slow growth rate of, especially, *S. mellifera* reported by Joubert *et al.* (2017) and the findings of Smit (2014), whereby remaining plants grow faster in bush-thinned areas, are critical for the management of these plants. The removal of woody plants in bush-thickened areas can, therefore, be paced at the rate of growth to avoid an "environmental vacuum" which can result in the intrusion in dominance of other species, most likely aggressive pioneer woody species, or desertification.

2.8. Broad description of *Senegalia mellifera* and *Vachellia reficiens*

Senegalia mellifera is a more studied plant than *V. reficiens.* Amongst others, the major and more detailed studies on *S. mellifera* include its reproductive dynamics (Hagos, 2001), the influence of rainfall, competition, and predation on seed production germination and establishment (Joubert *et al.*, 2013), a conceptual model of vegetation dynamics in the arid

Highland Savanna of Namibia with particular reference to bush thickening by *S. mellifera* (Joubert *et al.,* 2008), growth rates, and mortality patterns of *Acacia mellifera* subsp. *detinens* in the semi-arid Highland Savanna (Joubert *et al.,* 2017).

Both *S. mellifera* and *V. reficiens* belong to the Fabaceae plant family (Mannheimer and Curtis, 2009). Both species are high wood-potential species and are harvested for charcoal production in the Thornbush Savanna (Smit *et al.,* 2015). *Senegalia mellifera* is known to cause impenetrable thickets (Smit, 1999a), whereas *V. reficiens* is not yet known to cause bush thickening to a large extent. *Senegalia mellifera* can grow either as a multi-stemmed bush or a single-stemmed tree, with heights of up to 7 and 9 m, respectively (Hagos, 2001; Mannheimer and Curtis, 2009). *Vachellia reficiens* is also multi- or single-stemmed and can grow to a height of 5 m (Mannheimer and Curtis, 2009). Both species are readily browsed by livestock and game, thus providing a good source of fodder (Hagos, 2001; Mannheimer and Curtis, 2009). It becomes important for an in-depth study of *V. reficiens* because of its occurrence in the central and northern savannas of Namibia, and especially its contribution to the charcoal industry.

CHAPTER 3: STUDY AREA

3.1. Location

The study was conducted on the farms Arcadia and Omatjenne, located northwest of Otjiwarongo (Figure 3.1) in an area described as the North-Central Plateau of Namibia. The vegetation is classified as Thornbush Savanna (Giess, 1998). Both farms are located in the Otjozondjupa Region of Namibia.

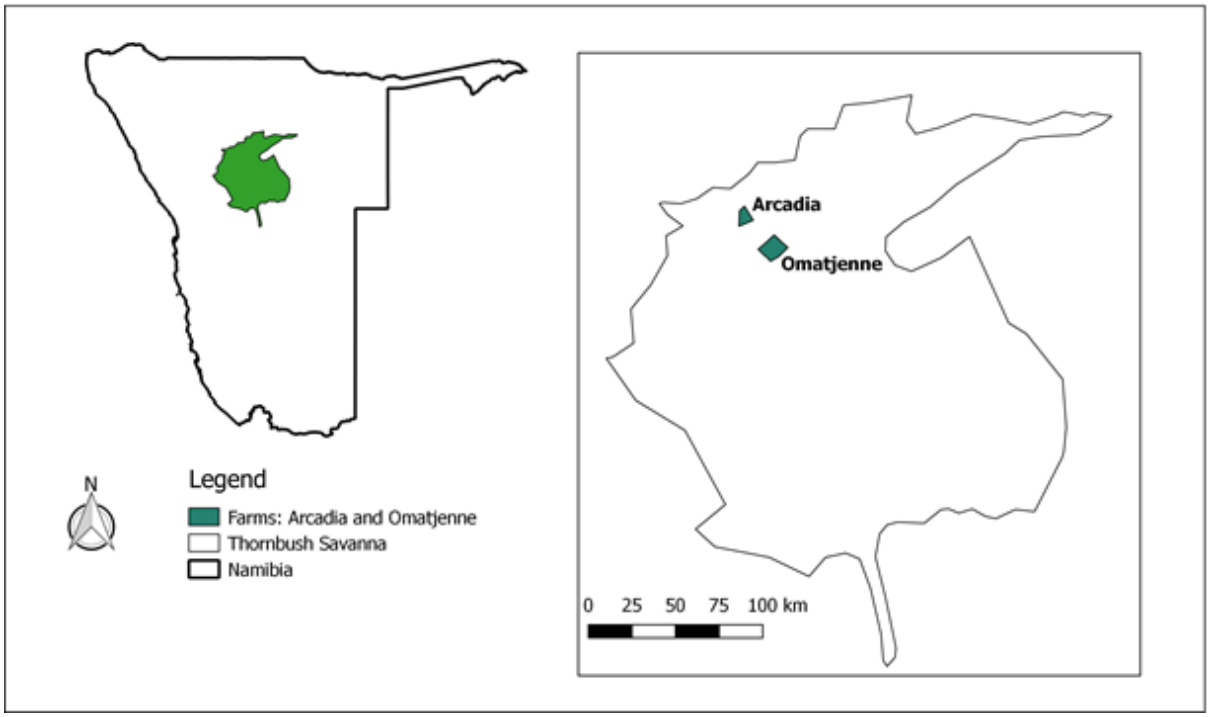


Figure 3.1: Location of the farms Arcadia and Omatjenne in the Thornbush Savanna of Namibia (green area) on which the study was conducted

The farms in the Thornbush Savanna - including Arcadia and Omatjenne - 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 *Antidorcas marsupialis* (Springbok), *Oryx gazella* (Gemsbok), *Alcelaphus buselaphus* (Red-Hartebeest), *Tragelaphus strepsiceros* (Greater Kudu), and *Phacochoerus africanus* (Warthog) are still common on all the farms in the area. In extensive cattle farms, the productivity of the natural vegetation - specifically the grasses - is critical to the success of these farming enterprises and thus heavily dependent on the annual rainfall.

3.2. Climate

The average long-term annual rainfall of the Otjiwarongo constituency is approximately 450 mm (CV = 15.14%) and was calculated from data provided by van der Waal *et al*. (2021) that was used for the national carrying capacity and agro-ecological zones project in Namibia

(van der Waal *et al.*, 2021). 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 3.2.

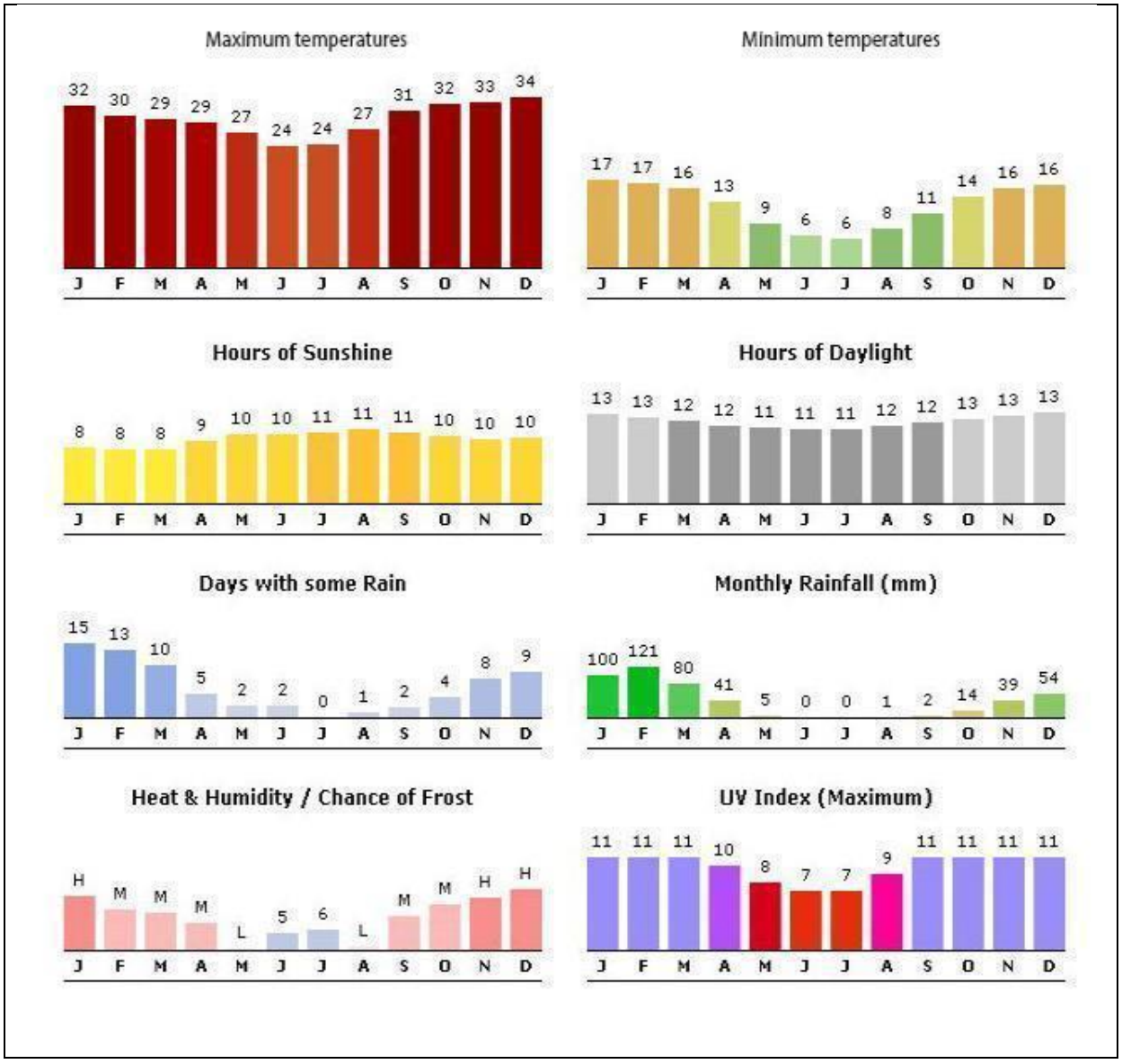


Figure 3.2: Summary of the average long-term climate variables of the Otjiwarongo district of Namibia (World Climate Guide, Smit et al., 2015)

The rainy season usually extends from October to April inclusively, but rainfall is irregularly distributed and unpredictable (Table 3.1). Three rainfall gauges were set up on the study area to have as accurate rainfall data on the study area as possible. Rainfall was recorded after every precipitation event, from which the total seasonal rainfall was calculated. The monthly rainfall for farms Arcadia and Omatjenne is presented in Table 3.1 for the study period.

Table 3.1: Monthly rainfall (mm) for farms Arcadia and Omatjenne during the study period

	Arcadia			Omatjenne		
Months	**2018/19 (Season 1)**	**2019/20 (Season 2)**	**2020/21 (Season 3)**	**2018/19 (Season 1)**	**2019/20 (Season 2)**	**2020/21 (Season 3)**
August	0	0	0	0	0	0
September	0	0	0	0	0	0
October	6	12	0	2.8	15.4	4.8
November	7	4	1	0.8	35.4	5.2
December	44	78	134	8	109.8	94
January	66	59	187	56.4	40.2	128.6
February	27	209	85	38.2	198.2	4.8
March	23	97	76	53.2	104.6	4.6
April	45	16	0	47.2	3.6	0.2
May	0	0	0	0	0	0
June	0	0	0	0	0	0
July	0	0	0	0	0	0
TOTAL	**218**	**475**	**483**	**206.6**	**507.2**	**242.2**
Standard deviation	**(±22.77)**	**(±63.44)**	**(±65.00)**	**(±23.77)**	**(±63.22)**	**(±43.25)**

3.3. Vegetation of the Thornbush Savanna

The Thornbush Savanna, also known as the Acacia Tree and Shrub Savanna (Giess, 1998), is situated in the central region of Namibia (Figure 3.3). The characteristic feature of the vegetation in a Thornbush Savanna is grassland with trees and bigger shrubs in dense or open clumps of varying sizes (Giess, 1998; Mendelsohn *et al.*, 2003). This has been altered over the years to more dense shrubby vegetation. *Vachellia* and *Senegalia* species are the dominant woody plants and in some areas bush thickening by *Senegalia mellifera* subsp. *detinens* is taking place (Giess, 1998). Other dominant woody plant species in the area are *Vachellia reficiens, V. hebeclada* subsp. *hebeclada*, *Senegalia erubescens, Ziziphus mucronata* and *S. fleckii* (Giess, 1998).

The main vegetation is associated with Calcisols (calcareous soils), Kastanozems (Cambisols/Luvisols), and Vertisols (clay-rich) of the Damara sequences. According to Giess (1998), *Vachellia erioloba* mostly occurs in the riverine woodland on the alluvial banks of rivers, whereas *Boscia albitrunca* is quite frequent in some localities. Giess (1998) further stated that *Philenoptera nelsii* is more common in sandy areas, whereas *Combretum apiculatum* often dominates on limestone and rocky outcrops.

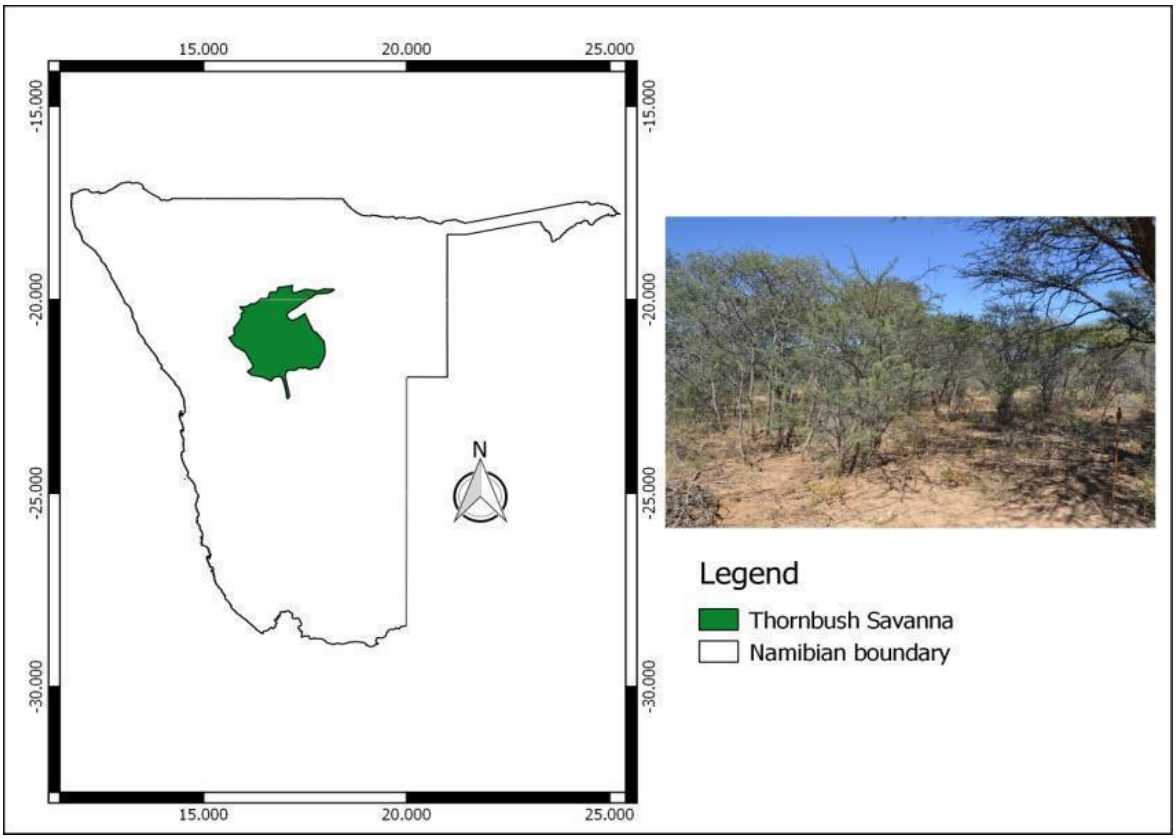


Figure 3.3: Map indicating the Thornbush Savanna within Namibia and a picture of how this veld type generally looks

The area has the potential for palatable perennial grasses (Muller, 2007). However, for the duration of the study, annual grass species were generally the most abundant species in the herbaceous layer. The dominant annual grasses are *Eneapogon cenchroides, Pogonarthria fleckii* and *Chloris virgata.* Giess (1998) did not report on grass species in the preliminary vegetation map of Namibia.

The Thornbush Savanna is a predominantly livestock farming area, especially for cattle. The rainfall varies from as low as 300 mm to 450 mm per annum (van der Waal *et al.*, 2021). Strohbach (2019) discovered extreme rainfall variation in the Thornbush Savanna and advised against using carrying capacities as an indicator for livestock productivity, but rather livestock suitability.

3.4. Geology and soils of the Thornbush Savanna

3.4.1. Geology

The geology of farms Arcadia and Omatjene is fairly homogenous in terms of lithology and terrain. The main rock types in the study area are sedimentary Damara schists (*Precambian* and

lower *Palaeozioc* basement) (Geological Survey of Namibia, 1980). The granite complex of the Paresis Mountain (*Cretaceous* intrusion) forms the land west of Arcadia farm. Large planation surfaces are due to the Tertiary denudation process (King, 1967).

Dolomite, granite, and quartzite form the harder rocks in the region and mostly occupy the ridges found around both farms (Geological Survey of Namibia, 1980). Kalahari sand, which covers the bulk of the Omatjene and Otjiwarongo area, in association with dolomite, generally weathers into sandy textured soils with relatively flat to gently undulating plains (King, 1967).

3.4.2. Topography

Arcadia and Omatjene farms are part of the flat to gently undulating landscape of the Central Plateau (De Pauw *et al.*, 1998). A few small scattered pans occur on the farms. Rocky outcrops and ridges also form part of the landscape character. Arcadia's altitude is about 1 000 m above sea level at the data collection sites.

3.4.3. Soils

The broad soil types where both farms Arcadia and Omatjenne are located are *chromic* Cambisols (Figure 3.4). Rock outcrops are also found in the broader area. The soils of the study area were classified as *Ochric* dark brown Kastanozems and the entire site has a slope classification of 2, very gently undulating with slopes of 0.5–2% (National Soil Survey Report, 2001).

Soils derived from the Damara sequence (schist, quartzite) are generally shallow, gravely, skeletal and well-drained, with low nutrient content and alkaline characteristics (Thomas and Shaw, 1990). Soils derived from the dolomite and limestone dykes are fine-textured, clayey, well-weathered, and generally deep. These moderately to poorly drained soils are prone to erosion along the floodplains and slopes. Soils derived from the *Aeolian* Kalahari sands are medium-grained, deep sands (Thomas and Shaw, 1990). Large areas along the ridge slopes contain no soil, consisting only of the exposed underlying granite, dolomite, and limestone material.

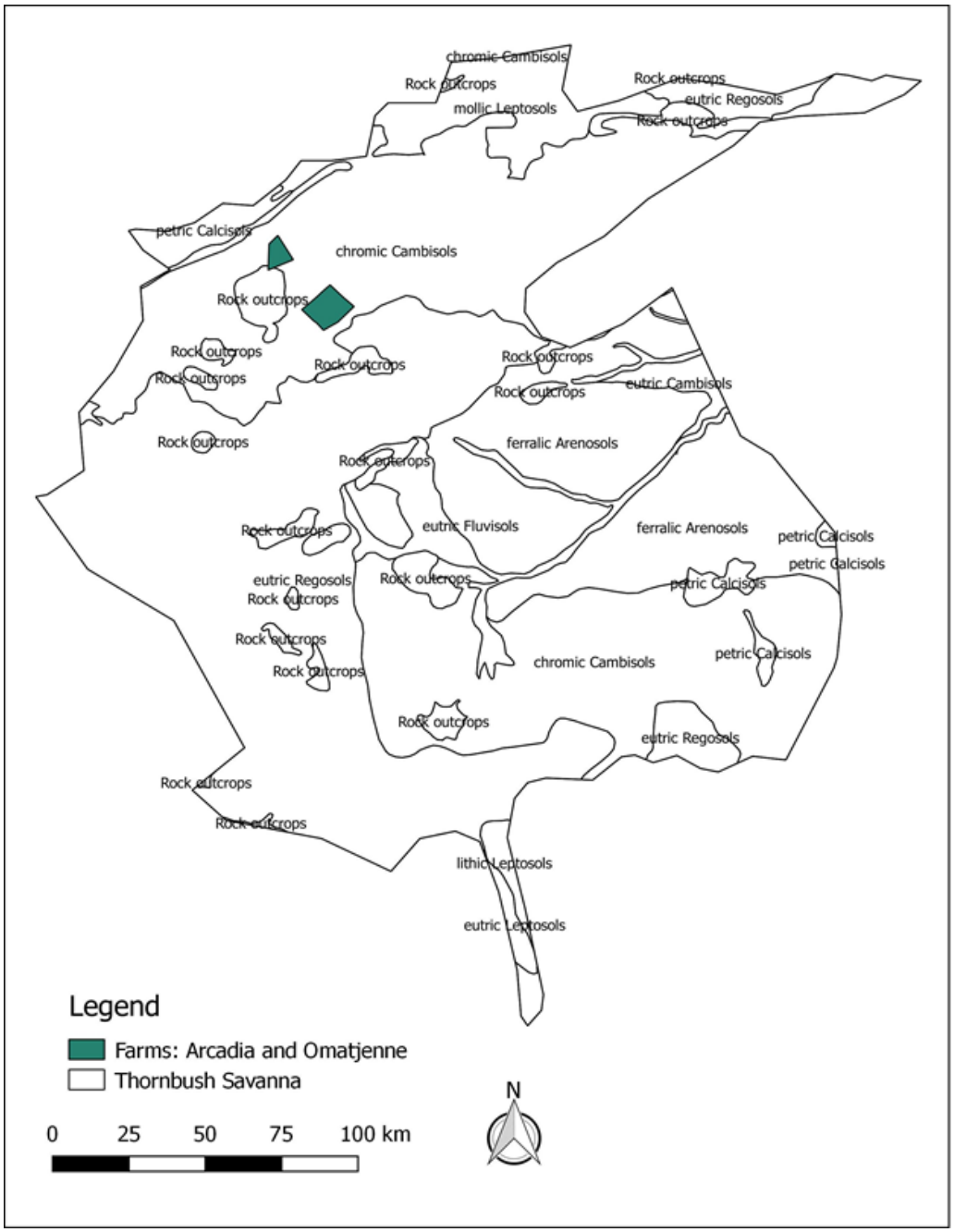


Figure 3.4: Broad soil types of the Thornbush Savanna and the location of the farms Arcadia and Omatjenne (van der Waal *et al*., 2021)

In addition to the broad soil classification, the specific soils of the study sites were described from six soil profile pits that were dug at representative locations at each of the study sites - four at Arcadia and two at Omatjenne (Figure 3.5).

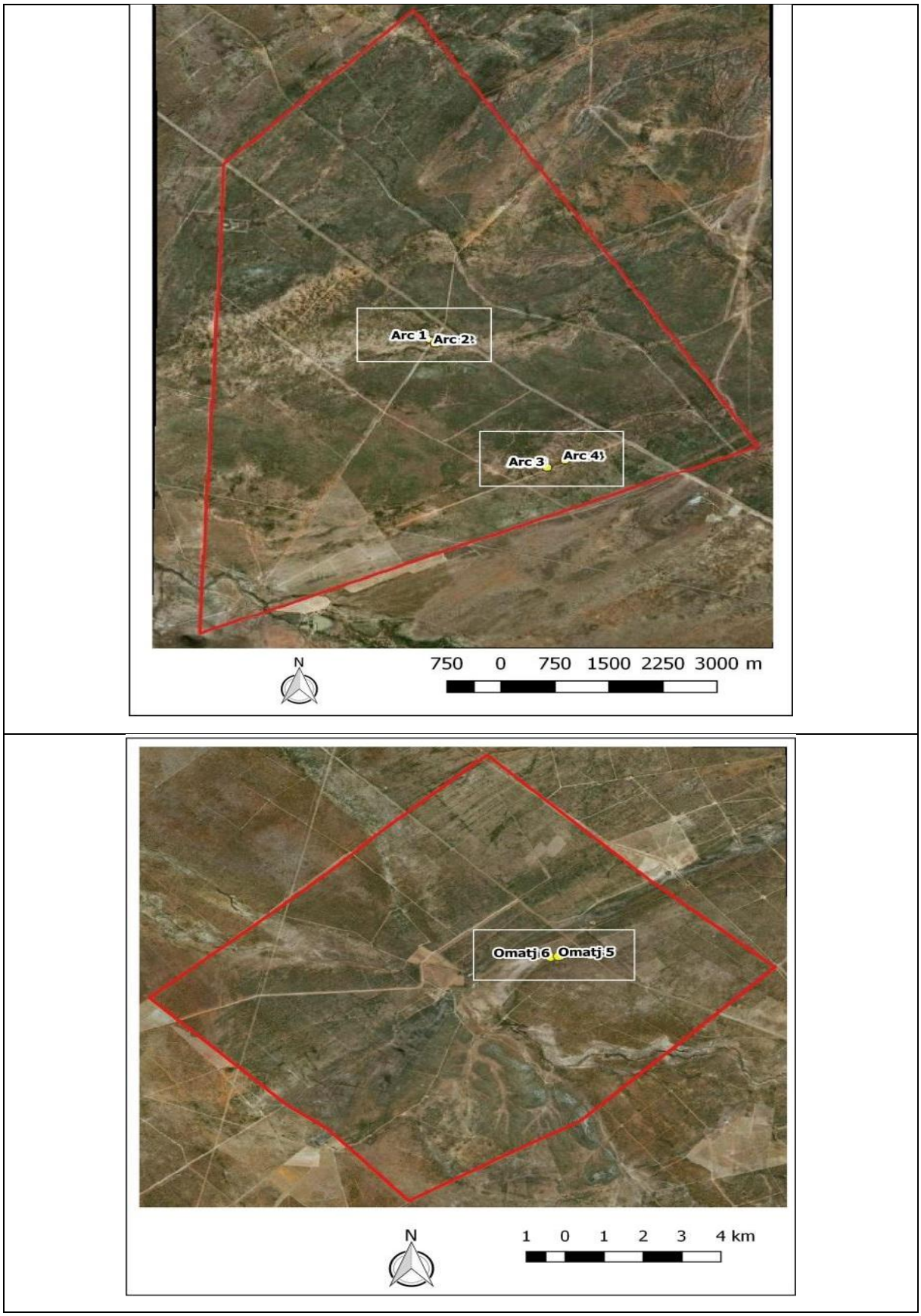


Figure 3.5: Locations of study sites and the soil profile pits that were dug for the description of the soil on farms Arcadia (top) and Omatjenne (bottom)

Although the areas where the soil profiles were dug at each site appear relatively similar and uniform, and the distances between soil profiles were relatively small (<150 m between Arc 1 & 2 and <300 m between Arc 3 & 4) (Figure 3.5), the soil varied more than expected (Table 3.2).

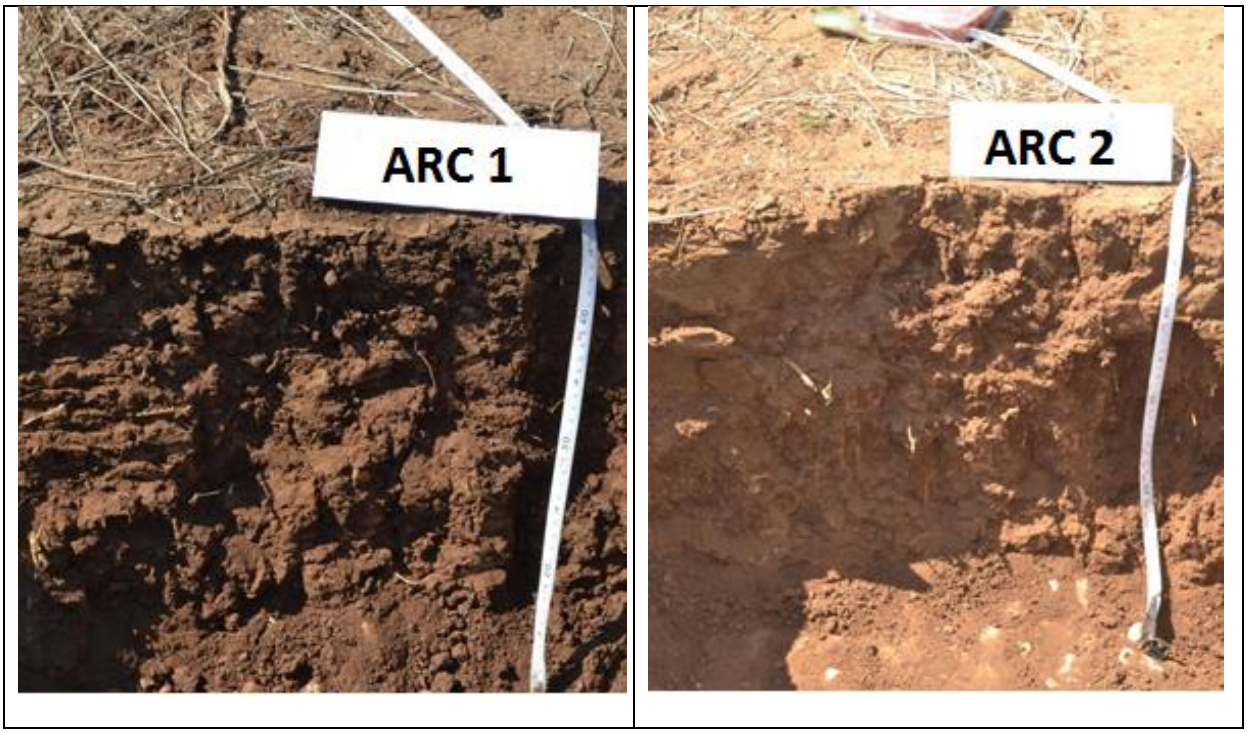


Figure 3.6: Soil profiles on farm Arcadia (Arc 1 on the left & Arc 2 on the right)

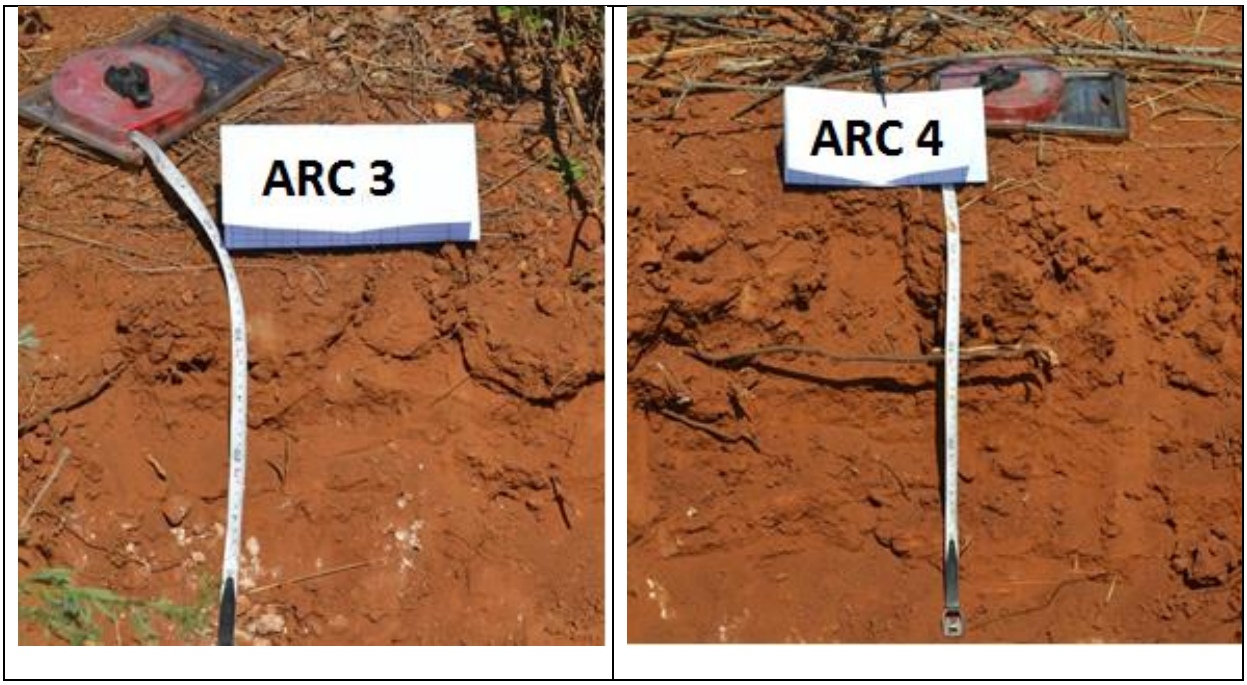


Figure 3.7: Soil profiles on farm Arcadia (Arc 3 on the left & Arc 4 on the right)

Table 3.2: Full description of the soil profiles on Arcadia

	Profiles			
	Arc 1	**Arc 2**	**Arc 3**	**Arc 4**
Horizon & Depth	A: 0 - 10 cm Bw: 10 - 25 cm C: >25 cm	A: 0 - 10 cm Bw: 12 - 45 cm C: >45 cm	A: 0 - 15 cm C: >15 cm	A: 0 - 15 cm Bw: 15 - 40 cm C: >40 cm
Horizon & Texture	A: SL (54.7% Sand, 37.3% Silt, 8.1% Clay) Bw: L (44.2% Sand, 33.7% Silt, 22.1% Clay) C: Rock	A: SL (70.2% Sand, 24.5% Silt, 5.3% Clay) Bw: SL (54.3% Sand, 30.0% Silt, 15.7% Clay) C: Rock	A: SL (75.4% Sand, 17.3% Silt, 7.5% Clay) C: Rock	A: SL (53.3% Sand, 40.7% Silt, 6.0% Clay) Bw: SL (53.7% Sand, 41.1% Silt, 5.2% Clay) C: Rock
Colour	A: Dark grey (10YR 4/1) Bw: Very dark grey (10YR 3/1)	A: Very dark greyish brown (10YR 3/3) Bw: Very dark greyish brown (10YR 3/2)	A: Dark reddish brown (5YR 3/3)	A: Very dark greyish brown (10YR 3/2) Bw: Very dark grey (7.5YR 4/6)
Structure	A: Moderate medium sub-angular blocky Bw: Strong coarse prismatic	A: Moderate fine sub-angular blocky Bw: Strong medium angular blocky	A: Weak very fine sub-angular blocky	A: Weak fine sub-angular blocky Bw: Moderate medium sub-angular blocky
Consistency	A: Very friable, plastic and sticky B: Very fine, plastic and sticky	A: Very friable, plastic and sticky B: Friable, plastic and sticky	A: Very friable, non-plastic and non-sticky	A: Slightly sticky B: Very fine, Sticky and plastic
Soil form (WRB)	Calcic Vertisols	Haplic Luvisols	Haplic Lixisols	Luvic Calcisols
Soil form (SAWG)	Arcadia	Oakleaf		

WRB: World Reference Base, SAWG: South Africa Working Group

The soils on Arcadia were generally very shallow, ranging from 25 – 45 cm, with colours ranging from dark grey-brown to dark red-brown (Figures 3.6 & 3.7, Table 3.2). The soils were mainly sandy loam in both A and B horizons with fine to course roots in the A horizon and no roots in the B horizon. The soil structure varied from fine to medium, sub-angular, blocky in

the A horizons to strong, medium, sub-angular, blocky in the B horizons. A detailed description of the representative soil profiles at each study location on Arcadia is presented in Table 3.2.

The soils on Omatjenne were relatively deep (70-80 cm), with colours ranging from brown to yellow red (Figure 3.8). The A horizons were predominantly sandy loam with a sandy loam/sandy clayey loam B horizon. The soil structure was also fine to sub-angular, blocky in horizon A with an abundance of roots and course, sub-angular, blocky with no roots in horizon B. Soil consistency was medium to course when dry and firm when moist. Both soils were classified as Luvisols.

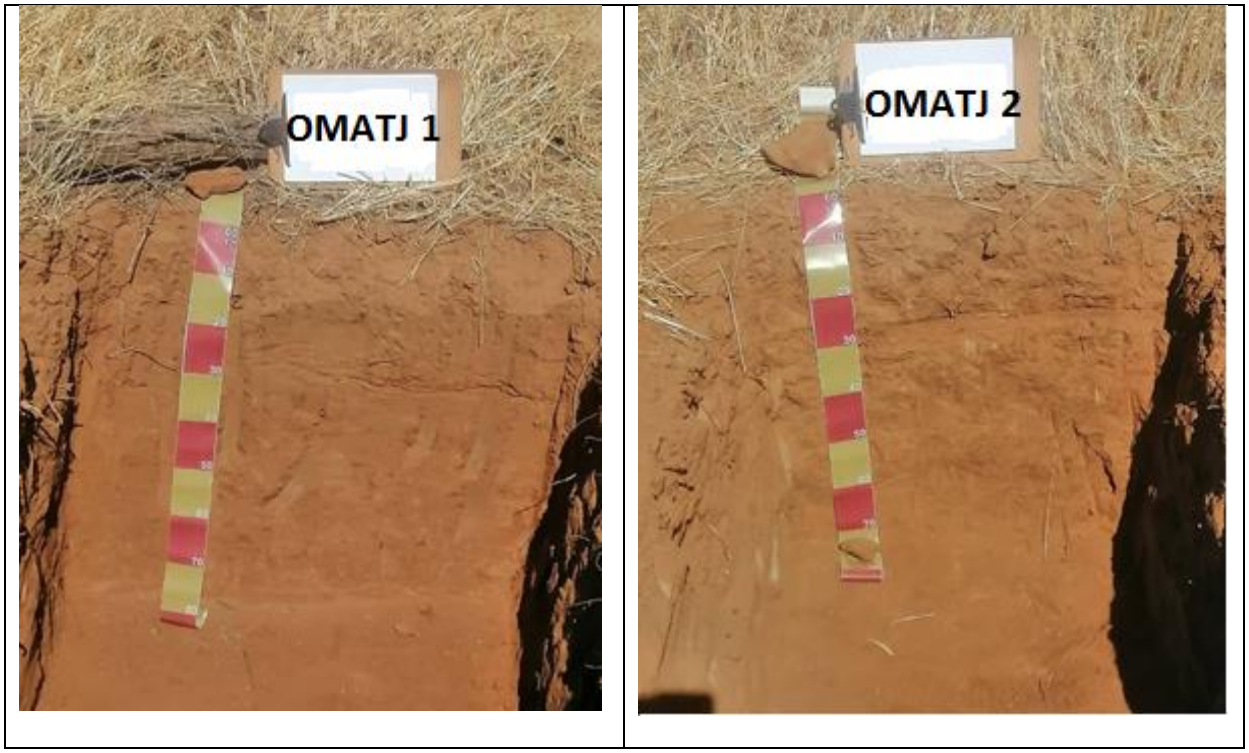


Figure 3.8: Soil profiles on farm Omatjenne (Omatj 1 on the left & Omatj 2 on the right)

Table 3.3: Full description of the soil profiles on Omatjenne

	Profiles	
	Omatj 1	**Omatj 2**
Horizon & Depth	A: 0 - 30 cm Bw: 30 - 80 cm C: >80 cm	A: 0 - 30 cm Bw: 30 - 70 cm C: >70 cm
Horizon & Texture	A: SL (70.2% Sand, 24.5% Silt, 5.3% Clay) Bw: SL/SCL (44.2% Sand, 33.7% Silt, 22.1% Clay) C: Rock	A: SL (75.4% Sand, 17.3% Silt, 7.5% Clay) Bw: SL/SCL (44.2% Sand, 33.7% Silt, 22.1% Clay) C: Rock
Colour	A: Brown Bw: Yellow red	A: Brown Bw: Yellow red
Structure & plant roots	A: Fine to course sub-angular blocky. Many fine to course roots Bw: Course sub-angular blocky No roots	A: Fine to course sub-angular blocky. Many fine to course roots Bw: Course sub-angular blocky No roots
Consistency	A: Medium to course when dry and firm when moist B: Course when dry and firm when moist	A: Medium to course when dry and firm when moist B: Course when dry and firm when moist
Soil form (WRB)	Luvisols	Luvisols
Soil form (SAWG)	Clovelly	Clovelly

WRB: World Reference Base, SAWG: South Africa Working Group

3.4.4. Agro-Ecological Zones

According to De Pauw *et al.* (1998), the study areas stretch over two Agro-Ecological Zones (AEZ); the Western-Central Plateau (CPL 16-3 & CPL-2) on the west towards Outjo, and Eastern-Central Plateau on the east towards Otjiwarongo. The Western-Central Plateau (CPL 16-3) is characterized by reddish Kalkveld with an average growing period of 61-90 days (De Pauw *et al.,* 1998). The Eastern-Central Plateau (CPL-2) is characterized by low fringes of plains and hills with an average growing period of 61-90 days (De Pauw *et al.,* 1998).

The Agro-Ecological Zones (AEZ) were further updated and refined and the former Central Plateau (De Pauw *et al.,* 1998) is now separated into the Karst Plateau and Lowlands (van der

Waal *et al.,* 2021). Arcadia and Omatjenne, therefore, now falls in the Karst Plateau and Lowlands respectively. The improved main AEZ for the Thornbush Savanna in Namibia is illustrated in Figure 3.9.

Farms Arcadia and Omatjenne are located in the Karst Plateau and Lowlands, respectively, with land suitability ranging from S - 3 to S - 4. The land suitability is classed as follow:

S – 0: Unsuitable

S – 1: Very marginal

S – 2: Marginal

S – 3: Moderately suitable

S – 4: Suitable

S – 5: Highly suitable

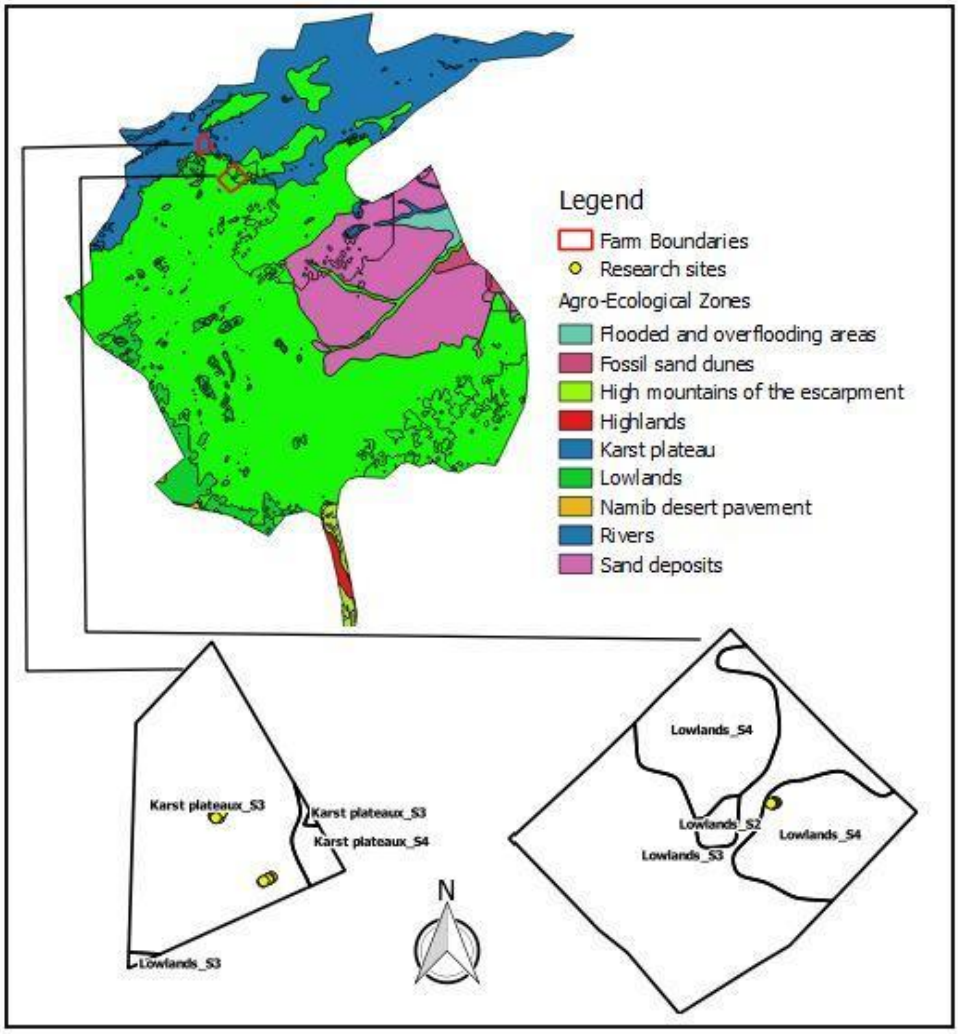


Figure 3.9: Agro-Ecological Zones of the Thornbush Savanna, location of the farms, and the specific study sites (van der Waal *et al.*, 2021)

These suitability classes represent good growing conditions (soil and climate) for plants. This indicates good grazing potential of the study area if in a healthy savanna state. The average long-term animal carrying capacity for the study area is 25 – 30 kg Animal Biomass per ha (van der Waal *et al.*, 2021).

CHAPTER 4: COPPICING ABILITY AND SEEDLING ESTABLISHMENT OF WOODY PLANTS AFTER NON-SELECTIVE WOOD HARVESTING

4.1. Introduction

Most southern African woody plants, especially trees, occur over a fairly broad distribution range, extending over several countries, of which Namibia is the driest and provides the most extreme conditions for these widespread savanna woody plant species (Burke, 2006). Apart from the climatic variations to adapt to, African savannas co-evolved with herbivores (Du Toit, 2003) and were frequently subjected to natural damages such as heavy browse by large herbivores (elephants, black rhinos, and giraffes), fire (Anderson *et al.*, 2016) and drought (Abraham *et al.*, 2019). In order to survive these natural damages, the woody plants had to develop strategies to survive and ensure their co-existence in savannas. Savanna woody plants have morphological, structural and chemical defense mechanisms against these natural damages (Borchard et al., 2011). In turn, large herbivores have counteracted the effects of plant defense by selective foraging, fragmentation of intact plant tissues, microbial fermentation, and expanded guts for microbial breakdown (Borchard *et al*., 2011). African savanna ecosystems under heavy browsing have hardy woody species that are resistant to or defensive against defoliation (Sebata, 2013). More specific survival strategies are the ability to coppice after physical damage, the development of a thick bark on the stems and trunk to protect the plant from fire damage, and the production of large quantities of seed, some of which are hard scaled and are able to form persistent soil seed banks that can stay viable in the soil for long periods of time.

A key characteristic of the resilience and productivity of savannas is the ability of woody plants to regenerate quickly after disturbance by fire, browsing, or cutting (Shackleton 2001; Smit 2003; Scogings *et al.* 2013). This adaptation of woody plants makes it difficult to control these woody plants in situations where they increase to unacceptable densities. This phenomenon, whereby indigenous woody plants increase to unacceptable densities at the expense of the grass layer, is known as bush thickening. Bush thickening has long been considered an ecological and economic problem in southern African rangelands, including Namibia (De Klerk, 2004; Joubert *et al.*, 2008; O'Connor *et al*., 2014).

In an attempt to control woody plants in bush-thickened areas for savanna restoration, farmers often remove the woody plants to "open up" the thickened savanna shrubland for increased grazing for their livestock. The method used for harvesting the wood usually involves some form of heavy bush-roller measure during which the entire woody plant is removed close to

ground level, leaving the stem base behind. The harvested bush resource is often used for bush feed and wood value-chain products such as charcoal, biochar, woodchips and firewood for extra income, and has become a growing, profitable industry in Namibia with an export market (DAS, 2017).

Considering the growing industry of bush resources, the harvesting process is often non-selective and a large number of plants are removed, leaving the harvested area in a state of sudden and severe ecological disturbance. After physical damage in the form of wood harvesting, the woody plants then employ their acquired natural survival strategies to re-establish themselves. This re-establishment after harvesting often happens in the form of coppice from the above-ground stem base, suckering from underground stems and/or roots, and seedling establishment (Scholes, 1990). More aggressive pioneer woody species such as *Dicrostachys cinerea, Catophractes alexandri, Phaeoptilum spinosum,* and *Grewia* species are often the first species to establish in the disturbed harvested areas.

In order to test the effects of non-selective wood harvesting, most commonly known as bush clearing, a heavy bush-roller (mechanical harvesting) and chainsaws (semi-mechanized/manual harvesting) were used for harvesting. Large harvesting machinery often causes soil disturbance which can be detrimental to the grass layer and beneficial for the establishment of these aggressive pioneer woody species, which will result in a denser woody community (Smit *et al*., 1999). The specific objectives of this study were to determine and assess the effect of two non-selective wood harvesting techniques (a heavy bush-roller and chainsaws) on:

- The regeneration of woody plants,
- Change in the vegetation size structure of woody plants,
- Species composition of woody plants, and
- Rate of wood biomass production of woody plants.

4.2. Procedure

4.2.1. Study area

The study was conducted on farm Arcadia, located northwest of Otjiwarongo (Chapter 3, Figure 3.1) in an area described as the North-Central Plateau of Namibia and the vegetation classified as Thornbush Savanna (Giess, 1998). This area was selected for this study as it is the "hotspot" of most of Namibia's bush harvesting and charcoal production. The dominant woody plant species are *Senegalia mellifera* and *Vachellia reficiens,* and they are also the most sought-after

for charcoal production. Other dominant woody genera are *Boscia, Combretum, Dichrostachys, Terminalia* and *Grewia* (Nghikembua *et al.*, 2021).

4.2.2. Site selection and trial layout

The different treatments were conducted on plots of 50 x 30 m (1 500 m^2), located in a homogeneous, densely wooded area on farm Arcadia in the Thornbush Savanna of Namibia (Chapter 3, Section 3.1). The plot sizes were determined by the abundance of *Senegalia mellifera* and *Vachellia reficiens*, of which at least 10 individual plants of a harvestable size for wood (2.0-4.0 m height size class) of each species were required per plot for the various treatments. These two species were selected in view of their abundance (dominant species), and high wood biomass potential (Smit *et al.*, 2015). Amongst others, *S. mellifera* and *V. reficiens* are also potential problem species in terms of woody plant thickening and are currently harvested for wood on several farms in the Thornbush Savanna where the study was conducted.

4.2.3. Treatments

There were two replications for each treatment applied and two control plots (Figure 4.1). The treatments were mechanical (heavy bush-roller) and semi-mechanised/manual (mainly chainsaws) harvesting (see Section 4.2.5).

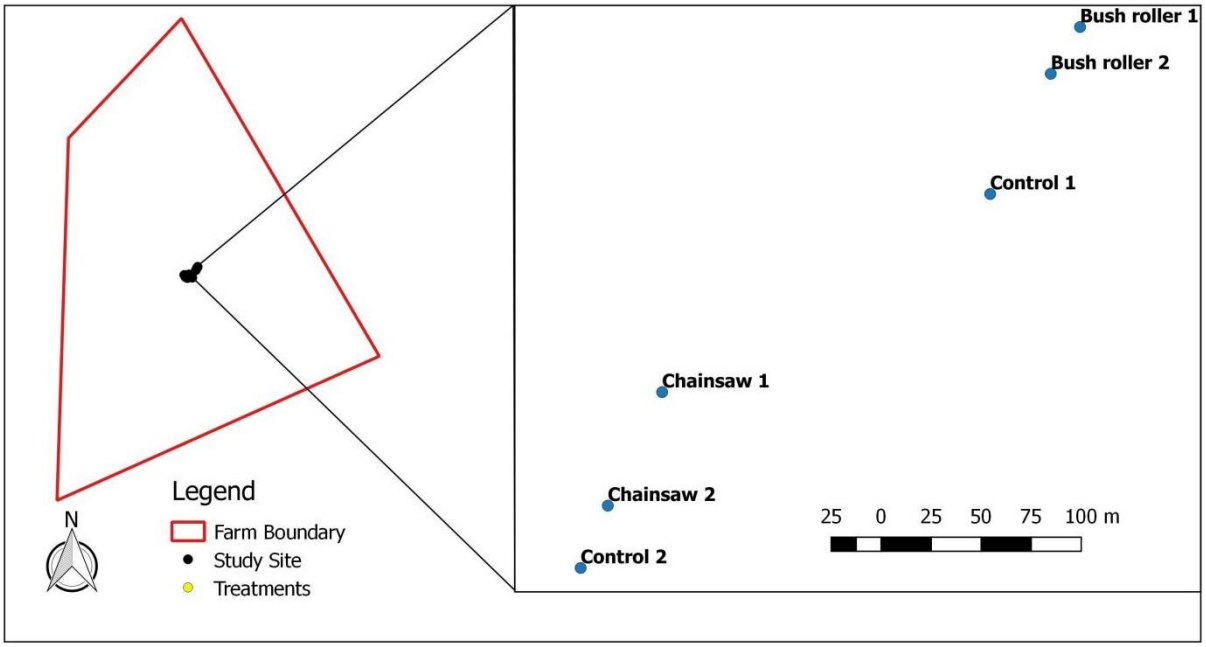


Figure 4.1: Trial layout showing the different treatments for non-selective harvesting

In each plot, a total of 10 harvestable (2-4 m height size class) plants of both *S. mellifera* and *V. reficiens* was randomly selected, marked and measured according to the third version of Biomass Estimate from Canopy Volume (BECVOL-3) procedure (Smit, 2014) before

harvesting (see Section 4.2.4). In addition, a fixed belt transect of 40 x 2.5 m (100 m^2) was also demarcated in each plot for detailed woody data collection. A BECVOL-3 survey was carried out for both the marked plants and the overall woody layer in each plot before harvesting.

The surveys were carried out in May 2017 and all the woody plants in the plots were harvested non-selectively/cleared by means of a heavy bush-roller (mechanical) and chainsaws (semi-mechanized/manual) shortly thereafter in the same month and year (see Section 4.2.5). The regrowth of the woody layer was then measured in May each year for four years after initial harvesting. The distance and nearest plant species to the marked *S. mellifera* and *V. reficiens* as species of interest were recorded. The average stem diameter and number of stems of the marked species were also recorded.

4.2.4. Woody plant surveys

The dimensions of all rooted, live woody plants above 0.5 m in height were measured according to the BECVOL-3 procedure (Smit, 2014) and included 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 at the height of the first leaves (Smit,1989a; 2014) (Figure 4.2). Measuring poles were used to measure the above-mentioned dimensions.

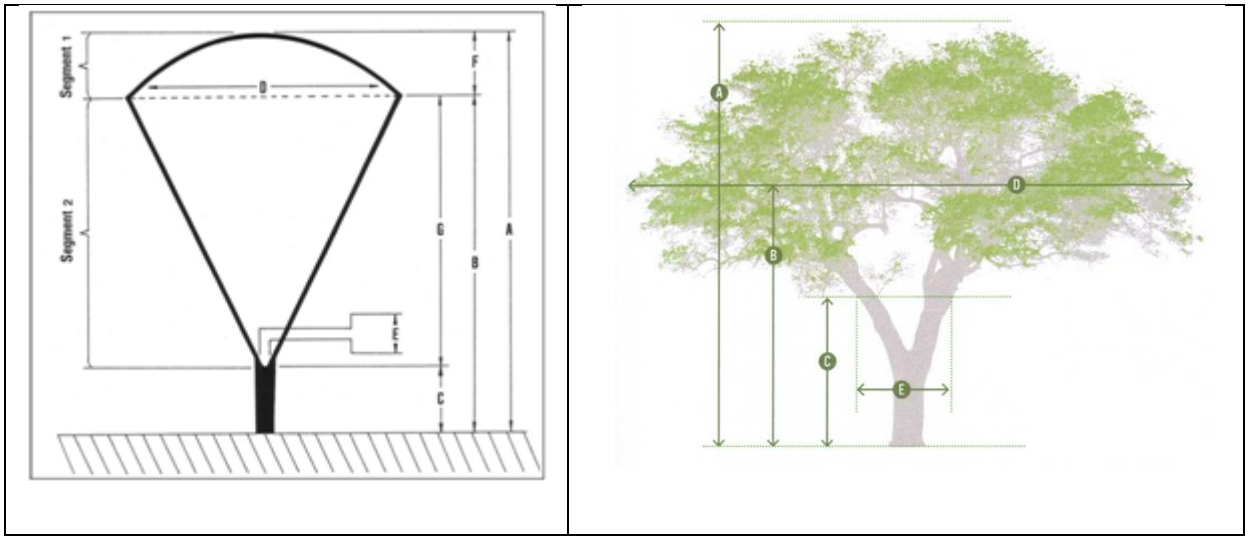


Figure 4.2: Schematic illustration of an ideal woody plant, its measurements, and its structure (Smit, 1989a)

The woody plant height was taken as the height of the main woody plant crown, ignoring any small stems protruding from the crown. Since the theoretical canopy is considered circular, the maximum canopy diameter is calculated as the average of two measurements perpenducular to each other (D_1 & D_2) whenever the woody plant canopy is elliptic (horizontally). The same

principle applies to the base diameter E (E_1 & E_2). All measurements are based on live woody plant parts only (Smit, 1989a). Therefore, the model also estimates the live woody plant densities on a species basis per hectare.

The original BECVOL model includes regression equations, developed from harvested woody plants, which relate the spatial canopy volume to the actual leaf volume and leaf dry mass (Smit, 1989a, Smit, 1996). The BECVOL 3-model (Smit, 2014) is the latest version that estimates the available browse from woody plant/shrub canopy volume. Additional regression equations were also developed for *S. mellifera* and *V. reficiens* during the course of this study. **Chapter 9** discusses the development of the additional regression equations that were added to the BECVOL 3-model.

The previous BECVOL-model (version 2) (Smit, 1996) only included estimates of the leaves as the browseable component of woody plants, while the BECVOL 3-model (Smit, 2014) includes estimates of both the leaves and young, new season's shoots less than 0.5 cm in diameter. This made the BECVOL 3-model (Smit, 2014) more accurate and useful, as browsing herbivores are generally selective feeders, selecting young shoot regrowth and fresh plant material. The most important addition to the BECVOL 3-model is developing additional regression models to estimate the dry mass of the wood component in different diameter classes (Smit, 2014). The BECVOL 3-model enables the user to calculate the following values (Smit, 2014):

- Woody plant density (plants ha^{-1})
- 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}),

- Total woody plant dry mass - leaves and wood combined (kg ha^{-1}), and
- Canopy sub-habitat index.

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

In addition to the total leaf and shoot DM ha^{-1}, stratified estimates of the leaf and shoot DM ha^{-1} below 1.5 m, 2.0 m, and 5.0 m, respectively, can also be calculated using the BECVOL-3 model. The height of 1.5 m represents the mean browsing height of the impala (*Aepyceros melampus*) (Dayton, 1978) and Boer goat (Aucamp, 1976), while 2.0 m and 5.0 m represent the mean browsing heights of the kudu (*Tragelaphus strepciseros*) and giraffe (*Giraffa camelopardalis*) (Skinner & Smithers, 1990), respectively. These browsing heights are mean, not maximum browsing heights. It is known that large individuals can reach higher than these mean heights, e.g. 2.5 m and 5.5 m for kudu and giraffe, respectively (Dayton, 1978), while the breaking of branches may enable some browsers to utilize browse at even higher strata (Rutherford, 1979; Styles 1993). Teague (1989) reported that some mature goats can browse up to a height of 2.0 m. Indigenous cattle, especially in the northern communal areas of Namibia, also browse up to a height of 2.0 m.

4.2.5. Harvesting

Harvesting was done by a large bush-roller, chainsaws and other hand cutting tools. The bush-roller used for wood harvesting in this study was a 215 horsepower (HP) front-end loader fitted with a single bush-roller (Figure 4.3). The front-end loader was also fitted with rubber tyres, covered with a chain net to prevent tyre damage. The rubber wheels and slightly elevated bush-roller had minimal soil disturbance during the harvesting process. Most plants were then rolled over, breaking the woody plant stems at ground level.

All woody plants were non-selectively harvested to reduce the influence of competition from undamaged woody plants on the coppice growth of the marked plants and to monitor the overall plant regrowth after clear-cutting of the land. The decision is further motivated by Smit and Goodman (1986) and Smit (2001), as they found that individual plant growth is highly dependent on total woody plant biomass as a result of inter-tree competition. Generally, clear-cutting is common practice in Namibia, occasionally leaving only the rare and/or desirable plants during woody plant control operations.

Generally, the bush-roller was not as effective as the chainsaw in harvesting as the slightly elevated bush-roller did not break the young, thin-stemmed plants, leaving them relatively undamaged. The operator also avoided large protected species during the harvesting process.

After the woody plants were felled by the bush-roller or chainsaw, the wood fraction (all stems > 2 cm) was removed as soon as possible (within a week) from the plots, as would be the normal procedure for charcoal production. All the thin stems (< 2 cm) and most of the leaves were not removed from the plots.



Figure 4.3: Front-end loader fitted with a heavy bush-roller and large wheels which caused minimal soil disturbance

4.2.6. Data analysis

A generalized linear model (GLM) was used for the modeling task to investigate the impacts of treatment on the vegetation structure (Venables and Ripley, 2002). The number of ETTE ha^{-1}, plants ha^{-1}, and wood mass (kg ha^{-1}) was used as the response variable, and explanatory variables were treatment type (control, chainsaw, bush-roller), and the year since treatment application (0, 1, 2, 3, and 4).

A binary GLM was used to investigate the effect of treatment on the coppicing of woody species. For each woody species, the response variable was coded as 1 where coppicing had taken place (yes) and 0 otherwise (no). Similar dependent variables were used (treatment type: control, chainsaw, bush-roller, and the year since treatment application: 0, 1, 2, 3, and 4).

Model fit was examined graphically by evaluating the trends and homoscedasticity of the Pearson residuals, and non-constant residual variance was modeled by updating initial models with a weighted variable (Mehtatalo and Kansanen, 2020).

The Jaccard similarity distances were calculated to determine how close treatment plots were in species composition by exploring the number of species shared between two sites divided by the total number of species (Oksanen *et al*., 2022).

Species richness and diversity were calculated using the package Vegan (Oksanen *et al*., 2022). Richness was calculated as the total number of species represented in a sample; diversity was calculated using the Shannon-Wiener diversity index (H'). All analyses were performed within R (version 4.1.2; R Core Team, 2021).

The wood biomass and ETTE were obtained from the BECVOL-3 data collection procedure (see Section 4.2.4). Species composition was calculated as the proportion of woody species in relation to the total number of individuals in each sample plot. The final composition estimates per treatment type were expressed as percentages (%) averaged across the plots for each respective area. All the descriptive statistics, such as graphs and tables, were generated using Microsoft Excel (Microsoft, 2010).

The woody vegetation growth (wood (kg ha^{-1}) and ETTE ha^{-1}) was projected using logistic population growth models (Case, 1999). The formula applied for projections was:

$$N = N_t (1 + R (1 - N_t / K))$$

N = Projected population size

N_t = Population size at a starting time

R = Population growth rate

K = Capacity of projected parameter (see explanation below)

The average wood biomass (kg ha^{-1}) and plant density (ETTE ha^{-1}) for three years were used as population size at starting time (N_t) for wood biomass and plant density projections. The population growth rate (R) for e.g. wood biomass (kg ha^{-1}) was calculated as follows:

R = wood biomass (kg ha^{-1}) at year 3 / wood biomass (kg ha^{-1}) before initial harvesting

In view of the assumption that wood harvesting is done with the aim of restoring rangelands, the capacity of the projected parameter (K) was calculated based on an extrapolation calculation adjusting wood biomass to the expected equivalent of the ETTE ha^{-1} and rainfall rule of thumb (Smit *et al.,* 2015). The capacity of the projected parameter (K) calculation for e.g. wood biomass (kg ha^{-1}) was calculated as follows:

K = (Wood biomass (kg ha^{-1}) before harvesting) x (Allowable ETTE (4500 ETTE ha^{-1})) / ETTE ha^{-1} before harvesting

The above calculation is an extrapolation of the wood biomass (kg ha^{-1}) at the allowable plant density (4 500 ETTE ha^{-1}), calculated from the pre-harvest wood biomass and plant density. The allowable ETTE ha^{-1} is a long-term rainfall-based "general rule of thumb" that stipulates that the median number of ETTE ha^{-1} that can be supported in a specific rainfall region without adversely affecting the grass layer should not exceed ten times the mean annual rainfall (Smit *et al.,* 2015) and is based on research done by Dye & Spear (1982), Richter *et al.* (2001) and Smit (2005).

The wood biomass (kg ha^{-1}) and plant densities (ETTE ha^{-1}) were obtained from the BECVOL-3 data collection procedure (see Section 4.2.4). The logistic growth models (Case, 1999) were calculated in Microsoft Excel. All other descriptive statistics, such as graphs and tables, were generated using Microsoft Excel (Microsoft, 2010).

4.3. Results and Discussion

4.3.1. Regeneration of woody plants after harvesting

Regeneration of woody plants in the form of coppice and/or new sapling recruitment should logically be influenced by competition from existing woody plants in the community. Coppice of the marked plants, *Senegalia mellifera* and *Vachellia reficiens*, as the species of interest (see Section 4.2.2), was recorded in both the bush-roller and chainsaw harvested plots. There were no significant differences ($P>0.05$) in coppicing rate between the bush-roller and chainsaw harvested treatments (Table 4.1).

Statistically, the nearest-neighbour plant species did not have an influence (P>0.05) on the coppicing probability of *S. mellifera* and *V. reficiens.* Although not significant (P>0.05), *Dichrostachys cinerea* and *Grewia flava,* as nearest plant species, positively influenced the coppicing probability of the marked species of interest (Table 4.1).

Table 4.1: GLM showing the effect of treatment, distance to nearest plant/neighbour, and nearest neighbour/plant species on the coppicing probability of *Senegalia mellifera* and *Vachellia reficiens*

	Estimate	**Std. Error**	**z Value**	**Pr(>|z|)**	
Intercept (Chainsaw harvested)	-1.586	0.419	-3.789	0.00015	***
Treatment (Bush-roller harvested)	-0.442	0.396	-1.117	0.264	
Distance	0.005	0.002	2.089	0.037	*
Neighbour: *Boscia albitrunca*	-15.830	1140.000	-0.014	0.989	
Neighbour: *Catophractus alexandri*	-16.080	2284.000	-0.007	0.994	
Neighbour: *Commiphora* spp.	-15.890	1614.000	-0.01	0.992	
Neighbour: *Dichrostachys cinerea*	0.210	0.591	0.356	0.722	
Neighbour: *Grewia flava*	0.200	0.525	0.38	0.704	
Neighbour: *Grewia flavescens*	-0.387	0.560	-0.691	0.490	
Neighbour: *Senegalia mellifera*	-0.043	0.726	-0.059	0.953	
Neighbour: *Vachallia reficiens*	-15.810	2284.000	-0.007	0.994	

It is generally argued that competition between woody plants has an effect on vegetation structure and productivity (Smith and Goodman, 1986; Teague and Smit, 1992; Scholes and Walker, 1993; Smit, 2001; Shackleton, 2002; Nghikembua *et al.*, 2021). Unlike the findings of Smith and Goodman (1986) and Smit (2001), where it was found that the growth rate of a plant is influenced by the total canopy biomass in its surroundings, this study was done on bush-cleared areas where all plant species had an equal opportunity to regrow. There was, therefore, only competition from the regrowth (coppice and saplings) of different species and no competition from undamaged mature plants.

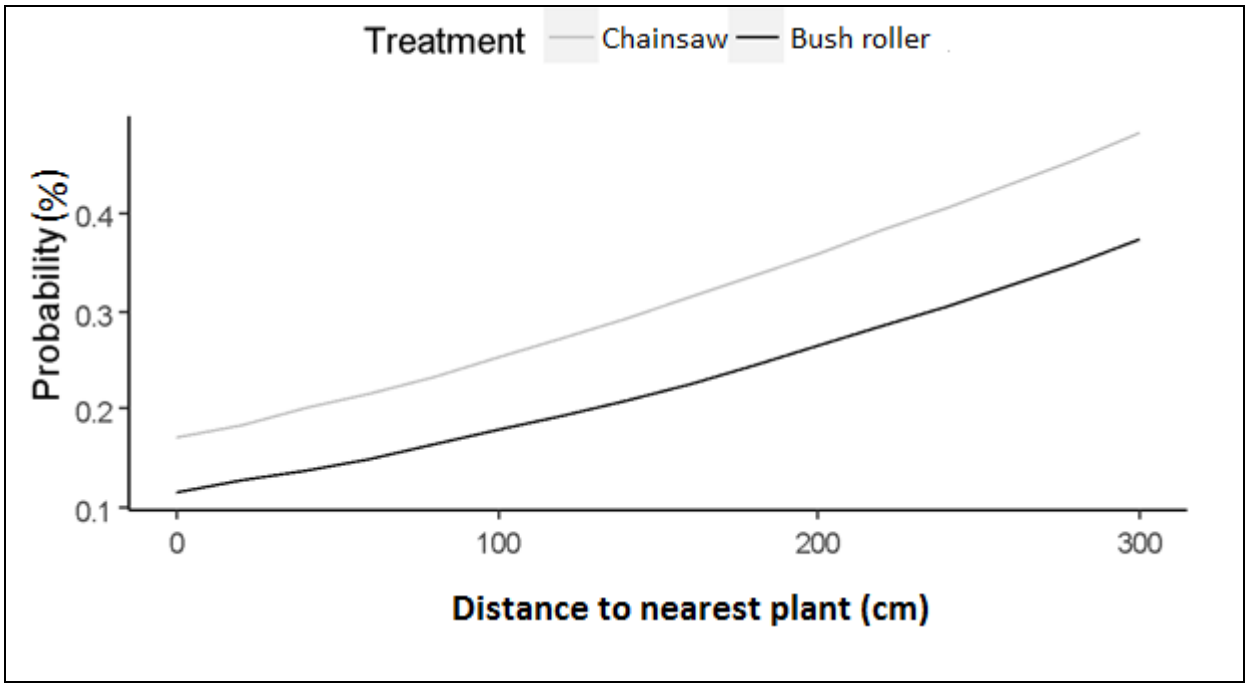


Figure 4.4: The relationship of nearest plant distance (cm) on the coppicing probability (%) of *Senegalia mellifera* and *Vachellia reficiens*

Although the entire plots were non-selectively harvested, the distance of the nearest plants (coppice, sapling or less-damaged plants) had a significant ($P<0.05$) effect on the coppicing probability of the *S. mellifera* and *V. reficiens* plants (Table 4.1). The coppice probability of *S. mellifera* and *V. reficiens* plants increased with increasing distances from the nearest plant neighbour (Figure 4.4).

It is accepted that the nearest plants are not the only competitors influencing the coppicing probability of a specific plant of interest due to the large and widely spread root systems of these savanna woody plants. However, it can therefore also be argued that, if the nearest plant did not have any influence on the coppicing probability of a given plant, then the clear positive correlation between the distance of the nearest plant and coppice probability would not have existed (Figure 4.4).

Shackleton (2002) conducted a similar study, and although not on coppice, the findings were that nearest plant competition is not as prevalent as previously suggested. However, intra-specific competition was found to be more prevalent than inter-specific competition (Shackleton, 2002). In the current study, *V. reficiens* appears to exert higher intra-specific competition against the coppicing focus species (*V. reficiens* and *S. mellifera*), whereas *S. mellifera* does not (Table 4.1). Species such as *Albiza anthelmintica, Boscia albitrunca, Catophractus alexandri* and C*ommiphora* species exert higher inter-specific competition. None

of the inter- and intra-specific competition influences were statistically significant (P>0.05) (Table 4.1).

Similar to this study, Shackleton (2002) found that the distance of the nearest neighbour had a significant influence on plants, and therefore, the further away the nearest neighbour, the larger the summed canopy area of the studied plant.

The low survival rate of coppice can therefore be as a result of several causes which, apart from method of harvesting (Table 4.2), include browsing impact, rainfall, plant species, soil type, the season of harvest, and size of plants harvested (Cunningham and Detering, 2017). These factors that affect coppice and its survival are discussed in detail in Chapter 5, Section 5.3.1.

Although the chainsaw harvested plots had significantly higher (P<0.001) coppicing rates than the bush-roller harvested plots (Table 4.1), the survival of the coppice was the same in year 3 for both treatments, as some coppice died off in years 2 and 3 (Table 4.2). *Vachellia reficiens* coppiced best in year 1 (rainfall = 218 mm, sd. = ±22.77, long-term average rainfall = 450 mm) for both treatments but survived better in the semi-mechanized harvested plots. *Senegalia. mellifera* survived better in the heavy bush-roller harvested plots (Table 4.2).

Table 4.2: Coppicing percentage of *Senegalia mellifera* and *Vachellia reficiens* in the chainsaw and bush-roller harvested plots

			Years of study		
Treatment	**Species**	**n**	**Year 1 % Coppice**	**Year 2 % Coppice**	**Year 3 % Coppice**
Chainsaw harvested	*Senegalia mellifera*	20	20	0	0
	Vachellia reficiens	20	70	25	20
Bush-roller harvested	*Senegalia mellifera*	20	20	15	15
	Vachellia reficiens	20	25	5	5
Annual rainfall (mm)			218	475	483
Standard deviation			(± 22.77)	(± 63.44)	(±65.00)

Stehn (2020) found that *Tarchonanthus camphoratus* coppiced readily in the first year after cutting. In the present study, *S. mellifera* and *V. reficiens* did not coppice as readily as expected, even with reduced competition on the bush-cleared plots. In this case, aggressive growers such as *D. cinerea, Grewia* species, and *C. alexandri* in the form of coppice, saplings and undamaged plants, especially in the heavy bush-roller harvested plots competed immediately with the coppice. It is evident from the findings of Shackleton (2002) that fast-growing woody plants can establish and develop into mature plants despite competition from other existing plants, especially if the existing plants are not fast growers. Joubert *et al.* (2017) reported that *S. mellifera* is a relatively slow-growing species, contrary to popular perceptions of the species

being an aggressive encroacher. It is noticeable that *V. reficiens* has similar growth characteristics and can also be regarded as a slow grower.

The treatments in this study were such that all plants had an equal opportunity to establish themselves. However, the aggressive pioneer species (*D. cinerea, Grewia* species, and *C. alexandri*) grew faster, and it appears as if they were able to outcompete the *S. mellifera* and *V. reficiens* saplings.

The low survival rate of coppice can therefore be as a result of several causes which, apart from method of harvesting (Table 4.2), include below average rainfall in year one (rainfall = 218, sd. ±22.77), immediate competition from the aggressive pioneer species, coppicing survival success of the harvested size class (Cunningham and Detering, 2017), season of harvesting (Strohbach, 1998; Luoga *et al.,* 2004; Schutz *et al.,* 2011) and general coppicing ability and survival of the species of interest (Cunningham and Detering, 2017). Along with carbohydrate availability, other factors such as moisture availability and the plant's phenological state also explain the variability in the coppicing ability of woody plants (Milton, 1998; Sebata, 2017).

Since woody plants, especially the sought-after slow-growing high wood-potential plants such as *S. mellifera, V. reficiens,* and *Vachellia tortilis* (Joubert *et al.,* 2017; Cunningham and Detering, 2017), undergo major physiological changes during harvesting, the chances of these plants coppicing will be rainfall dependent to a large extent. In this study, the first year's rainfall was below average (rainfall = 218, sd. ±22.77; long-term average rainfall = 450 mm, CV = 15.14%), followed by above average rainfall in the second (rainfall = 475 mm, sd. ±63.44) and third (rainfall = 483, sd. ±65.00) years (Table 4.2). During this follow-up above-average rainfall year, there was still coppice die-off. The assumption that can be made for this trend is that growth reserves were used in year one and the moisture availability was limited, which therefore caused a depletion of growth reserves without adequate aboveground growth for the production of reserves for the next year's growth.

The die-back of coppice was also reported by Stehn (2020) for *T. camphoratus,* although it is an aggressive, fast grower. Stehn (2020) also reported inconsistent rainfall patterns during the study duration, with rainfall well below the long-term average. This undoubtedly influenced the coppicing ability of *T. camphoratus* after cutting. *Tarconanthus camphoratus* is an encroacher and aggressive grower since it: (a) can increase significantly in numbers in an area; (b) can reduce the grazing capacity of the herbaceous layer; (c) is semi-deciduous to evergreen

and can grow all year round; (d) is not readily browsed by livestock or game; (e) can reproduce both sexually (seed) and asexually (root suckers); and (f) is fire tolerant (Stehn, 2020).

Apart from coppicing, sapling establishment is another form of woody plant regeneration after harvesting. From the data presented in Table 4.3, it is clear that the chainsaw harvested plots had on average fewer saplings ha^{-1} compared to the bush-roller harvested plots, although not of statistical significance ($P>0.05$). This may be as a result of the soil disturbance caused by the bush-roller, although it is minimal. *Dichrostachys cinerea* had a significantly higher ($P<0.01$) sapling density (saplings ha^{-1}) establishment compared to other species (Table 4.3).

Table 4.3: GLM showing the effect of harvest treatment on sapling establishment

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept (Bush-roller harvested)	83.25	25.19	3.304	0.00163	**
Treatment (Chainsaw harvested)	-22.12	15.78	-1.401	0.1664	
Species: *Boscia albitrunca*	-73.25	47.07	-1.556	0.1251	
Species: *Boscia foetida*	-51.13	45.14	-1.133	0.26201	
Species: *Catophractus alexandri*	-49.25	35.59	-1.384	0.1718	
Species: *Commiphora* spp.	-73.25	41.09	-1.783	0.07989	
Species: *Dichrostachys cinerea*	87.81	27.33	3.213	0.00214	**
Species: *Grewia flava*	-45.19	28.28	-1.598	0.11547	
Species: *Grewia flavescens*	-51.13	45.14	-1.133	0.26201	
Species: *Grewia retinervis*	-18.5	31.43	-0.589	0.55837	
Species: *Senegalia mellifera*	-31.83	28.49	-1.117	0.26854	
Species: *Vachellia reficiens*	44.48	27.33	1.628	0.10902	

Nghikembua (2020) also found *D. cinerea* as the dominant species in regeneration after wood harvesting through thinning in the Thornbush Savanna of Namibia. Smith and Goodman (1986) investigated sapling establishment in savanna and found two forms of sapling establishment: (a) sapling establishment associated with an under-canopy environment and (b) sapling establishment restricted to open or between-canopy environments. In the present study, a higher sapling establishment was recorded in the bush-roller harvested plots (Table 4.4), and therefore the findings of Joubert and Zimmerman (2002) are supported where they argue that mechanical harvesting causes soil disturbance, which promotes woody seedling emergence.

According to Smit *et al.* (1996), a survival strategy of woody plants is the production of large amounts of seed, hence the sapling establishment after harvesting. Some seeds have hard, permeable seed coats (Leistner, 1961; Gwynne, 1969; Hoffman *et al*., 1989; Miller, 1995), whereas others are small and can escape mastication (Coughenour & Detling, 1986; Coe &

Coe, 1987). Section 5.3.3 provides more detail on species percentage changes over the years, coupled to rainfall.

Following the classification of Smit *et al.* (2015), the woody plant species of the study area were categorized into three groups, namely: high wood-potential (*S. mellifera, V. reficiens*), low wood-potential (all *Grewia* species, *D. cinerea, C. alexandri* and *T. camphoratus*), and protected (*Boscia* species, *A. anthelmintica, Ziziphus mucronata* and *Commiphora* species) species. This classification was used as a measure of the potential value of the various woody plant species for commercial wood production.

A summary of the coppice, sapling establishment, and woody plants that survived the damage by the bush-roller in the first year following non-selective wood harvesting is presented in Table 4.4. The plants that survived the bush-roller damage were normally the young, flexible, thin-stemmed woody plants belonging predominantly to the low wood-potential species. The data presented in Table 4.4 support the statistical findings (Tables 4.1 and 4.3), although no statistical significance ($P>0.05$) was found. This indicates that the bush-roller harvested plots had higher sapling and lower coppice densities as opposed to the chainsaw harvested plots where the complete opposite was observed, with lower sapling and higher coppice densities. It was also clear that the low wood-potential species had the highest coppice and sapling establishment in both treatments (Table 4.4).

The results presented in Table 4.4 are supported by Cunningham and Detering (2017), where they found that coppice after cutting was 45% and 92.8% for *V. reficiens* and *D. cinerea,* respectively. These two species are classified as high and low wood-potential species, respectively.

Table 4.4: Comparison between bush-roller and chainsaw wood harvesting with relation to coppice, saplings and less-damaged plants (total plants ha^{-1}) the first year after harvesting

	Bush-roller harvested Plants ha^{-1}			**Chainsaw harvested Plants ha^{-1}**		
Plant categories	**Saplings**	**Coppice**	**Less-damaged plants**	**Saplings**	**Coppice**	**Less-damaged plants**
High wood-potential species	2 150	13	0	875	1 050	0
Protected species	50	200	150	150	200	0
Low wood-potential species	2 700	1 550	1 000	1 675	2 600	0
AVERAGE	**1 633**	**588**	**383**	**900**	**1 283**	**0**

The low wood-potential species in the bush-roller harvested areas regrew significantly ($P<0.05$) faster (111.4% from the original ETTE ha^{-1}) and even exceeded the original ETTE before

harvesting in comparison to the chainsaw harvested area (78.5% from the original ETTE ha^{-1}) within the four-year period (Table 4.5). Although the results were non-significant (P>0.05), the protected species established themselves faster in the chainsaw harvested areas (Table 4.5).

Table 4.5: Comparison in percentage re-growth (ETTE ha-1) of bush-roller and chainsaw harvested plots

	Bush-roller harvested ETTE ha^{-1}			**Chainsaw harvested ETTE ha^{-1}**		
Plant categories	**Before harvesting**	**Year 4 after harvesting**	**Percentage regrowth**	**Before harvesting**	**Year 4 after harvesting**	**Percentage regrowth**
High wood-potential species	5 162	203	3.9	3 754	262	7.0
Protected species	763	102	13.4	1 271	163	13.8
Low wood-potential species	2 154	2 400	111.4	2 233	1 752	78.5

The harvesting process with the bush-roller did not cause extensive soil disturbance, but was ineffective in controlling, especially, the flexible and thin-stemmed woody plants, mainly belonging to the low wood-potential species (Figure 4.5, Table 4.4).

This contributed largely to the fast regrowth percentage of the low wood-potential species dominating the woody vegetation on post-harvest land where harvesting was done non-selectively (Table 4.5). The protected species were mature and were mostly avoided by the machine operator where possible, hence the high number of undamaged plants in this category for bush-roller harvested plots (Table 4.4).



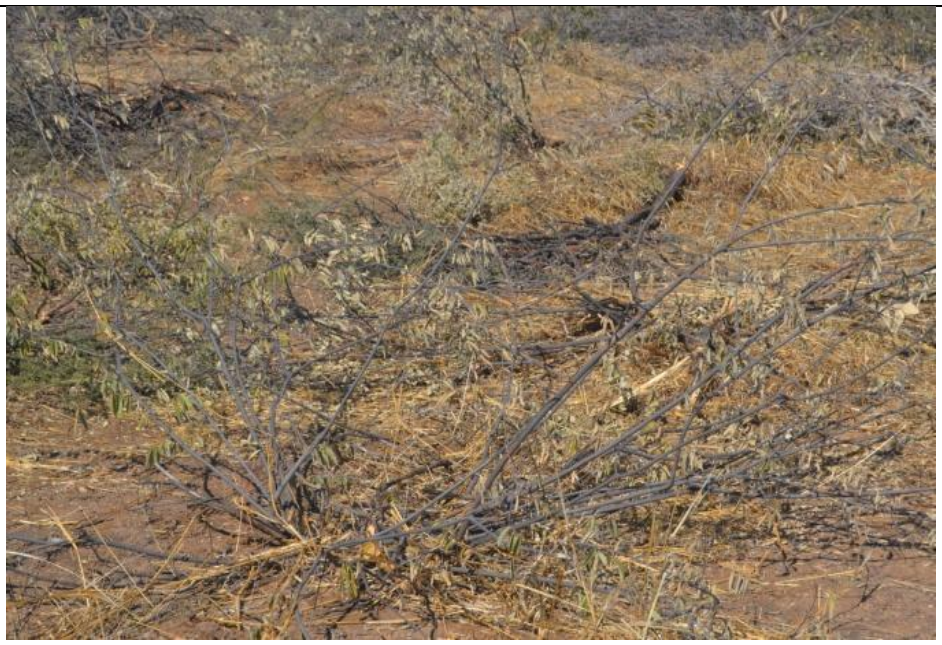


Figure 4.5: Larger trees are effectively damaged by the bush-roller when used for harvesting (Top) whereas younger or thin-stemmed plants are not effectively damaged (Bottom)

4.3.2. Changes in vegetation size structure after initial harvesting

The baseline conditions (β_0) of the GLM model showed that, on average, the estimated ETTE per species in the control plots was 857.9 ETTE ha^{-1} (Table 4.6). The negative values for the effect of chainsaw and bush-roller treatment show that the estimated ETTE ha^{-1} was less than the amounts in the control plots.

Table 4.6: Effect of treatment type and post-treatment period (years) on the ETTE ha^{-1} measured per species in the study area

	Parameter (β)	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept (Control)	β_0	857.9	123.6	6.939	1.19E-10	***
Chainsaw harvested (1)	β_1	-734.8	167	-4.399	2.08E-05	***
Chainsaw harvested (2)	β_2	-710.6	151.1	-4.703	5.89E-06	***
Chainsaw harvested (3)	β_3	-527	194.6	-2.707	0.00759	**
Chainsaw harvested (4)	β_4	-547.1	183	-2.99	0.00327	**
Bush-roller harvested (1)	β_5	-811.4	141.6	-5.73	5.53E-08	***
Bush-roller harvested (2)	β_6	-679.2	156.3	-4.344	2.60E-05	***
Bush-roller harvested (3)	β_7	-436.8	195.7	-2.232	0.02711	*
Bush-roller harvested (4)	β_8	-629.5	157	-4.009	9.67E-05	***

Numbers in brackets: Years

Compared to the baseline conditions (β_0), the predicted number of ETTE ha^{-1} in the chainsaw harvested treatment was significantly less by 734.8 (P<0.001) for year one, 710.6 (P<0.001) for year two, 527 (P<0.008) for year three, and 547.1 (P<0.003) for year four. In the same scenario, the predicted number of ETTE ha^{-1} in the bush-roller harvested treatment was significantly less

by 811.4 (P<0.001) for year one, 679.2 (P<0.001) for year two, 436.8 (P<0.027) for year three, and 629.5 (P<0.001) for year four. In all treatment types, the largest differences were observed in the first two years following wood harvesting.

The baseline conditions (β_0) of the GLM model show that on average, the estimated plants in the control plots were 282 plants ha^{-1} (Table 4.7). The positive values on the effects of the chainsaw and bush-roller harvested treatments show that the estimated plants ha^{-1} were higher than in the control plots. There were no significant differences (P>0.05) in plant densities for all post-harvest years for both heavy bush-roller and chainsaw harvested plots.

Table 4.7: Effect of treatment type and post-treatment period (years) on the plants ha^{-1} measured per species in the study area

	Parameter (β)	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept (Control)	β_0	281.522	53.179	5.294	<0.001	***
Chainsaw harvested (1)	β_1	5.978	139.407	0.043	0.966	
Chainsaw harvested (2)	β_2	27.853	108.457	0.257	0.798	
Chainsaw harvested (3)	β_3	223.895	149.299	1.5	0.136	
Chainsaw harvested (4)	β_4	193.478	136.036	1.422	0.157	
Bush-roller harvested (1)	β_5	-137.772	105.504	-1.306	0.194	
Bush-roller harvested (2)	β_6	65.353	113.34	0.577	0.565	
Bush-roller harvested (3)	β_7	202.012	133.13	1.517	0.131	
Bush-roller harvested (4)	β_8	-31.522	92.758	-0.34	0.734	

Numbers in brackets: Years

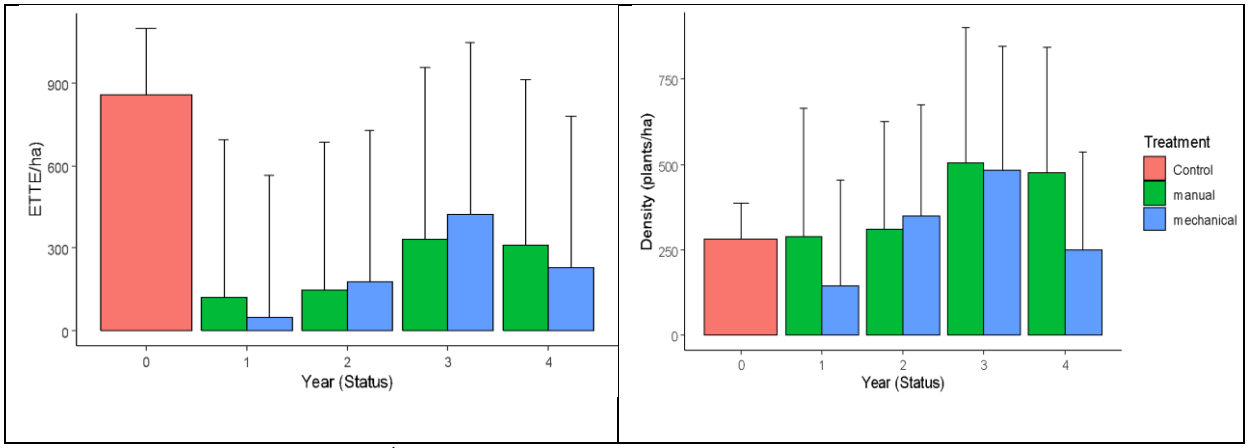


Figure 4.6: ETTE and plants ha^{-1} before (year 0) and after harvesting (year 1-4) for both chainsaw and bush-roller harvested plots. The error bars represent standard error (SE)

The data presented in Tables 4.6 and 4.7 are supported by Figure 4.6. The ETTE ha^{-1} dropped significantly (P<0.001) from pre-harvest (year 0) to the first year post-harvest and continued to be significantly (P<0.05) lower than pre-harvest conditions. In the same scenario, the plants ha^{-1} were comparable to the control plot in the first year after harvesting and throughout year

four post-harvest (Figure 4.6). These changes in ETTE and plants ha^{-1} are used to determine the change in vegetation size structure before and after harvesting.

Before wood harvesting, the woody vegetation mainly consisted of mature high wood-potential and protected species (high ETTE ha^{-1} with low plants ha^{-1}) and younger and/or smaller low wood-potential species (high plants/ha with low ETTE ha^{-1}) (Figure 4.7). After harvesting and re-growth monitoring for up to four (4) years, the woody vegetation changed to mature low wood-potential species (high ETTE ha^{-1} with low plants ha^{-1}) and young high wood-potential and protected species (high ETTE ha^{-1} with low plants ha^{-1}) (Figure 4.7).

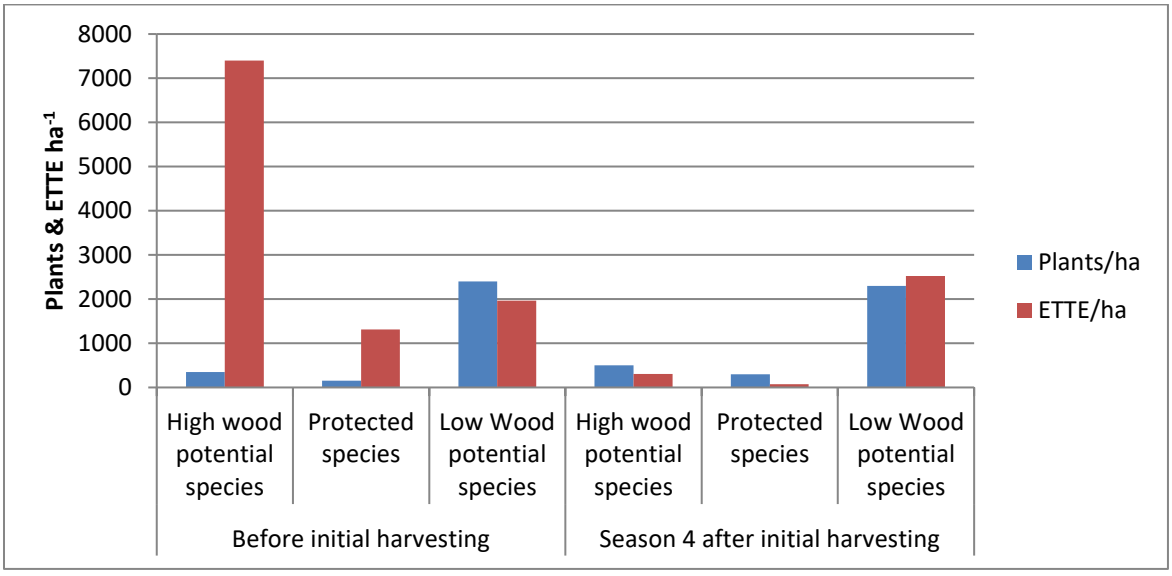


Figure 4.7: Comparison of vegetation size structure before and after harvesting, using the plants ha^{-1} and ETTE ha^{-1} relationship as determinants

A significant ($P<0.05$) change in dominance (ETTE ha^{-1}) was also observed for the high wood-potential species before and four years after harvesting (Figure 4.7). There was no significance ($P>0.05$) in dominance (ETTE ha^{-1}) for the low wood-potential species before and four years after harvesting (Figure 4.7).

The slow growth rates of *S. mellifera* (Joubert *et al.*, 2017), and assumably the same for *V. reficiens*, as dominant (Table 4.9) high wood-potential species and the fast growth rate of the low wood-potential species explain the observed change in vegetation size structure.

4.3.3. Change in species composition of woody plant regrowth after initial wood harvesting

Overall, the control area (β_0) had the highest average species richness (Table 4.8). Both the chainsaw and bush-roller treatments caused a reduction in the species richness. However, the differences were not significantly different ($P>0.05$) from the control area. The effect of the

year shows a positive, although statistically insignificant (P>0.05), influence on species richness, which suggests that with every unit increase in the period (year) following treatment, species richness recovered on average by 0.2 index values.

Regarding species diversity (*H'*), the control area (β_1) had the highest average index (Table 4.8). The chainsaw treatment caused a significant reduction of species indices by 0.83 (P = 0.021). The bush-roller treatment was also negative towards the diversity indices; however, this was not statistically significant (P>0.05). The effect of the year shows a positive and statistically significant (P<0.05) influence on diversity indices. Thus, with every unit increase in the period (year) following treatment application, diversity indices recovered progressively on average by 0.22 species indices.

Table 4.8: GLM showing the effect of treatment and time on the species richness and diversity. The treatments are control/before harvesting, chainsaw, and bush-roller plots

	Parameter (β)	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**	
1. Richness						
Intercept (Control)	β1	2.037	0.408	4.989	0.000	***
Chainsaw harvested	β2	-0.838	0.781	-1.072	0.284	
Bush-roller harvested	β3	-0.648	0.783	-0.828	0.408	
Year	β4	0.229	0.224	1.022	0.307	
2. Diversity						
Intercept (Control)	β1	2.0369	0.1895	10.748	<0.001	***
Chainsaw harvested	β2	-0.8251	0.3585	-2.301	0.0214	*
Bush-roller harvested	β3	-0.6284	0.363	-1.731	0.0834	
Year	β4	0.2219	0.1008	2.201	0.0277	*

The significant difference (P=0.277) in species diversity and the positive species indices for species richness (although not significant (P>0.05)) between the control plots and year after harvesting indicates some recovery of species abundance and richness (Table 4.8). It is, however, uncertain how long it will take to recover fully to its original species richness and diversity. Most concerning is the fact that the high wood-potential species that have the ability to become trees regenerate much slower than the low wood-potential, aggressive growers such as *D. cinerea* and *Grewia* species (Table 4.9). Another concern is the fact that the vegetation composition has changed post-harvest within four years from a plant community dominated by mature, high wood-potential species to a plant community dominated by young, low wood-potential species (Figure 4.7). It is clear that the plant community dominated by mature, high wood-potential species represents a higher plant succession stage and the disturbance caused

by the wood harvesting results in retrogression to a lower plant succession stage dominated by more pioneer woody species.

The similarities and differences between the treatments and years are outlined in Figure 4.8. The Jaccard similarity clusters indicate that the control (before harvesting) and the bush-roller harvested plots in year four have a similarity in species composition and are different from the rest of the treatments and years. There is, however, an indication of similarity earlier after harvesting (year 1 and 2) and later after harvesting (year 3 and 4) and a difference between earlier and later, with an exception with the chainsaw harvested plot in year 2 (Figure 4.8).

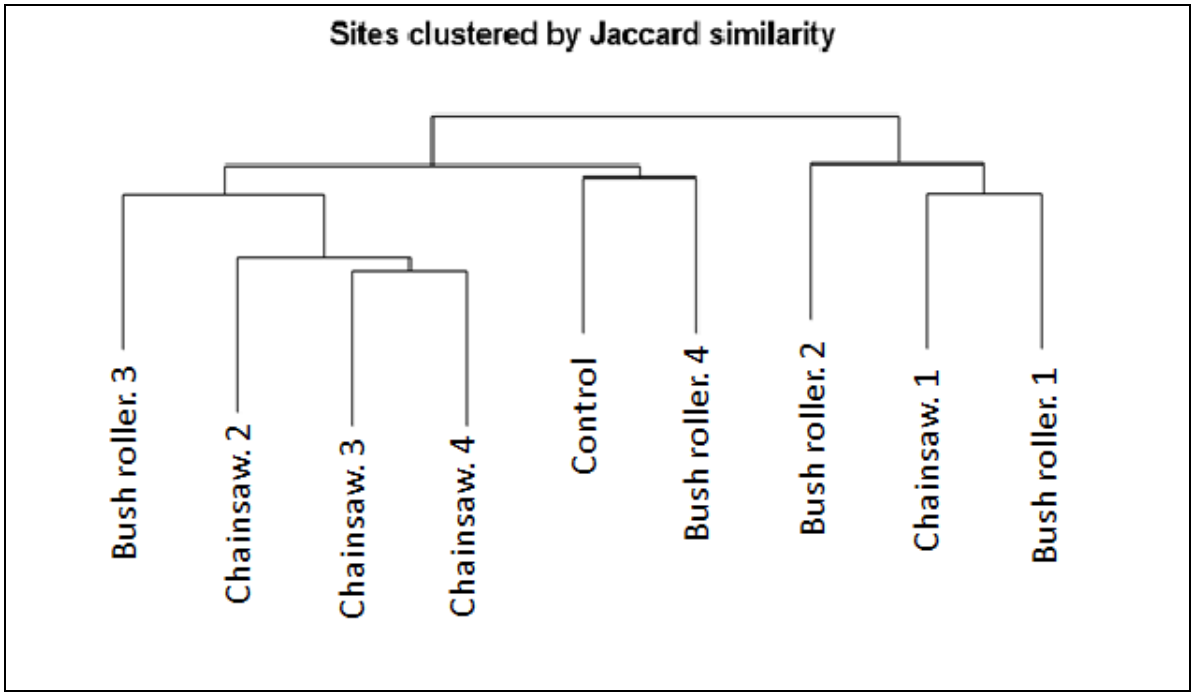


Figure 4.8: Jaccard similarity model showing similarities and differences between the different treatments and years

There was high species richness in all plots before harvesting, in which *D. cinerea* and *S. mellifera* dominated the percentage composition (Table 4.9). The lowest species richness was recorded in the first year after harvesting for both the bush-roller and chainsaw harvested plots. The second to fourth years had inconsistent trends in species richness, which are not clear but could possibly be a result of browsing activity and/or die-back and germination of saplings. The same inconsistency is noted for all species from the second to fourth years after harvesting. Similarly to the results in section 4.3.1, inconsistency in species richness was most probably caused by the below average rainfall in year one (rainfall = 218 mm, sd. ±22.77) after harvesting and above average rainfall from years two (rainfall = 475 mm, sd. ±63.44) to three (rainfall = 483 mm, sd. ±65.00) (see Chapter 3, Table 3.1). Joubert *et al.* (2017) found that seedling

emergence of woody plants was significantly higher in above-average rainfall years, and a similar finding is evident from the data presented in Table 4.9.

Table 4.9: Plant composition (%) before and after non-selective wood harvesting on both chainsaw and bush-roller harvested plots

	Non-harvested/year	Chainsaw harvested/year				Bush-roller harvested/year			
	0	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Protected species									
Albizia anthelmintica	6.9	-	2.9	8.2	12.6	-	-	1.8	2.1
Boscia albitrunca	2.6	-	2	-	-	14.7	4.2	2	6.7
Boscia foetida	1.5	10	1.9	1	0.6	-	1.9	1.5	-
Low wood-potential species									
Commiphora africana	-	-	-	-	-	-	2.2	-	1.3
Catophractes alexandri	10.6	-	-	-	-	-	4.5	8.5	2.8
Commiphora glandulosa	-	-	-	-	-	-	-	-	0.8
Commiphora pyracanthoides	0.6	-	-	-	-	-	-	0.8	-
Dichrostachys cinerea	27.3	34.1	52.9	53.9	50.5	18.3	36.4	33.6	24.7
Grewia avellana	-	-	-	-	-	-	1.9	-	3.6
Grewia bicolor	2.7	-	-	-	-	-	-	-	-
Grewia flava	11.6	23.7	12.8	13.3	16.7	57.9	-	34.4	22.8
Grewia flavescens	7.2	-	1	-	-	5.6	35.7	-	-
Grewia retinervis	7.4	12.2	17.3	13.3	12.3	3.6	10.9	13.8	15.3
Senegalia erubescens	0.3	-	-	-	-	-	-	-	-
Tarchonanthus camphoratus	-	-	-	-	-	-	1.1	-	-
High wood-potential species									
Senegalia mellifera	13.7	-	4.2	4.1	3.7	-	-	-	2.9
Vachellia hebeclada	0.7	-	1	-	-	-	-	-	-
Vachellia reficiens	6.9	-	3.1	6.1	2.8	-	1.1	3.5	17
Vachellia tortilis	-	20	1	-	0.6	-	-	-	-
Richness	**14**	**5**	**11**	**7**	**8**	**5**	**10**	**9**	**11**

This observation holds true for most species, with the notable exception of the aggressive pioneer woody plant species such as *D. cinerea, G. flava* and *G. retinervis.* The data in Table 4.9 particularly show that these pioneer, aggressively growing woody plants can flourish in drier years. This allows them to outcompete the high wood-potential species, which can only multiply significantly in the wetter years.

Compared to the plant density (plants ha^{-1}) before harvesting, there was a drastic increase in plant density of all species after harvesting (Table 4.9, Figure 4.9). This increase was due to an explosion of new seedlings/saplings.

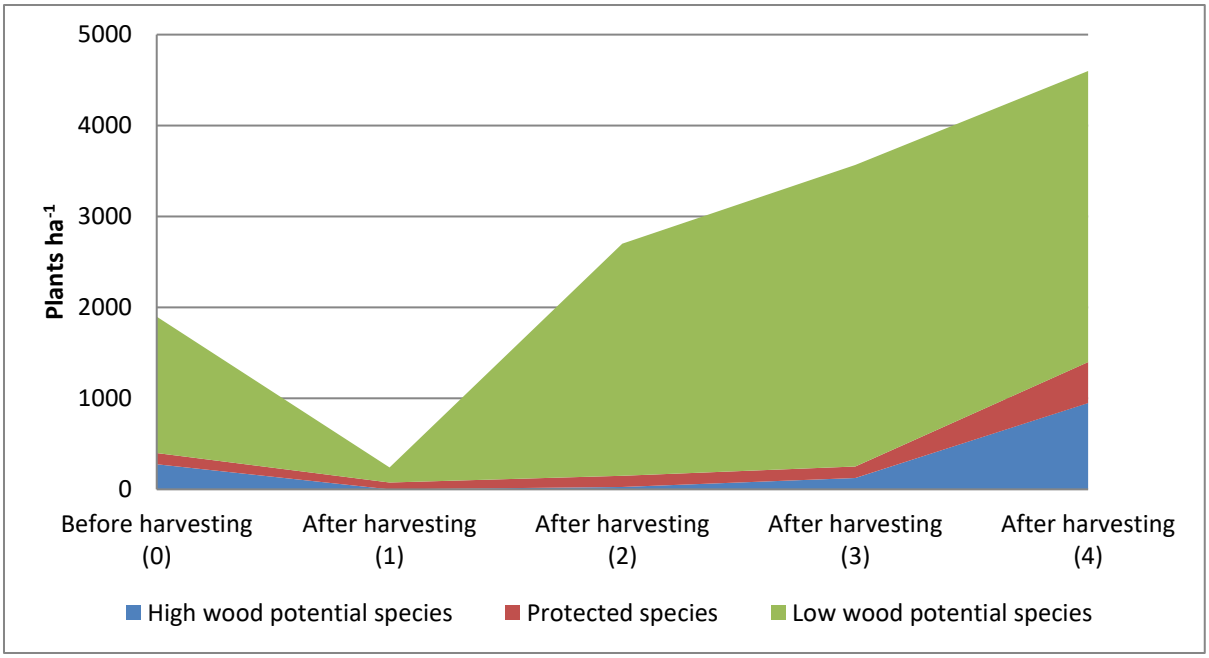


Figure 4.9: Woody plant densities (plants ha^{-1}) before and after non-selective wood harvesting

Although plants ha^{-1} for all species categories increased drastically, even exceeding plants ha^{-1} before harvesting (Figure 4.9), the decrease in ETTE ha^{-1} of the high wood-potential and protected species and the increase in ETTE ha^{-1} of the low wood-potential species (Figure 5.8) indicate a much faster and more aggressive growth rate of the low wood-potential species as compared to the high wood-potential and protected species (Table 4.5). The high wood-potential species were, therefore, largely replaced by the low wood-potential species (Figure 4.10).

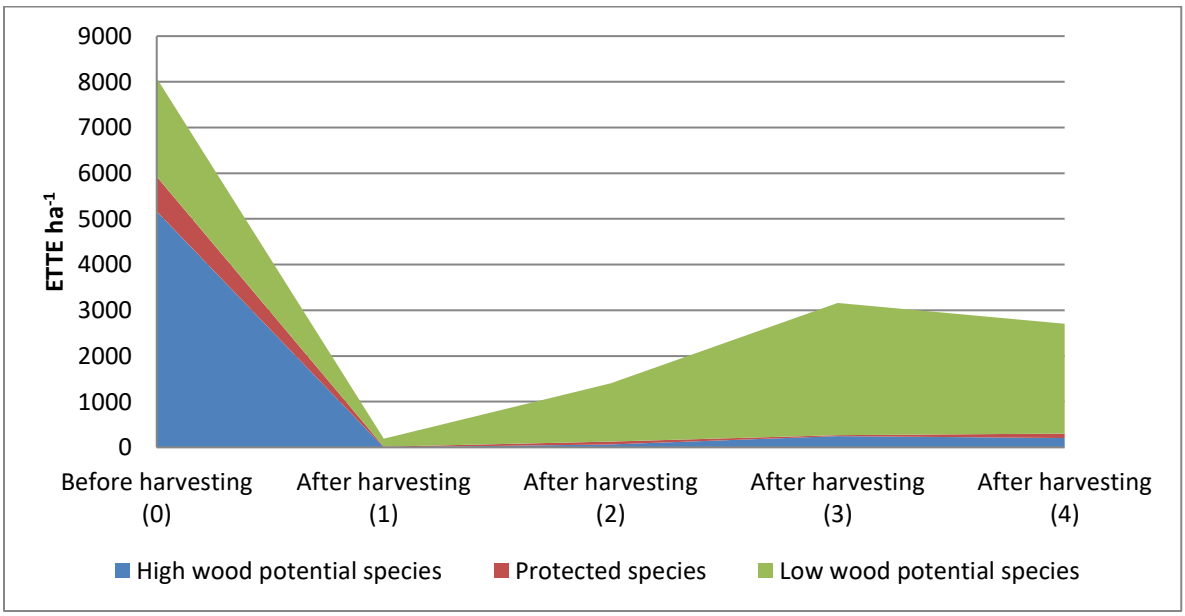


Figure 4.10: Woody plant densities (ETTE ha^{-1}) before and after non-selective wood harvesting. The values in the brackets represents the years after harvesting

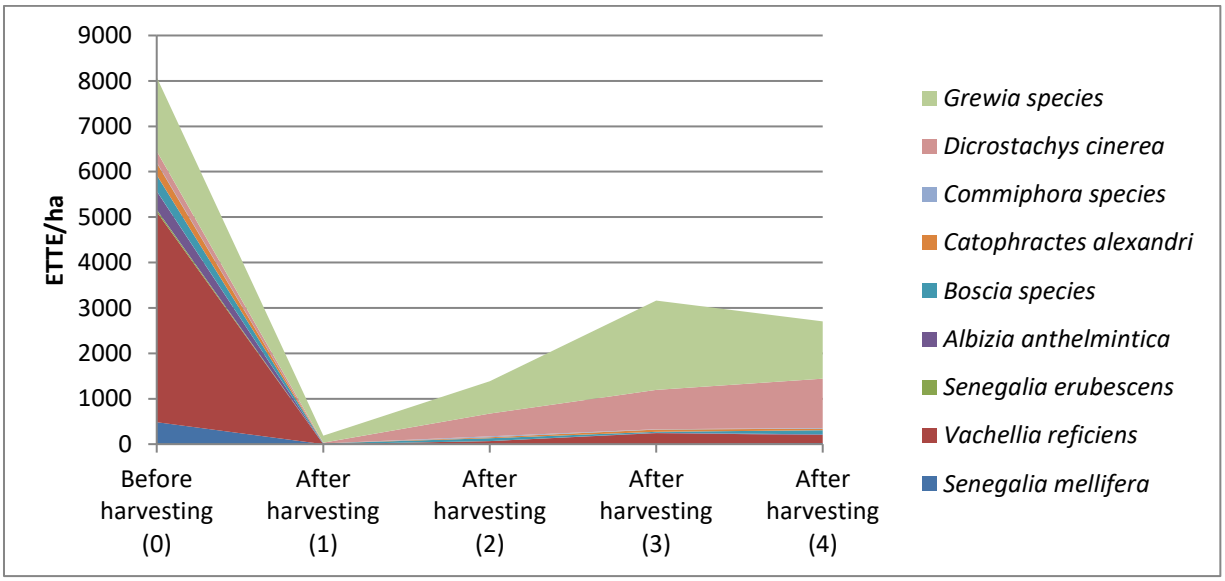


Figure 4.11: Woody species densities (ETTE ha^{-1}) before and after non-selective wood harvesting. The values in the brackets represents the years after harvesting

A decline in ETTE ha^{-1} for the low wood-potential species could be observed between the 3rd and 4th year after harvesting (Figure 4.10), although plant ha^{-1} was increasing during the same period (Figure 5.7). With further investigation, it could be found that the *Grewia* species were the dominant contributor to the low wood-potential species category and were responsible for the decline (Figure 4.11).

The *Grewia* species declined over time and were steadily replaced by *D. cinerea*, which increased in numbers. The decline in *Grewia* species during the study period could not be clearly explained. Signs of browsing were observed on the *Grewia* species, which could partly be a contributing factor to their decline. Another possibility is that *D. cinerea* benefited more from the improved rainfall of the subsequent years, especially with viable seed from a large soil seed bank readily available for germination in response to improved environmental conditions.

4.3.4. Rate of biomass production of woody plants after initial wood harvesting

The baseline conditions (β_0) of the GLM model show that, on average, the estimated total wood biomass in the control plots was 2 606 kg ha $^{-1}$ (Table 4.10). The negative values for the effect of chainsaw and roller treatments show that the estimated wood biomass ha^{-1} was less than the amounts in the control plots. Compared to the baseline conditions (β_0), the predicted kg dry wood biomass ha^{-1} in the chainsaw treatment was significantly less by 2 557.7 ($P<0.001$) for year one, 2 531.7 ($P<0.001$) for year two, 2436.2 ($P<0.001$) for year three and 2 465.8 ($P<0.001$) for year four.

In the same scenario, the predicted kg dry wood biomass ha^{-1} in the bush-roller treatment was significantly less by 2 591.9 (P<0.001) for year one, 2 535.5 (P<0.001) for year two, 2 366.7 (P<0.01) for year three, and 2 472.1 (P<0.001) for year four. In all treatment types, the largest differences were observed in the first two years following non-selective wood harvesting.

Table 4.10: Effect of treatment type and post-treatment period (years) on the total wood biomass (kg DM ha^{-1}) measured per species in the study area

	Parameter (β)	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept (Control)	β_0	2605.7	624.4	4.173	5.20E-05	***
Chainsaw harvested (1)	β_1	-2557.7	656.7	-3.895	1.50E-04	***
Chainsaw harvested (2)	β_2	-2531.7	649.4	-3.898	1.50E-04	***
Chainsaw harvested (3)	β_3	-2436.2	698	-3.49	6.40E-04	***
Chainsaw harvested (4)	β_4	-2465.8	677.3	-3.641	3.80E-04	***
Bush-roller harvested (1)	β_5	-2591.9	633.8	-4.089	7.10E-05	***
Bush-roller harvested (2)	β_6	-2535.5	648.2	-3.912	1.40E-04	***
Bush-roller harvested (3)	β_7	-2366.7	706.8	-3.348	1.00E-03	**
Bush-roller harvested (4)	β_8	-2472.1	660.2	-3.744	2.60E-04	***

The GLM model shows highly significant (P<0.001), but very slight increments in wood biomass gain after harvesting. The trend in biomass gain is supported by the logistic wood biomass growth model, predicting biomass growth based on past growth trends (first three years) and the capacity (wood biomass equivalent at 4 500 ETTE ha^{-1}) set as target (Case, 1999). The logistic wood biomass growth model is presented in Figure 4.12.

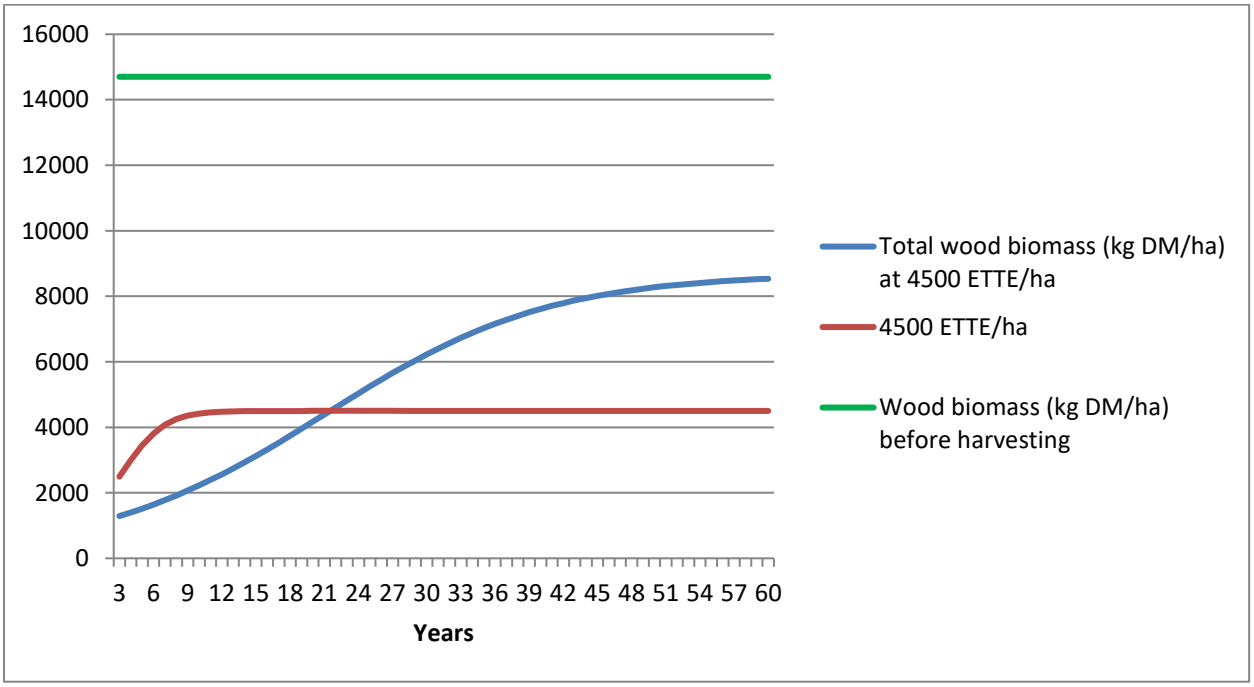


Figure 4.12: Logistic wood biomass growth model (Case, 1999)

The logistic wood biomass growth model (Figure 4.12) is supported by the GLM model (Table 4.10) in terms of wood biomass regrowth. Reasons for the slow wood biomass growth are further supported by the replacement of high wood-potential species with low wood-potential species (Figure 4.10) and the change in vegetation size and structure from mature high wood-potential and young low wood-potential to mature low wood-potential and young high wood-potential dominated plant species (Figure 4.7). The high coppicing ability, sapling establishment and undamaged plants of low wood-potential species (Table 4.4), and the fast and aggressive growth rate of, especially, *D. cinerea*, *Grewia* species and *C. Alexandri* (Mannheimer and Curtis, 2009) of the low wood-potential species (Table 4.5), further support the slow wood biomass regeneration (Table 4.10, Figure 4.10).

Smit (2003) argues that during coppice regrowth of cut plants, leaf growth rather than wood biomass will be prioritized to facilitate photosynthesis. This ensures that leaf mass and ETTE are restored much faster to pre-harvesting levels as opposed to wood biomass. The fast restoration of ETTE and slow wood mass regeneration was also reported by Cunningham and Detering (2017), who estimated a time span of 21-26 years to restore wood of a size class of 8-10 cm in diameter.

4.4. Conclusions and management recommendations

Regeneration in the form of coppice and sapling establishment was found to be high after non-selective wood harvesting regardless of whether harvesting was done by chainsaw or by a bush-roller. Sapling density (plants ha^{-1}) after harvesting even surpassed the original plant density before harvesting. During harvesting, the ecosytem was subjected to a sudden and severe disturbance, and the vacuum created had to be filled by plants. The vacuum was predominantly filled by fast and aggressively growing low wood-potential species. This caused a change in vegetation composition and size structure in favour of low wood-potential encroachers that are much harder to manage. It can thus be concluded that the high wood-potential species are climax species in this specific ecosystem and that the disturbance caused by the wood harvesting benefits the low wood-potential species. These species act as pioneer species that largely replace the previous dominance of the climax species.

It is emphasized that not all bush thickened areas have the ability to yield usable wood biomass for charcoal, and therefore bush control for rangeland restoration should not always be done with the aim of making an income from charcoal. In some instances, bush control will have to

be done with the sole purpose of restoring rangelands without an additional income, but rather to invest in rangeland restoration for the long-term.

Chainsaw harvesting is more effective for the harvesting of young and thin-stemmed plants. These thin-stemmed woody plants are normally low wood-potential species such as *D. cinerea, C. alexandri* and *Grewia* species, which are aggressive growers and can dominate the rangeland much faster than the high wood-potential species. Definite after-care measures are needed in areas where bush clearing has been done. This study shows that non-selective bush clearing/harvesting is not advisable for rangeland restoration as it will invariably worsen the problem of bush thickening by creating a state that is unstable and less productive, with frequent follow-up actions being required to prevent re-thickening.

CHAPTER 5: THE EFFECT OF ANNUAL TOTAL DEFOLIATION OF COPPICE RE-GROWTH FOLLOWING NON-SELECTIVE WOOD HARVESTING

5.1. Introduction

Woody plants in the savanna ecosystem are typically able to tolerate a wide range of soil water and temperature conditions (Burke, 2006). These woody plants have also evolved under herbivory by both insects and mammals, as well as fire, and subsequently are tolerant to defoliation (Du Toit, 1972; Trollope, 1981). Apart from being tolerant to defoliation, woody plants also have the ability to coppice strongly after physical damage such as fire (Teague and Walker, 1988) or damage caused by other means such as large herbivores and humans. Coppice is the natural regeneration of stems from the stem base after harvesting or damaging the plant (Santiago *et al.,* 2018).

Apart from coppice, sapling establishment is another form of woody plant regeneration. Sapling establishment and its development into a mature tree can take a long time, and therefore it is generally assumed that coppice from a damaged woody plant with a well-established root system will produce biomass much faster than saplings. This general assumption may not always be true, as demonstrated by Cunningham and Detering (2017), who reported that it may take up to 21-26 years to obtain wood of a size class of 8-10 cm in diameter from the coppice. The wood biomass produced by the multi-stemmed coppicing plants is also much lower than what was obtained from the original harvest. Due to this structural change from the original single-stemmed tree to a multi-stemmed bush, coppice plants produce a lower amount of wood biomass. This is because a coppicing plant will always prioritize the regeneration of leaf biomass as opposed to wood biomass, which will facilitate photosynthesis essential for the survival of the plant (Smit, 2003). There are also changes in the vegetation composition and structure as a result of bush thickening (Bester, 1998; De Klerk, 2004), which changes the productivity in terms of grazing capacity of the semi-arid savannas of central Namibia (Strohbach, 2019).

The regeneration strategies of woody plants, such as sapling establishment and, more especially, coppice, make it difficult to control bush thickening. Bush thickening is a common problem in southern Africa (Archer, 1995; van Auken, 2000; Roques *et al.,* 2001; O'Connor and Chamane, 2012; O'Connor *et al.,* 2014), especially in Namibia (Bester, 1998; De Klerk, 2004; Joubert *et al.,* 2017; Strohbach, 2019; Nghikembua *et al.*,2021). In an attempt to restore rangelands in Namibia, the most common practice is the cutting down of woody plants and the

harvesting of wood for wood value chains such as firewood, charcoal, biochar and woodchips (DAS, 2017). After cutting, the woody plants do coppice, and new saplings are established. Given the fact that coppice regrowth from cut plants results in plants that are structurally altered with a priority on the replacement of leaf biomass rather than wood biomass (Smit, 2003), and considering the extended time for coppice to reach harvestable biomass (Cunningham and Detering, 2017), annual wood harvesting on a sustainable basis does not seem viable. The non-selective, manual harvesting of woody plants without any after-care is a common practice in Namibia. For this reason, this practice does not solve the problem of bush thickening and may in fact worsen it. In order to achieve some measure of rangeland restoration, it is thus essential to control the coppice re-growth post-harvesting in a cost-effective way.

While the use of arboricides in the treatment of cut plants can be effective in controlling coppice re-growth, many landowners do not consider this a cost-effective solution. Claims that annual defoliation of coppice may result in plant mortality due to resource depletion by limiting photosynthesis may have validity and have the added benefit of being able to apply it selectively to different tree species.

The objective of this study was to investigate whether woody plants of the two dominant woody species of the area (*Senegalia mellifera* and *Vachellia reficiens*) will coppice after initial non-selective harvesting and if annual total defoliation of the coppice will lead to some die-off of these plants over time. The establishment of saplings of *S. mellifera* and *V. reficiens* as replacements for the harvested adult plants was also investigated. The specific objectives of this study were to determine if:

- There is a difference between once-off, and annual total defoliation on coppice,
- There is an increase in sapling establishment of the woody species due to reduced competition from the cut plants, and
- There is a change in overall woody species composition with annual removal of coppice regrowth from the cut plants.

5.2. Procedure

5.2.1. Study area

The study was conducted on the farm: Arcadia, located northwest of Otjiwarongo in an area described as the North-Central Plateau of Namibia, and the vegetation is classified as

Thornbush Savanna (Giess, 1998). A detailed description of the study area is presented in Chapter 3.

5.2.2. Site selection and trial layout

As described in Chapter 4, Section 4.2.2, the different treatments were conducted on plots of 50 x 30 m (1 500 m^2) located in a homogeneous, densely-wooded area on the farm Arcadia. Detailed information on the determination of plot sizes and target species is presented in Chapter 4, Section 4.2.2.

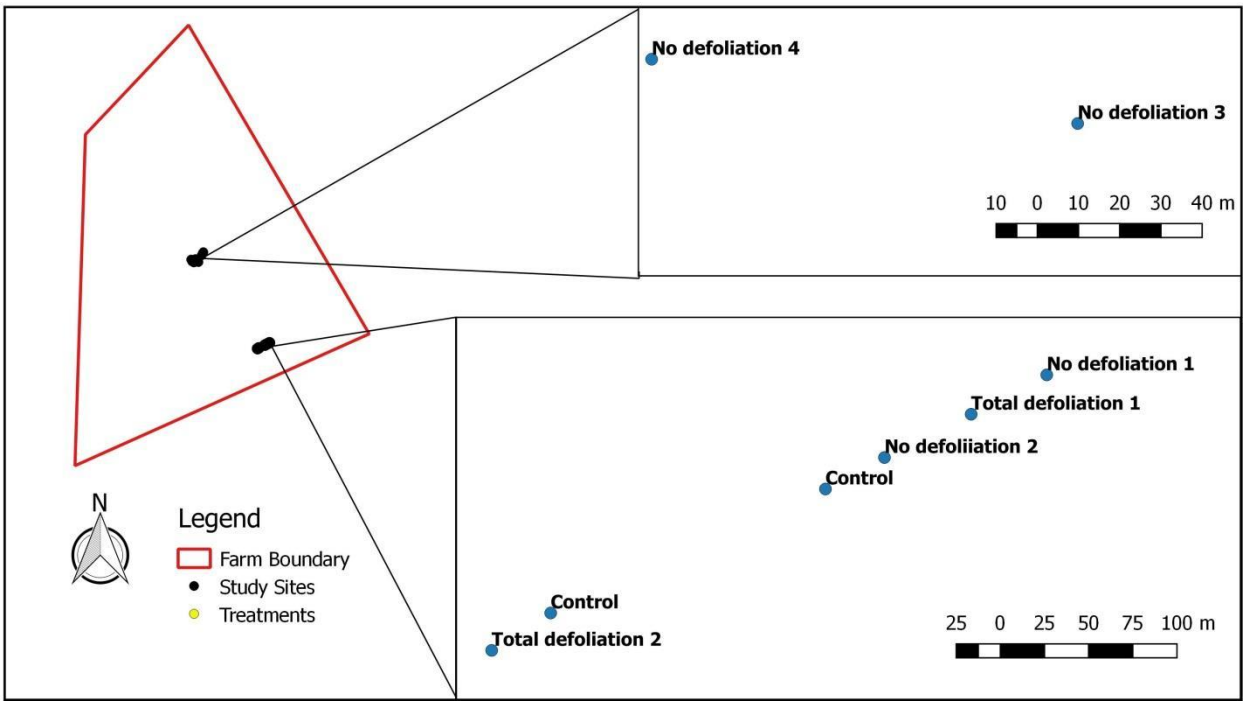


Figure 5.1: Trial layout showing the different defoliation and non-defoliation treatment plots following initial non-selective harvesting

5.2.3. Treatments

The treatment trial layout consisted of eight 50 x 30 m (1 500 m^2) plots. There were two treatments applied, with two replications for annual total defoliation, four replications for no post-harvest defoliation, and two control plots. The plots harvested in summer for the season treatments (see Chapter 6) were also added to the summer treatment, hence the two extra replications for no post-harvest defoliation.

The number and size class of *Senegalia mellifera*, and *Vachellia reficiens* plants monitored, the fixed point survey for biomass quantification in the various plots, and the use of the third version of the Biomass Estimate from Canopy Volume (BECVOL-3) model are described in detail in Chapter 4, Sections 4.2.3 & 4.2.4.

5.2.4. Harvesting and coppice defoliation of cut plants

Harvesting was done once-off, non-selectively in the active growing season, mainly with chainsaws (Figure 5.2). All plants, including the few plants of protected species, were harvested. This was done to ensure that regrowth from coppice or sapling establishment had the same regeneration conditions without the potential influence of competition from undamaged plants.



Figure 5.2: Harvesting of the woody plants in the experimental plots using chainsaws

All the marked plants of the species of interest (*S. mellifera* and *V. reficiens*) were assessed for coppice during May of the same year after the plots were harvested in February 2018 (season one) (Table 5.1). The same plants were subsequently manually defoliated (removing all leaves and shoot growth from the cut stump) in February 2019 using a panga, and plants were again assessed for coppice during May of that year (season two). The same procedure was repeated for the third season (2020).

5.2.5. Data analysis

A generalized linear model (GLM) was used for the modeling task to investigate the impacts of treatments on the vegetation structure (Venables and Ripley, 2002). The Evapotranspiration Tree Equivalents (ETTE) and plants ha^{-1} were used as the response variables, whereas the

explanatory variables were treatment type (annual total post-harvest defoliation, no post-harvest defoliation), control, and the year since treatment application (0, 1, 2, and 3).

A binary GLM was also used to investigate the effect of treatment on the coppicing of woody species. For each woody species, the response variable was coded as 1 where coppicing had taken place (yes) and 0 otherwise (no). Similar dependent variables were used (treatment type: (annual total post-harvest defoliation, no post-harvest defoliation), control, and the year since treatment application: 0, 1, 2, and 3.

Model fit was examined graphically by evaluating the trends and homoscedasticity of the Pearson residuals, and non-constant residual variance was modeled by updating initial models with a weighted variable (Mehtatalo and Kansanen, 2020).

Species richness was calculated as the total number of species represented in a sample using the package Vegan (Oksanen *et al*., 2022). These analyses were performed using R (version 4.1.2; R Core Team, 2021).

The wood biomass and ETTE were obtained from the BECVOL-3 data collection procedure (Chapter 4, Section 4.2). Species composition was calculated as the proportion of each woody species in relation to the total number of individuals in each sample plot. The final composition estimates per treatment type were expressed as percentages (%) averaged across the plots for each respective area. All other descriptive statistics, such as graphs and tables, were generated using Microsoft Excel (Microsoft, 2010).

5.3. Results and Discussion

5.3.1. The effect of once-off, and annual total defoliation on coppice

Despite the below-average annual rainfall of 218 mm in season one (Table 5.1), the percentage of plants that coppiced (May 2018) after the initial wood harvesting (February 2018) was very high (81.25% on average). Though both *Senegalia mellifera* and *Vachellia reficiens* coppiced prolifically, *S. mellifera* had a higher coppicing rate than *V. reficiens.* Notwithstanding the above-average annual rainfall during seasons two and three (Table 5.1), there was a drastic die-back of the initial coppice (81.25% on average) to 33.75% and 23.75% on average for seasons two and three respectively for both post-harvest annual total defoliation and non-defoliation treatments. The plants in the annual total defoliation treatment plots also had a higher die-back rate than the plants in the non-defoliation treatment plots. Considering the above-average

rainfall in seasons two and three post initial harvest (Table 5.1), the die-back of such a large number of plants in the non-defoliation plots was unexpected.

Table 5.1: Coppicing percentage of *Senegalia mellifera* and *Vachellia reficiens* after initial harvesting and consequent defoliation. Harvesting and follow-up defoliation took place in February of each year, and the coppice was assessed in May

					Season				
					Season 1		Season 2		Season 3
Treatment	**Species**	**n**	**Plots**		**% Coppice**		**% Coppice**		**% Coppice**
Annual total defoliation	*Senegalia mellifera*	20	2	Initial harvest	85	Defoliation	20	Defoliation	5
	Vachellia reficiens	20			65		20		10
No annual defoliation	*Senegalia mellifera*	40	4	Initial harvest	95	No defoliation	60	No defoliation	55
	Vachellia reficiens	40			80		35		25
Total seasonal rainfall					**218 mm**		**475 mm**		**483 mm**
Standard deviation					**(±22.77)**		**(±63.44)**		**(±65.00)**

Considering the large, well-established root systems of savanna woody plants (Smit and Rethman, 1998), it stands to reason that the harvested woody plants possess a significant stored carbohydrate resource for regrowth (Schultz *et al.* 2011). The only logical explanation for this die-back is the effect of the low rainfall during season one, which most likely prevented the harvested plants from adequately utilizing these stored reserves to regrow enough leaf biomass for photosynthesis above the limit required for survival (Schutz *et al.*, 2011). High mortality of coppicing plants in the total seasonal defoliation plots was as expected and confirms the claims that repeated defoliation will deplete the growth reserves of the plant to such an extent that they may die (Milton, 1998; Schutz *et al.*, 2011).

Cunningham and Detering (2017) argue that coppice and its survival depend on several factors, such as browsing impact, rainfall, plant species, soil type, method of harvest, season of harvest, and size of plants harvested. Cut height above the soil surface was also found to have an influence on the coppicing ability and survival of woody plants (Stohbach, 1999; Smit, 2003; Neke *et al.*, 2006). In a similar study, Teague and Killilea (1990) also manually removed coppice on *Terminalia sericea* and found high mortality rates.

Although the farm is a cattle farm with fenced camps to control grazing, the area still has an abundance of free-roaming game. Consequently, browsing on coppice - especially by Steenbok

(*Raphicerus campestris),* which are specialized selective feeders - cannot be ignored. The impact of browsing was investigated by Scogings and Macanda (2005), who managed to reduce *Vachellia karroo*'s available foliage by 87% in a 10.5 ha area with 250 goats over three weeks in the early dormant season (May). The plants, however, recovered in the next growing season in the absence of goats (Scogings and Macanda, 2005).

The negative impact of the low rainfall in season one - aggravated by a poor distribution over the season (see Chapter 3, Table 3.1) - on coppice regrowth is supported by the findings of Milton (1987), who reported a positive correlation between shoot production and soil moisture. Even with no total defoliation, the coppice of some plants still managed to die-back although at a slower rate than the heavily defoliated plants (Table 5.1). Strohbach (1999) also reported the die-back of *S. mellifera* over time after the initial harvest in the Thornbush Savanna of Namibia.

Strohbach (1999), as well as Cunningham and Detering (2017), also demonstrated differences in the coppicing ability of different woody species. They reported that the coppice rate for *Dichrostachys cinerea* and *Terminalia sericea* is extremely high, while it is much lower for other species such as *S. mellifera* and *V. reficiens*. Cunningham and Detering (2017) further reported that the coppicing rate of *V. reficiens* was as low as 45% on soils with a high clay content (45–50% clay), followed by higher coppicing rates on soils with reduced clay contents. This finding is supported by Sebata (2017), who reported that sandy soils tend to favour woody over herbaceous plants. Therefore, woody plant cover declines as soil clay content increases, because the higher water holding capacity of the finer textured clay soils favour the shallow-rooted grasses over the deep-rooted woody plants (Sebata, 2017). Scholes (1990) also reported that nutrient-poor savannas generally support higher woody biomass than nutrient-rich ones. This is normally in deep sandy soils that are nutrient poor and therefore the presence of woody plants is critical for nutrient recycling. The soils in the study area were found to be predominantly sandy-loam with an average clay content of 6.2% (see Chapter 3, Section 3.4.3), which should have been favourable for a high coppicing rate.

The distinction between the effects of heavy bush rollers and chainsaws on coppicing is presented in Chapter 4, Table 4.4. The “clean cut” by the chainsaws encouraged better coppice as opposed to the “crushing stem action” of the bush roller. The season of harvesting also plays a role in the coppice and survival of woody plants. Strohbach (1999) found that the least regrowth and highest coppice mortality of dominant Thornbush and Mountain Karstveld

Savanna plants, including *S. mellifera* and *V. reficiens*, take place when cut/harvested in the rainy season (January to May). The continuous removal of coppice leads to the depletion of growth reserves before the plant is fully established and can grow without dependence on growth reserves (Schutz *et al.*, 2011). Milton (1987) found that shoot production increased after winter pruning and decreased after summer pruning. The plants in this study were both harvested and defoliated in summer (see Section 5.2.4), in a below-average rainfall year (see Section 5.3.1), partially explaining the poor coppice survival presented in Table 5.1. **Chapter 6** provides a detailed discussion on the effect of season on coppice and regrowth.

Apart from the known factors affecting coppice (Strohbach, 1999; Smit, 2003; Neke *et al.*, 2006; Cunningham and Detering, 2017), other factors such as the number of stems, stem average diameter, distance to the nearest neighbour, and nearest neighbour species were also investigated (Table 5.2).

Table 5.2: GLM illustrating the effect of treatment, number of stems, stem diameter (cm), distance to nearest plant/neighbor (cm), and nearest neighbour/plant species on the coppicing probability of *Senegalia mellifera* and *Vachellia reficiens*

	Parameter (β)	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**	
Intercept (Total defoliation (1))	β_0	2.70E+00	9.61E-01	2.809	0.004964	**
Treatment: Total defoliation (2)	β_1	-2.94E+00	5.96E-01	-4.927	8.34E-07	***
Treatment: Total defoliation (3)	β_2	-4.18E+00	7.59E-01	-5.504	3.71E-08	***
Treatment: No defoliation (1)	β_3	1.01E-01	5.36E-01	0.188	0.850699	
Treatment: No defoliation (2)	β_4	-2.37E+00	5.25E-01	-4.514	6.35E-06	***
Treatment: No defoliation (3)	β_5	-2.81E+00	5.39E-01	-5.22	1.79E-07	***
Number of stems		1.07E-04	1.56E-01	0.001	0.999451	
Stem diameter		-1.91E-01	5.27E-02	-3.629	0.000285	***
Distance to nearest neighbour		7.07E-03	2.05E-03	3.459	0.000542	***
Neighbour: *Boscia albitrunca*		-5.09E-01	1.00E+00	-0.506	0.612576	
Neighbour: *Catophractes alexandri*		-1.03E-01	6.17E-01	-0.167	0.867218	
Neighbour: *Commiphora* species		-8.25E-01	9.67E-01	-0.853	0.393877	
Neighbour: *Dichrostachys cinerea*		1.56E+01	8.32E+02	0.019	0.985015	
Neighbour: *Grewia flava*		-6.52E-01	5.62E-01	-1.16	0.246042	
Neighbour: *Grewia flavescens*		-2.39E-01	6.10E-01	-0.391	0.695626	
Neighbour: *Grewia retinervis*		2.69E-01	5.05E-01	0.532	0.594519	
Neighbour: *Senegalia mellifera*		-4.08E-01	4.99E-01	-0.816	0.414237	
Neighbour: *Vachellia reficiens*		5.69E-01	5.71E-01	0.995	0.319571	

The GLM indicates that both stem diameter and distance had significant ($P<0.001$) effects on the coppice (Table 5.2). Greater distances from the nearest plants and smaller stem diameters positively influenced the coppice probability. Both plant species and the number of stems had no significant ($P>0.05$) effect on coppice probability. There was a highly significant ($P<0.001$)

reduction in coppice between season one and seasons two and three for both the annual totally defoliated and non-defoliated treatment plots. The negative values for the effect of both annual defoliation and non-defoliation treatments show that the estimated ETTE ha^{-1} was less than the amounts in the control plots.

Cunningham and Detering (2017) found a strong positive linear correlation between tree age and stem diameter. Therefore, the significantly high ($P<0.001$) coppice probability explained by smaller stem diameters indicated in Table 5.2 proves that coppice probability is higher in younger, actively growing as opposed to older plants. These older plants are normally in their senescence stage and, although alive, the cells stop dividing and growth ceases. The impact of proximity to, and species of, the nearest neighbour on the coppice of the species of interest is discussed thoroughly in Chapter 4, Section 5.3.1.

Coppice control through annual total defoliation seems to be successful, especially for *S. mellifera* and *V. reficiems* (Table 5.1). Coppice regrowth after initial harvesting is not desirable for either rangeland restoration or sustainable wood harvesting. It is, therefore, important to allow some woody plant regrowth to provide for both rangeland restoration and future wood harvesting as both require the regeneration of high wood-potential species. Since coppice regrowth is structurally multi-stemmed with a priority on leaf production (Smit, 2003) and takes a very long time (21-26 years) to produce useable wood for charcoal (Cunningham and Detering, 2017), the high wood-potential species regeneration should preferably be in the form of sapling establishment and/or maintenance of coppice through pruning of the coppice. However, the pruning should only commence after two to three seasons after the initial harvest since pruning after the first season may cause plant mortality. With both coppice maintenance and/or sapling establishment of the sought-after high wood-potential species, it is deemed necessary to control coppice of other low wood-potential species to reduce competition for the sought-after high wood-potential species.

5.3.2. Sapling establishment with reduced competition from cut plants

Considering the undesirability of coppice for both bush control and sustainable wood biomass production, the pruning of coppice to one or two remaining stems is an option to encourage the production of wood over a shorter time period. The existing plant already has a well-established root system (Smit and Rethman, 1998) as opposed to a sapling, and therefore the production of wood is considered to be more likely over a shorter time period.

An alternative to coppice pruning was coppice eradication, with the aim of reducing plant competition and making more growth resources available to sapling development of sought-after high wood-potential species. The unpredictable rainfall of the area and the high mortality of coppice when defoliated within the first three seasons (Table 5.1) emphasized the importance of considering alternatives such as the coppice eradication concept to promote sapling establishment and development. To assess the viability of benefitting sapling establishment of the *S. mellifera* and *V. reficiens* as species of interest, and other sought-after high wood-potential species with this approach, a GLM was used to analyze the data.

The GLM indicated no significant difference (P>0.05) in sapling establishment between the two treatments (Table 5.3).

Table 5.3: GLM indicating the effect of harvest and post-harvest treatments on sapling establishment. Post-harvest treatments include annual total defoliation and no defoliation of *Senegalia mellifera* and *Vachellia reficiens* after initial non-selective harvesting

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept (Total defoliation)	20	19.691	1.016	0.31353	
Treatment: No defoliation	-5	34.105	-0.147	0.8839	
Species					
*Albizia anthelmintica*_nd	-5	34.105	-0.147	0.8839	
*Boscia albitrunca*_td	-10	44.03	-0.227	0.82104	
*Boscia albitrunca*_nd	-5	39.381	-0.127	0.89936	
*Boscia foetida*_td	-7.5	27.847	-0.269	0.78853	
*Boscia foetida*_nd	-1.667	35.95	-0.046	0.96317	
*Catophractes alexandri*_td	46.667	25.421	1.836	0.07096	.
*Catophractes alexandri*_nd	53.333	32.155	1.659	0.10201	
Commiphora spp._td	5	27.847	0.18	0.85806	
Commiphora spp._nd	-5	35.95	-0.139	0.88982	
*Dichrostachys cinerea*_td	13.333	25.421	0.525	0.60171	
*Dichrostachys cinerea*_nd	35	48.232	0.726	0.47065	
*Grewia avellana*_td	-10	34.105	-0.293	0.7703	
*Grewia flava*_td	86.667	25.421	3.409	0.00112	**
*Grewia flava*_nd	88.333	35.95	2.457	0.01668	*
*Grewia retinervis*_td	10	26.418	0.379	0.70627	
*Grewia retinervis*_nd	31.667	35.95	0.881	0.38165	
*Phaeoptilum spinosum*_nd	5	35.95	0.139	0.88982	
*Senegalia mellifera*_td	-10	30.078	-0.332	0.74061	
*Senegalia mellifera*_nd	8.333	35.95	0.232	0.81742	
*Vachellia reficiens*_td	85	25.421	3.344	0.00138	**
*Vachellia reficiens*_nd	53.333	32.155	1.659	0.10201	
*Ziziphus mucronata*_td	-10	30.078	-0.332	0.74061	
*Ziziphus mucronata*_nd	NA	NA	NA	NA	

nd = no defoliation, td = total defoliation

However, in the case of *G. flava*, the GLM indicated a highly significant (P=0.001) and a significant (P<0.05) increase in sapling establishment in the annual totally defoliated and non-defoliated plots, respectively. The annual totally defoliated plots also had a highly significant increase (P=0.001) in sapling establishment of *V. reficiens*. Although not significant (P>0.05), *S. mellifera* also had a higher sapling establishment in the non-defoliated plots.

The significantly lower (P=0.001) sapling establishment of *S. mellifera* as opposed to *V. reficiens* is supported by the findings of Joubert *et al.* (2013) where it was reported that *S. mellifera* produced absolutely no seed pods in the low rainfall seasons. Additionally, *S. mellifera* needs exceptional rainfall years for sapling establishment as seedlings germinate on the soil surface and therefore require large amounts of initial moisture to survive to the stage where the root system is established in the soil (Joubert *et al.*, 2013).

Apart from seed production and germination, it was found by Hagos (2001) that seed from *S. mellifera* cannot be carried over from one season to the next and, therefore, no persisting seed bank exists. The seeds are also susceptible to decomposition due to moisture and other environmental factors. Their viability can be affected by high temperatures and moisture levels (Hagos, 2001). There is not much known about *V. reficiens* and its seed production, seed banks, and other germination requirements as it has not been a much-studied plant. Studies on the reproductive dynamics of *V. reficiens* should be considered as it is a sought-after plant, especially in the Thornbush Savanna, for charcoal production.

Generally, the defoliation of the coppice of *S. mellifera* and *V. reficiens* was expected to have a positive influence on the establishment of saplings of these same species as there is reduced competition from the coppicing plants. This assumption proved to be true, but the seed germination and sapling establishment of the pioneer, aggressively growing species also benefited (Table 5.3). The fast and aggressive growth rate of these pioneer species with reduced competition surpassed the dominance of the sought-after high wood-potential species.

According to Cunningham and Detering (2017), it may take up to 40 years for regeneration from seed to reach a pre-cleared state. This also demotes the perceived idea of eradicating coppice regrowth with the aim of benefiting the sapling establishment. The regeneration period is normally shortened by good rainfall and lengthened by droughts (Cunningham and Detering, 2017), based on simulations by Scholes (1990) on work done on *Colosphorpermum mopane.* This principle of rainfall as the most important limiting factor to plant growth can be regarded as applicable to savanna veld types and plants.

Wood biomass regeneration will remain a challenge, especially with initial non-selective wood harvesting (see Chapter 4, Section 4.3.4), and therefore woody plant thinning should be explored for both rangeland restoration and sustainable wood harvesting. There is much research on woody plant thinning for increased grass production (Smit *et al.*, 1996; Smit and Rethman, 1999; Richter *et al.*, 2001; Smit, 2014; Nghikembua *et al.*, 2020), but not much has been done on woody plant thinning for sustainable wood production in savannas. A detailed discussion on woody plant thinning for sustainable wood production is presented in **Chapter 7**.

5.3.3. The effect of coppice defoliation on overall woody species composition

It was evident that plants ha^{-1} had a much faster recovery as opposed to ETTE ha^{-1} in the period of three years (Figure 5.3). As discussed in Chapter 4, Section 4.3.2, the high plant ha^{-1} and low ETTE ha^{-1} represent a plant population consisting predominantly of a small, woody plant size class with the absence of mature, high wood-potential plants.

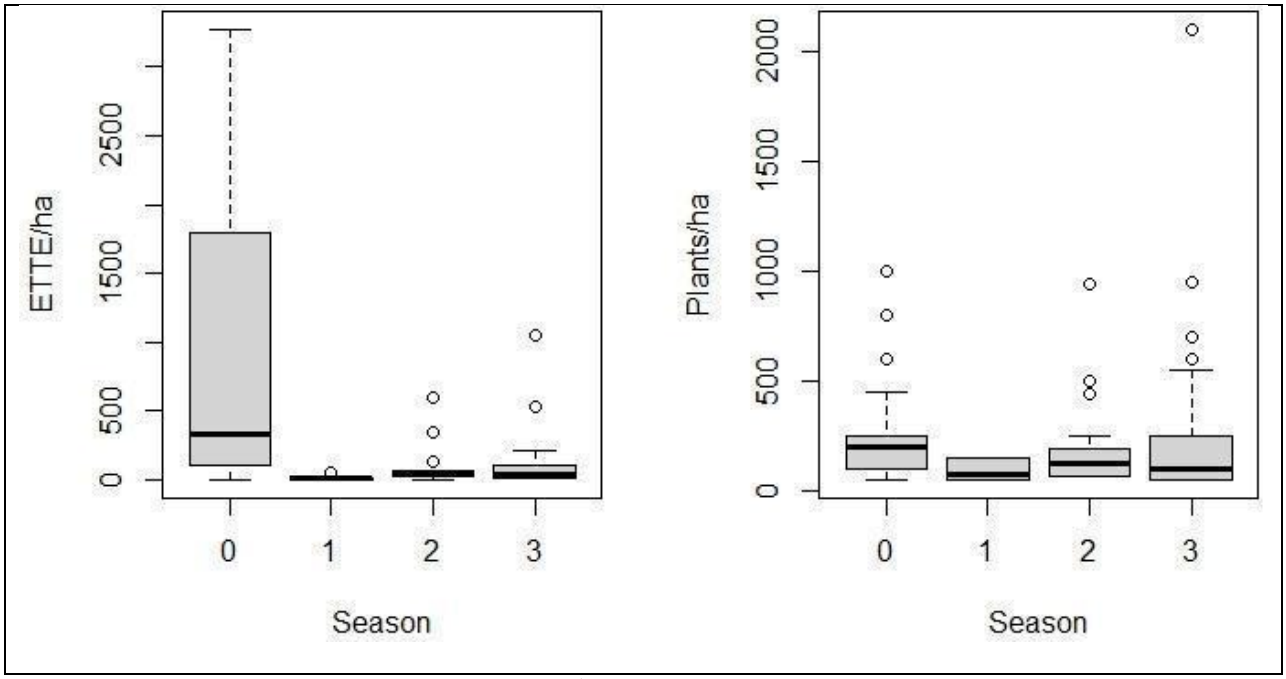


Figure 5.3: Plant densities (plants and ETTE ha^{-1}) of both treatment plots (total annual defoliation and no defoliation after harvesting) before harvesting (season 0) and after harvesting (seasons 1-3)

Considering the fast increase in plant densities (plants ha^{-1}) post harvest and the slow increase in size (ETTE ha^{-1}) (Figure 5.3), it was investigated further by means of a GLM (Tables 5.4 and 5.5) to determine which plant species are responsible for these trends.

The GLM shows no significant difference ($P>0.05$) in plants ha^{-1} between the annual total defoliation and non-defoliation treatments at the end of the three-year growing period (Table

5.4). *Grewia flava* had a highly significant (P<0.001) increase in plant density (plants ha^{-1}) for both treatments after initial non-selective harvesting. Although not significant (P>0.05), species such as *V. reficiens* and *Catophractes alexandri* also regenerated at a faster rate than the rest of the species.

Table 5.4: GLM illustrating the effect of harvest and post-harvest treatments on plant densities (plants ha^{-1}). Post-harvest treatments include seasonal total defoliation and no defoliation of *Senegalia mellifera* and *Vachellia reficiens* after initial non-selective harvesting of all plants

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept (Control)	213.179	91.754	2.323	0.0224	*
Treatment: Total defoliation	-31.111	69.555	-0.447	0.6558	
Treatment: No defoliation	-55.091	72.941	-0.755	0.4521	
Species					
Vachellia reficiens	27.814	103.099	0.27	0.788	
Vachellia tortilis	-122.623	184.404	-0.665	0.5078	
Albizia anthelmintica	-68.583	98.333	-0.697	0.4873	
Boscia albitrunca	-94.741	156.011	-0.607	0.5452	
Boscia foetida	-121.097	109.036	-1.111	0.2697	
Catophractes alexandri	135.264	94.155	1.437	0.1543	
Commiphora species	-51.766	108.443	-0.477	0.6343	
Dichrostachys cinerea	-89.212	112.688	-0.792	0.4307	
Grewia avellana	-132.068	249.018	-0.53	0.5972	
Grewia flava	518.375	96.222	5.387	5.79E-07	***
Grewia flavescens	-97.623	184.404	-0.529	0.5978	
Grewia retinervis	-7.408	156.011	-0.047	0.9622	
Ziziphus mucronata	-132.068	249.018	-0.53	0.5972	

The data presented in Tables 5.4 (plants ha^{-1}) and 5.5 (ETTE ha^{-1}) illustrate a statistical explanation of the regeneration and size structure of *G. flava*. The significantly (P<0.001) higher plants ha^{-1} and no significant difference (P>0.05) in ETTE ha^{-1} three years after harvesting suggest that *G. flava* densities were low before harvesting and increased drastically thereafter in both density and size. The data presented in Table 5.6 support the observed, highly significant (P<0.001) increase in *G. flava* after initial non-selective harvesting. Based on the logistic growth modeling concept (Case, 1999), the ETTE ha^{-1} is estimated to return to its target (4 500 ETTE ha^{-1}) in approximately 12–15 years (Chapter 4, Figure 4.12).

Table 5.5: GLM illustrating the effect of harvest and post-harvest treatments, on plant densities (ETTE ha^{-1}). Post-harvest treatments include annual defoliation and no defoliation of *Senegalia mellifera* and *Vachellia reficiens* after initial non-selective harvesting of all plants

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept (Control)	1939.6	278	6.977	5.14E-10	***
Treatment: Total defoliation	-594.3	210.7	-2.82	0.005916	**
Treatment: No defoliation	-680.2	221	-3.078	0.002768	**
Species					
Vachellia reficiens	-332.1	312.4	-1.063	0.290531	
Vachellia tortilis	-1403	558.7	-2.511	0.013836	*
Albizia anthelmintica	-1152.8	297.9	-3.87	0.000207	***
Boscia albitrunca	-1297.7	472.7	-2.745	0.00731	**
Boscia foetida	-1389.1	330.3	-4.205	6.20E-05	***
Catophractes alexandri	-1231.6	285.3	-4.318	4.08E-05	***
Commiphora species	-1403.6	328.5	-4.272	4.84E-05	***
Dichrostachys cinerea	-1370.4	341.4	-4.014	0.000124	***
Grewia avellana	-1338.3	754.4	-1.774	0.079492	.
Grewia flava	-394.6	291.5	-1.354	0.179238	
Grewia flavescens	-1388.5	558.7	-2.485	0.014814	*
Grewia retinervis	-1268	472.7	-2.683	0.008706	**
Ziziphus mucronata	-1331.3	754.4	-1.765	0.08105	.

The species of interest (*S. mellifera* and *V. reficiens*) with a high wood-yield potential declined after initial harvesting in plots of both treatments (Table 5.6). The annual total defoliation treatment plots had a higher decline in high wood-potential species than the non- defoliation treatment plots. On the other hand, the low wood-potential species such as *D. cinerea* and *G. flava* increased over the three years after initial harvesting. The protected species also increased in the three years, with a higher increase in the annual total defoliation as compared to the non-defoliation treatment plots.

The low wood-potential species such as *Grewia flava* (see Table 5.6) are shrubby with not much use for wood and tend to thicken the savannas much faster due to their aggressive growth nature. They are pioneer woody plants, dominating areas disturbed by fire, large-scale arboricide application and non-selective wood harvesting. The species composition (Table 5.6) once again clearly shows that coppice control of all plants is needed if sapling establishment of high wood-potential species is a priority.

Table 5.6: Plant composition (%) before and after non-selective wood harvesting with total and no defoliation post-harvesting treatments

	Control	Heavy defoliation (Season)			No defoliation (Season)		
	0	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
Protected species							
Albizia anthelmintica	3.4	11.4	9.7	9.5	8.6	0.8	4.0
Boscia albitrunca	–	–	5.0	0.8	–	2.6	–
Boscia foetida	2.5	–	3.1	2.9	4.3	0.4	1.4
Ziziphus mucronata	–	1.0	0.4	1.0	1.4	0.8	0.5
Commiphora species	5.9	7.6	0.7	4.8	2.9	2.6	2.3
Low wood-potential species							
Catophractes alexandrii	23.3	36.2	11.9	12.8	34.3	30.1	25.3
Dichrostachys cinerea	1.3	5.7	7.3	5.9	7.1	–	3.5
Phaeoptilum spinosum	–	–	–	–	1.4	1.3	0.7
Grewia avelana	–	–	0.4	1.0	–	–	–
Grewia flava	36.9	8.6	46.5	47.7	20.0	40.2	42.6
Grewia flavescens	1.7	–	–	–	–	–	–
Grewia retinervis	–	11.4	0.4	6.7	1.4	–	2.3
High wood-potential species							
Senegalia mellifera	11.4	1.0	–	1.1	1.4	5.2	8.4
Vachellia reficiens	12.3	17.1	14.7	6.0	17.1	15.9	8.9
Vachellia tortilis	1.3	–	–	–	–	–	–
Species richness	**10**	**9**	**11**	**12**	**11**	**10**	**11**

In other parts of Africa, such as Senegal, similar findings were recorded by Lykke (1998), where woody plant composition changes from tree to shrub-dominated size structure in fire-disturbed savannas. Apart from frequent forest fires, the logging of trees for building materials also adds to the concern (Lykke, 1998). In Namibia, although also problematic when in a thickened state, the declining species are normally more appreciated than the shrubby species with good rejuvenation.

5.4. Conclusion

The rate of coppice growth and survival is influenced by a variety of factors, but annual total defoliation of coppice, has proven to be effective in controlling coppice re-growth. However, the control of coppice on certain species only, does not necessarily increase the sapling establishment of sought-after species of high wood-potential, as competition is reduced for all species, including the less desired shrubby pioneer woody species of low wood-potential.

Given that coppicing plants have a well-established root system, producing wood biomass should be possible in a shorter amount of time as long as the variables affecting coppice and its

survival are taken into account to maximize coppice during the harvesting process. Coppicing plants have structural changes that result in low wood biomass as they prioritize leaf production. The pruning of coppice must be considered in follow-up research but should be done over a longer time period as total pruning of coppice in the first season after initial harvesting can cause severe coppice die-back. Pruning at a later stage, after the coppice has become well-established, must therefore be investigated for a possible increase in wood biomass production over a shorter period of time. It is also critical to control the coppice of other competitive plants to reduce competition for the establishment of the sought-after high wood-potential plants.

CHAPTER 6: THE EFFECT OF SEASON OF HARVESTING ON THE COPPICING ABILITY OF WOODY PLANTS

6.1. Introduction

Woody plants in southern Africa, especially in Namibia, have evolved and adapted to generally long summers and relatively short winters, which include extremely hot summers with unpredictable rainfall patterns. Furthermore, Moyo *et al.* (2015) and Sebata (2017) stated that savannas occur in landscapes where rainfall is not only unpredictable, but also strongly seasonal. Woody plants represent an integral component of the savannas and have a decisive effect on rangeland condition and biodiversity (Tews and Jeltsch, 2004).

More recently, it has become increasingly evident that climate change is altering the pattern and quantity of rainfall - the most important environmental driver for the growth and survival of woody plants (Tews and Jeltsch, 2004; Musekiwa *et al.*, 2022; Denboba, 2022). Species respond differently to climate change due to the different adaptations to their environment. Both rainfall and temperature are climate change drivers and can alter vegetation composition. However, Bond and Midgley (2012) argue that changes in arid savannas seem less obviously linked to CO_2 effects and may be driven more by overgrazing. According to Sebata (2017), plant communities are influenced by the water shortage during the dry season, with most growth occurring during the wet season. These climate variables, such as rainfall and temperatures, are not the only factors that can alter vegetation, but on-farm management plays a major role as well. Apart from changes in species composition, the increase in density of the local indigenous woody species also poses a threat and has major economic implications for the livestock sectors across southern Africa.

In an attempt to restore bush-thickened rangelands in savanna ecosystems or to utilize the wood for charcoal production, farmers often resort to felling woody plants without the application of arboricides to the cut stumps due to the high cost. Subsequently, the cut stumps will either regrow (coppice) or, on rare occasions, the plant may not recover and die. It may coppice less vigorously, or the coppice may die-off in the following year. In this regard, there are indications that, amongst other factors, the season (cool, dry, dormant winter season or hot, rainy, actively-growing summer season) may have an effect on the regrowth (coppice) of woody plants.

Studies were conducted by Teague and Killilea (1990), Strohbach (1999), Smit (2003) and Neke *et al.* (2006) on the coppicing ability of different savanna woody plants, cut at different heights above the soil surface and found varying results. Other studies were done by Milton

(1987) and Strohbach (1999) on the effect of the season of and found varharvesting on the coppicing ability of different savanna woody plants. Milton (1987) found that the shoot production of coppice was positively influenced by winter pruning. Similarly, Strohbach (1999) found that species had the least regrowth and the highest mortality when harvested in the rainy season.

In Namibia, and especially in the Thornbush Savanna, *Senegalia mellifera* and *Vachellia reficiens* are the dominant high wood-potential bush-thickening species in historically non-harvested areas, and the most sought-after for the charcoal industry. Harvesting of wood takes place throughout the year, except in the middle of the rainy season. This study, therefore, aimed at investigating the coppicing ability and survival of *S. mellifera* and *V. reficiens* harvested in the dormant (winter) and growing (summer) seasons. The results of this study could be particularly significant, especially for harvesting guidelines that will allow for opportunities to either benefit or suppress coppice from plants, depending on the desired outcome the rangeland manager wants to achieve. The specific objectives of this study were to determine - in a non-selectively harvested area - if the season of harvesting would affect the:

- Regeneration (coppice) of woody plants,
- Species composition of the regrowth, and
- Biomass regeneration of the regrowth.

6.2. Procedure

6.2.1. Study area

The study was conducted on the farm Arcadia, located northwest of Otjiwarongo in an area described as the North-Central Plateau of Namibia, and in vegetation classified as Thornbush Savanna (Giess, 1998). A detailed description of the study area is presented in Chapter 3.

6.2.2. Site selection and trial layout

As described in Chapter 4, Section 4.2.2, the different treatments were conducted on plots of 50 x 30 m (1 500 m^2), located in a homogeneous, densely-wooded area on the farm Arcadia. Chapter 4, Section 4.2.2 gives detailed information on the determination of plot sizes and target species.

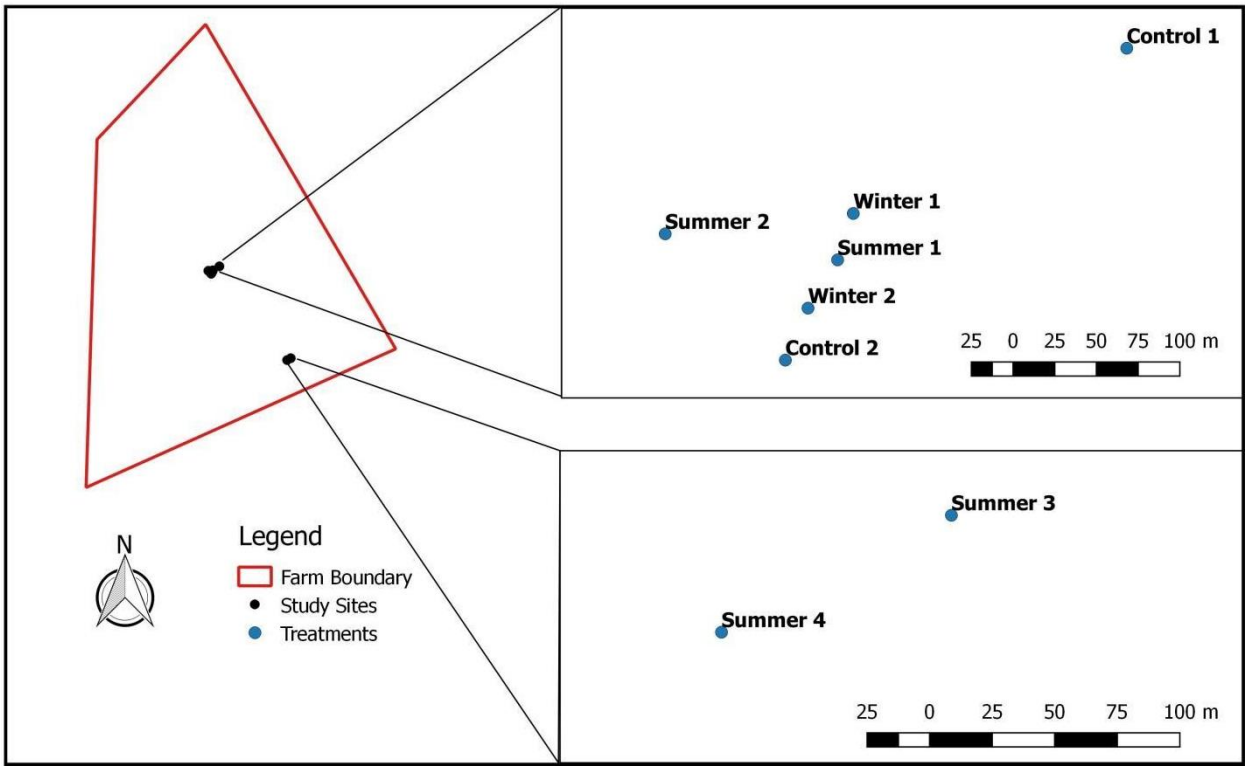


Figure 6.1: Trial layout illustrating the season (winter and summer) treatment plots following initial non-selective harvesting

6.2.3. Treatments

The treatment trial layout consisted of eight 50 x 30 m (1500 m^2) plots. There were two treatments applied, with two replications for winter harvesting, four replications for summer harvesting, and two control plots. The plots harvested in summer that were not defoliated (see Chapter 5) were also added to the summer treatment, hence the two extra replications for summer harvesting.

The number and size class of *Senegalia mellifera* and *Vachellia reficiens* plants to be monitored, the fixed point survey for biomass quantification in the plot, and the use of the BECVOL-3 model are discussed in detail in Chapter 4, Sections 4.2.3 & 4.2.4.

6.2.4. Harvesting and data collection

Harvesting was done once-off, non-selectively, mainly with chainsaws, both in the non-growing (winter) and actively-growing (summer) seasons. All plants, including the few plants of protected species, were harvested. This was done to ensure that regrowth from coppice or seedling establishment had the same regeneration opportunity without any influence from possible competition from undamaged plants. Details on the wood harvesting and time of data collection are presented in Table 6.1.

Table 6.1: Wood harvesting schedule, treatments, and data collection

Method of harvesting	Treatments	Initial harvesting	Data collection (for both treatments)
Non-selective harvesting	Winter harvesting	June 2017	Season 1 - May 2018
	Summer harvesting	February 2018	Season 2 - May 2019
			Season 3 - May 2020
			Season 4 - May 2021

The data collection procedure included coppice recording of all the marked plants of the two species of interest (*Senegalia mellifera* and *Vachellia reficiens*). A detailed BECVOL-3 survey (Smit, 2014) was also conducted on fixed point transects within each plot to determine overall woody vegetation regeneration (see Chapter 4, Sections 4.2.3 & 4.2.4).

6.2.5. Data analysis

A generalized linear model (GLM) was used for the modeling task to investigate the impacts of treatments on the vegetation structure (Venables and Ripley, 2002). The Evapotranspiration Tree Equivalents (ETTE) and plants ha^{-1} were used as the response variables, whereas the explanatory variables were treatment type (winter and summer non-selective harvesting). The control, plant species response, and the year since treatment application (seasons 0 (control), 1, 2, 3 and 4) were also used as explanatory variables.

A binary GLM was also used to investigate the effect of treatment on the coppicing of woody species. For each woody species, the response variable was coded as 1 where coppicing had taken place (yes) and 0 otherwise (no). The explanatory variables used for coppice analysis were also treatment types (winter and summer non-selective harvesting). Other explanatory variables incorporated to determine reaction towards coppice were stem diameter, number of stems, distance to nearest plant species neighbour, and the year since treatment application (seasons 1, 2, 3 and 4).

Model fit was examined graphically by evaluating the trends and homoscedasticity of the Pearson residuals, and non-constant residual variance was modeled by updating initial models with a weighted variable (Mehtatalo and Kansanen, 2020).

The Jaccard similarity distances were calculated to determine how close treatment plots were in species composition by exploring the number of species shared between two sites divided by the total number of species (Oksanen *et al*., 2022).

Species richness and diversity were calculated using the package Vegan (Oksanen *et al*., 2022). Richness was calculated as the total number of species represented in a sample; diversity was calculated using the Shannon-Wiener diversity index (H'). These analyses were performed using R (version 4.1.2; R Core Team, 2021).

The wood biomass and ETTE were obtained from the BECVOL-3 data collection procedure (Chapter 4, Section 4.2). Species composition was calculated as the proportion of each woody species in relation to the total number of individuals in each sample plot. The final composition estimates per treatment type were expressed as percentages (%) averaged across the plots for each treatment. All the descriptive statistics, such as graphs and tables, were generated using Microsoft Excel (Microsoft, 2010).

6.3. Results and discussion

6.3.1. The influence of season of harvesting on the regeneration of woody plants

There was a significant difference (P<0.01) between the seasons of harvest and coppicing ability of *Senegalia mellifera* and *Vachellia reficiens* as the species of interest (Table 6.2). The plants harvested in winter had lower coppicing ability than those harvested in summer.

Table 6.2: GLM showing the effect of treatment, number of stems, stem diameter (cm), distance to nearest plant/neighbor (cm), and nearest-neighbour/plant species on the coppicing probability of *Senegalia mellifera* and *Vachellia reficiens*

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept: (Summer)	0.5580737	0.123181	4.531	8.13E-06	***
Treatment: Winter	-0.1611247	0.0580281	-2.777	0.00579	**
Number of stems	0.0128109	0.027692	0.463	0.64393	
Stem diameter	-0.0278029	0.0083961	-3.311	0.00103	**
Distance	0.0009775	0.0003582	2.729	0.00668	**
Neighbour: *Boscia albitrunca*	0.1007205	0.1963353	0.513	0.60828	
Neighbour*: Catophractes alexandri*	0.0361227	0.1338522	0.27	0.78742	
Neighbour: *Commiphora* spp.	-0.1373359	0.197986	-0.694	0.48836	
Neighbour: *Dichrostachys cinerea*	0.0470756	0.1259932	0.374	0.70891	
Neighbour: *Grewia flava*	-0.0020016	0.0798687	-0.025	0.98002	
Neighbour: *Grewia flavescens*	-0.0370569	0.0857182	-0.432	0.66579	
Neighbour: *Grewia retinervis*	0.1664019	0.103329	1.61	0.10823	
Neighbour: *Senegalia mellifera*	-0.021083	0.0836703	-0.252	0.80121	
Neighbour: *Vachellia reficiens*	0.1340537	0.1173607	1.142	0.25415	

Regardless of the season of harvest and species, stem diameter and distance of nearest plants had an equally significant (P<0.01) positive effect on the coppicing probability of *S. mellifera*

and *V. reficiens*. The smaller the stem diameter of the cut plant and the further away from the nearest-neighbour, the better the coppicing probability was.

It is also evident that *S. mellifera* is more likely to coppice and survive when harvested in summer, whereas *V. reficiens* shows no significant differences (P>0.05) in coppice ability between winter and summer (Table 6.3). Although the results were not significant (P>0.05), *V. reficiens*, however, is more likely to coppice and survive when harvested in winter. The harvesting of *S. mellifera* in the winter led to poor coppice and complete plant death in the second and third seasons (Table 6.3).

Table 6.3: Coppicing percentage of *Senegalia mellifera* and *Vachellia reficiens* in summer and winter non-selectively harvested plots

			Season		
Treatment	**Species**	**n**	**Season 1 % Coppice**	**Season 2 % Coppice**	**Season 3 % Coppice**
Summer harvesting	*Senegalia mellifera*	40	90.0	42.5	32.5
	Vachellia reficiens	40	65.0	27.5	17.5
Winter harvesting	*Senegalia mellifera*	20	20.0	00.0	00.0
	Vachellia reficiens	20	73.7	25.0	20.0
Annual rainfall (mm)			218	475	483
Standard deviation			(± 22.8)	(± 63.44)	(±65.0)

In a study conducted in the same vegetation type as this study, Strohbach (1999) reported on the coppicing ability of five species (*Dichrostachys cinerea, Terminalia prunioides, Terminalia sericea, Senegalia nilotica,* and *Senegalia mellifera*) and found that the least regrowth and highest mortality of these species were reported when the plants were cut in the summer, actively-growing season. Hoveka (2019) also reported higher coppicing rates for woody plants cut in the summer, although with no statistical significance. The findings reported in Table 6.3 suggest a more species-specific response to cutting and can facilitate the harvesting and management of *S. mellifera* and *V. reficiens* by allowing for better-informed decisions regarding whether to promote or discourage coppicing of these species. As *S. mellifera* and *V. reficienns* are the sought-after, high wood-potential species in the Thornbush Savanna, especially in the charcoal industry, the season of harvest for each of these species will largely benefit the farmer's goal for rangeland restoration and/or sustainable wood harvesting. For rangeland restoration, winter harvesting will discourage coppice for both species and will therefore be a desirable outcome. Moreover, selective bush thinning (Smit and Rethman, 1999; Smit, 2004; 2005; 2014) is then advocated for rangeland restoration.

In **Chapter 7** the benefits of selective thinning for successful rangeland restoration from a bush-thickened state are discussed. If harvesting is done with the aim of encouraging coppice regrowth for wood production and/or browsing at the desired height strata for browsers, then harvesting in the summer will be the preferred option (Table 6.3). It is also known that coppice regrowth prioritizes leaf as opposed to wood production (Smit, 2003) and will therefore be favourable for a high browse production at a low stratum. It is further known that from a commercial point of view it will take too long for a coppicing plant to produce a second harvestable wood yield suitable for charcoal production (Cunningham and Detering, 2017). Existing coppicing plants already have well-established root systems, which will be an additional advantage for their survival. A possible alternative would then be to manage coppice regrowth through pruning of stems (leaving 2–3 stems/shoots) to encourage improved wood yield over a shorter time. This will require vigorously coppicing plants and average to above average rainfall to sustain the growth and development. Such experiments were not done in the Thornbush Savanna, especially not on species such as *S. mellifera* and *V. reficiens.* The viability of this option is supported by the report of Gessesse *et al.* (2015) who claim to have successfully increased the wood biomass of *S. nilotica* over a shortened time period by pruning back coppicing stems to two or three stems. However, the harvested wood biomass reported by Gessesse *et al.* (2015) was still low after 36 months, but definitely provides a possibility for pruning of coppice for high wood-potential species for increased wood production.

There was no significant difference ($P>0.05$) in the subsequent establishment of seedlings in the summer and winter harvested plots. However, *Dichrostachys cinerea* showed a highly significant ($P<0.001$) increase in sapling density (plants ha^{-1}). Both old and young *D. cinerea* plants can produce many viable seeds annually, which can survive for more than 5 years in the soil (Mudzengi *et al.,* 2014). This will increase the germination rate of the plant due to the availability, high production and survival ability of the seed. According to Mannheimer and Curtis (2009), *D. cinerea* is also widespread in a variety of habitats in the central and northern parts of Namibia. This ensures its adaptability to different climatic conditions, including drier areas. Species like *Catophractes alexandri, Grewia flava,* and *G. retinervis* also exhibited higher rates of regeneration in terms of sapling establishment, though this is not statistically significant ($P>0.05$).

Table 6.4: GLM showing the effects of non-selective harvesting during the wet, growing (summer) and dry, dormant (winter) seasons on sapling establishment

	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept: (Summer)	45.8921	11.68	3.929	0.000162	***
Treatment: Winter	13.6955	9.7891	1.399	0.165053	
Species: *Boscia albitrunca*	-25.8921	25.6788	-1.008	0.315869	
Species: *Boscia foetida*	-39.4933	20.8711	-1.892	0.061503	.
Species: *Catophractes alexandri*	22.4412	19.9477	1.125	0.263422	
Species: *Commiphora* spp.	-35.8921	25.6788	-1.398	0.165449	
Species: *Dichrostachys cinerea*	71.5385	15.5362	4.605	1.28E-05	***
Species: *Grewia avellana*	-35.8921	41.296	-0.869	0.38696	
Species: *Grewia flava*	-5.1569	15.2864	-0.337	0.736596	
Species: *Grewia flavescens*	-49.895	30.5205	-1.635	0.1054	
Species: *Grewia retinervis*	0.6158	15.596	0.039	0.968585	
Species: *Phaeoptilum spinosum*	-25.8921	25.6788	-1.008	0.315869	
Species: *Senegalia mellifera*	-12.7856	15.0188	-0.851	0.396738	
Species: *Vachellia reficiens*	-0.5256	14.4591	-0.036	0.97108	
Species: *Ziziphus mucronata*	-30.8921	30.3462	-1.018	0.311268	

Although there was no significance (P>0.05), considering that the plants were harvested in June 2017 (winter treatment) and February 2018 (summer treatment), it was expected that the winter treatment should have had a higher sapling establishment as opposed to the summer treatment (Table 6.4). Annual rainfall distribution may have had an influence on the sapling establishment. Both the 2017/18 and 2018/19 rainfall seasons were below average (218 mm, sd ±22.77 for the 2018/19 season, long-term average = 450 mm, CV = 15.14%). The 2017/18 rainfall was not recorded on the study sites but was generally a dry season, similar to the 2018/19 season. The findings in Table 6.4 necessitated a further statistical investigation into how the seasons (summer or winter) influence the sapling establishment of certain species.

The GLM shows that *D. cinerea* had significantly high (P<0.01) sapling establishment in both winter and summer harvested plots (Table 6.5). Although not statistically significant (P>0.05), the plant species that indicated higher densities (sapling ha^{-1}) in the summer harvested plots were *Catophractes alexandri* and *Grewia flava.* Although not statistically significant (P>0.05), the plant species that showed higher densities (sapling ha^{-1}) in the winter harvested plots were *Dichrostachys cinerea, Grewia retinervis, S. mellifera,* and *V. reficiens.* The sapling establishment of species such as *D. cinerea* and *Albizia anthelmintica* was not really affected by the season of initial harvesting.

Table 6.5: GLM indicating the effect of the season of initial non-selective harvesting on the sapling establishment of species occurring in the area

	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept (*Albizia anthelmintica*_s)	35.7143	14.9546	2.388	0.01902	*
Species: *Albizia anthelmintica*_w	35.9524	22.0126	1.633	0.10591	
Species: *Boscia albitrunca*_s	-15.7143	27.3033	-0.576	0.56636	
Species: *Boscia foetida*_s	-22.381	27.3033	-0.82	0.41454	
Species: *Boscia foetida*_w	-25.7143	31.7235	-0.811	0.41975	
Species: *Catophractes alexandri*_s	32.619	22.0126	1.482	0.14188	
Species: *Commiphora* spp._s	-25.7143	27.3033	-0.942	0.34881	
Species: *Dichrostachys cinerea*_s	68.5714	21.149	3.242	0.00166	**
Species: *Dichrostachys cinerea*_w	110.9524	22.0126	5.04	2.39E-06	***
Species: *Grewia avellana*_s	-25.7143	42.298	-0.608	0.54476	
Species: *Grewia flava*_s	16.5079	19.9395	0.828	0.40992	
Species: *Grewia flava*_w	-1.7143	23.1676	-0.074	0.94118	
Species: *Grewia flavescens*_w	-25.7143	31.7235	-0.811	0.41975	
Species: *Grewia retinervis*_s	10.9524	19.9395	0.549	0.58417	
Species: *Grewia retinervis*_w	24.2857	24.7994	0.979	0.33006	
Species: *Phaeoptilum spinosum*_s	-15.7143	27.3033	-0.576	0.56636	
Species: *Senegalia mellifera*_s	0.9524	19.9395	0.048	0.96201	
Species: *Senegalia mellifera*_w	5.9524	22.0126	0.27	0.78747	
Species: *Vachellia reficiens*_s	10.119	18.8175	0.538	0.59208	
Species: *Vachellia reficiens*_w	22.619	22.0126	1.028	0.30692	
Species: *Ziziphus mucronata*_s	-20.7143	31.7235	-0.653	0.51544	

s= summer, w = winter

The season of initial wood harvesting clearly influences coppice probability, survival of coppice, and sapling establishment. However, according to Flanigan *et al*. (2020), sapling establishment is not reliable as their survival is also highly rainfall and temperature-dependent. According to Joubert *et al.* (2013), *S. mellifera* especially requires several consecutive above-average rainfall years for seed production and successful sapling establishment and development. Joubert *et al.* (2017) also reported that *S. mellifera* is not as fast-growing as generally perceived. Moreover, Hagos (2001) found that viable seed for *S. mellifera* is not transferred from one growing season to the next. The annual total defoliation of coppice that results in the die-off of regrowth (see Chapter 5) also adds to these opportunities for land management for rangeland restoration. Browse, especially on saplings, can have a similar effect as annual total defoliation and may lead to the die-off of these plants (Scogings and Macanda, 2005).

6.3.2. The effect of season of harvesting on the species composition of woody plants

In both treatments (summer and winter harvesting), the ETTE ha^{-1} was significantly lower (P <0.01) than the control for all years post-harvest (Table 6.6). The winter harvested plots showed a faster recovery in ETTE ha^{-1} than the summer harvested plots. On the other hand, plants ha^{-1} showed no significant differences (P>0.05) between the treatments and years' post-harvest (Table 6.6). This means that the plant density (plants ha^{-1}) recovered at a faster rate than the plant size (ETTE ha^{-1}).

Table 6.6: Effect of treatment type and post-treatment period (years) on the ETTE and plants ha^{-1} measured per species in the study area

1. ETTE ha^{-1}	**Estimate**	**Std. Error**	**t value**	**Pr (>|t|)**	
Intercept: (Control)	1099.8	103	10.675	< 2e-16	***
Treatment: Summer (1)	-1053.6	249.3	-4.226	3.91E-05	***
Treatment: Summer (2)	-993.6	230.4	-4.313	2.74E-05	***
Treatment: Summer (3)	-980.4	195.9	-5.005	1.41E-06	***
Treatment: Winter (1)	-976.6	317.5	-3.076	0.00245	**
Treatment: Winter (2)	-952.4	236	-4.035	8.30E-05	***
Treatment: Winter (3)	-768.8	266	-2.89	0.00436	**
Treatment: Winter (4)	-789	249.3	-3.164	0.00185	**
2. Plants ha^{-1}					
Intercept: (Control)	294.118	43.223	6.805	1.73E-10	***
Treatment: Summer (1)	-176.261	104.605	-1.685	0.0939	.
Treatment: Summer (2)	-62.176	96.649	-0.643	0.5209	
Treatment: Summer (3)	-47.964	82.184	-0.584	0.5603	
Treatment: Winter (1)	-6.618	133.221	-0.05	0.9604	
Treatment: Winter (2)	15.257	99.036	0.154	0.8777	
Treatment: Winter (3)	211.299	111.6	1.893	0.06	.
Treatment: Winter (4)	180.882	104.605	1.729	0.0856	.

The use of ETTE ha^{-1} and plants ha^{-1} to determine the change in plant size structure is discussed in detail in Chapter 4, section 4.3.2. The use of this statistical analysis as an indication of growth rate is discussed in detail in Chapter 5, Section 5.3.3. A higher sapling establishment (Table 6.4), as well as better coppice (Tables 6.2 and 6.3), were recorded in the plots harvested during the summer. However, although not significant (P>0.05), a faster recovery in plant density (plants ha^{-1}) was recorded in the winter harvested plots as opposed to the summer harvested plots. This is mainly a result of the harvesting time as well as rainfall. The winter treatment was harvested in May 2017 and the summer treatment in February 2018 (see Section 6.2.4). Before harvesting the summer treatment in February 2018, some reasonable amounts of rainfall (although below average) were already recorded in the preceding months (see

Chapter 3, Table 3.1). This led to good germination and coppice regrowth in the winter harvested plots, whereas the summer treatment was harvested during the below average rainy season, and growth was subsequently negatively affected.

Apart from plant densities and sizes, the species richness and diversity were also investigated to determine the rate of recovery of the vegetation. Overall, the control plots had the highest average species richness (S) (Table 6.7). Both summer and winter harvesting treatments resulted in a reduction in the species richness. However, the differences from the control plots were not significant (P>0.05). The effect of the year shows a positive - although statistically insignificant (P>0.05) - influence on species richness, which suggests that with every unit increase in the period (year) following treatment, species richness recovered on average by 0.05 index value.

Regarding species diversity (*H'*), the control plots had the highest average species diversity (Table 6.7). The winter harvested treatment significantly reduced species indices by 0.93 (P = 0.015). The effect of the summer harvested treatment was also negative towards the diversity indices. However, this was not statistically significant (P>0.05). The effect of the year (time since harvesting) shows a positive, although not statistically significant (P>0.05) influence on diversity indices. Thus, with every unit increase in the time since harvesting (year) following treatment application, diversity indices recovered on average by 0.07 species indices.

Table 6.7: GLM showing the effect of treatment and season (years) on the species richness and diversity. The treatments are control (before harvesting), winter and summer harvesting of woody plants

	Estimate	**St. Error**	**z value**	**Pr(>|z|)**	
1. Species richness (S)					
Intercept: (Control)	2.56495	0.27735	9.248	<2e-16	***
Treatment: Summer	-0.42328	0.4127	-1.026	0.305	
Treatment: Winter	-0.62165	0.43009	-1.445	0.148	
Year	0.04561	0.11829	0.386	0.7	
2. Diversity (H')					
Intercept: (Control)	2.18	0.16739	13.023	0.000201	***
Treatment: Summer	-0.50419	0.22399	-2.251	0.087551	.
Treatment: Winter	-0.92971	0.22636	-4.107	0.014765	*
Year	0.06543	0.05659	1.156	0.311955	

The similarities and differences between the treatments (summer and winter) and the years are outlined in Figure 6.2. The Jaccard similarity model was used to point out similarities and differences in species change over years after initial harvesting. The Jaccard similarity broadly clustered the winter and summer harvested plots separately. The control plots had high

similarity with the summer harvested plots after three years of recovery. In both treatments (winter and summer), seasons one and two were different from each other, as well as from the control and seasons three and four. The species compositions for seasons three and four plots were similar and had a similarity with the control. This indicates regeneration, especially in species composition, as time advances, as also supported by Tables 6.7 and 6.8.

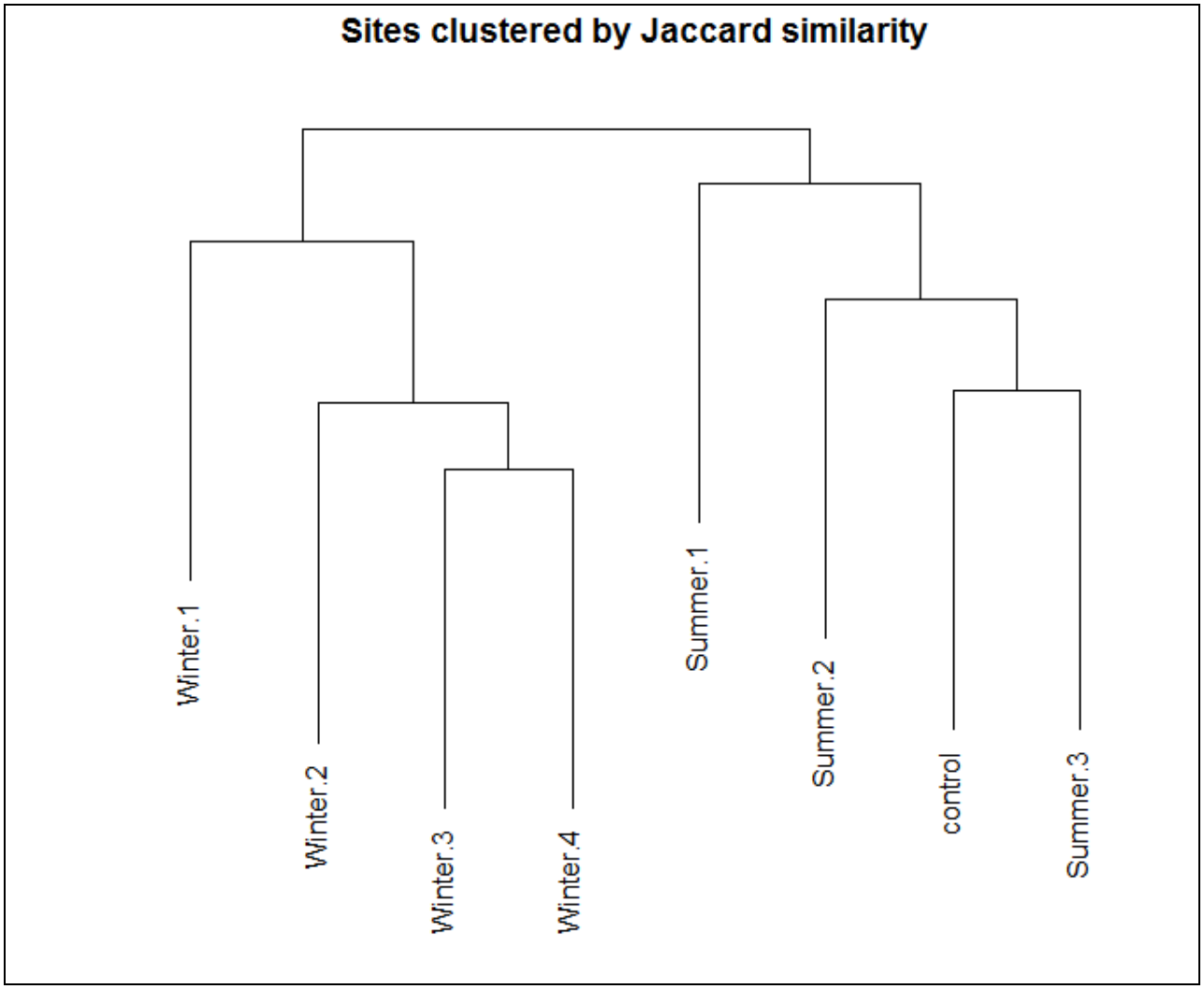


Figure 6.2: Jaccard similarity model showing similarities and differences between the different treatments (winter and summer harvesting) and years. The number at the end of treatment indicates the years after initial harvesting

The statistically analyzed species richness (Table 6.7) is supported by the plant species composition presented in Table 6.8. The highest species richness was found in the control plots. The summer harvested plots show a clear trend in progression in terms of species richness. The winter harvested plots, however, show inconsistencies in species richness over the years after harvesting. There is a positive trend in species richness and diversity regeneration (Table 6.7).

Table 6.8: Plant species composition (%) response to non-selective initial harvesting during winter and summer

Species	Control	Summer harvesting (Season)			Winter harvesting (Season)			
	0	**1**	**2**	**3**	**1**	**2**	**3**	**4**
Protected species								
Albizia anthelmintica	8.0	6	2	9	–	3	8	14
Boscia albitrunca	2.0	6	3	1	–	2	–	–
Boscia foetida	1.3	–	2	2	2	2	1	1
Low wood-potential species								
Commiphora spp.	2.3	–	–	2	–	–	–	–
Grewia flavescens	6.8	–	2	–	–	1	–	–
Grewia retinervis	4.3	24	6	9	22	18	13	14
Grewia flava	23.8	33	29	32	11	13	13	18
Catophractes alexandri	10.5	12	11	13	–	–	–	–
Dichrostachys cinerea	13.8	12	33	23	60	52	54	47
High wood-potential species								
Senegalia mellifera	18.0	–	3	5	–	4	3	4
Vachellia reficiens	8.8	6	10	5	–	3	6	3
Vachellia tortilis	0.5	–	–	1	4	1	–	1
Vachellia hebelcada	0.3	–	–	–	–	1	–	–
Species richness	**13**	**7**	**10**	**11**	**5**	**11**	**7**	**8**

The studies available on woody plant regeneration mainly focus on wood production after harvesting. According to Von Breitenbach (1965) and Scholes (1990), *Colophospermum mopane* recovers to a pre-cleared state within about 15 years after harvesting. In the same veld type as this study (see Chapter 3, Section 3.3), Cunningham and Detering (2017) argue that woody plants from the *Senegalia* and *Vachellia* genera can take up to 40 years to regenerate from seed to a pre-cleared state. However, it is clear that non-selective harvesting causes a shift in species dominance from high wood-potential to low wood-potential species. This shift in species dominance is more prevalent in the above 300 mm long-term rainfall areas. These are also the areas that, according to Joubert *et al.* (2014), are more inclined to woody plant thickening.

6.3.3. The effect of season of harvesting on the wood biomass regeneration

The GLM model shows that on average, the estimated total wood biomass in the control plots was 249 314 kg DM ha $^{-1}$ (Table 6.9). The negative values for the effect of winter and summer treatments show that the estimated wood biomass ha^{-1} was less than the amounts in the control plots. Compared to the control, the predicted wood biomass (kg DM ha^{-1}) in the summer

treatment was less by 2 951.31 (P>0.05) for year one, 2 913.61 (P>0.05) for year two, and 2 748.37 (P<0.05) for year three.

In the same scenario, the predicted wood biomass (kg DM ha^{-1}) in the winter treatments was less by 2 212.45 (P>0.05) for year one, 3 172.82 (P<0.05) for year two, 2 873.12 (P>0.05) for year three, and 3 182.63 (P>0.05) for year four. In both treatments, the largest differences were observed in the first two years following non-selective wood harvesting.

Table 6.9: Effect of treatment type and post-treatment period (years) on the total wood biomass (kg DM ha^{-1}) measured per species in the study area. The negative estimates indicate the removal of wood biomass after harvesting in comparison to the control

	Estimate	**Std. Error**	**t value**	**Pr (>|t|)**	
Intercept (Control)	2493.14	1385.54	1.799	0.0739	.
Treatment: Summer (1)	-2951.31	1682.72	-1.754	0.08143	.
Treatment: Summer (2)	-2913.61	1528.56	-1.906	0.05849	.
Treatment: Summer (3)	-2748.37	1308.79	-2.1	0.03735	*
Treatment: Winter (1)	-2212.45	2180.33	-1.015	0.31181	
Treatment: Winter (2)	-3172.82	1581.78	-2.006	0.04661	*
Treatment: Winter (3)	-2873.12	1781.38	-1.613	0.10881	
Treatment: Winter (4)	-3182.63	1674.16	-1.901	0.05915	.

The predominantly insignificant differences (P>0.05) in wood biomass during the post-harvest years give a good indication of the very slow wood biomass regeneration (Table 6.9). It is clear that the vegetation size structure is still young (high plants ha^{-1} and low ETTE ha^{-1}) for the protected and low wood-biomass species (Figure 6.3). The high wood-potential species, however, show non-significant differences (P>0.05) between plants ha^{-1} and ETTE ha^{-1}. Considering their low ETTE ha^{-1}, it means that there are just a few plants present, and they are young.

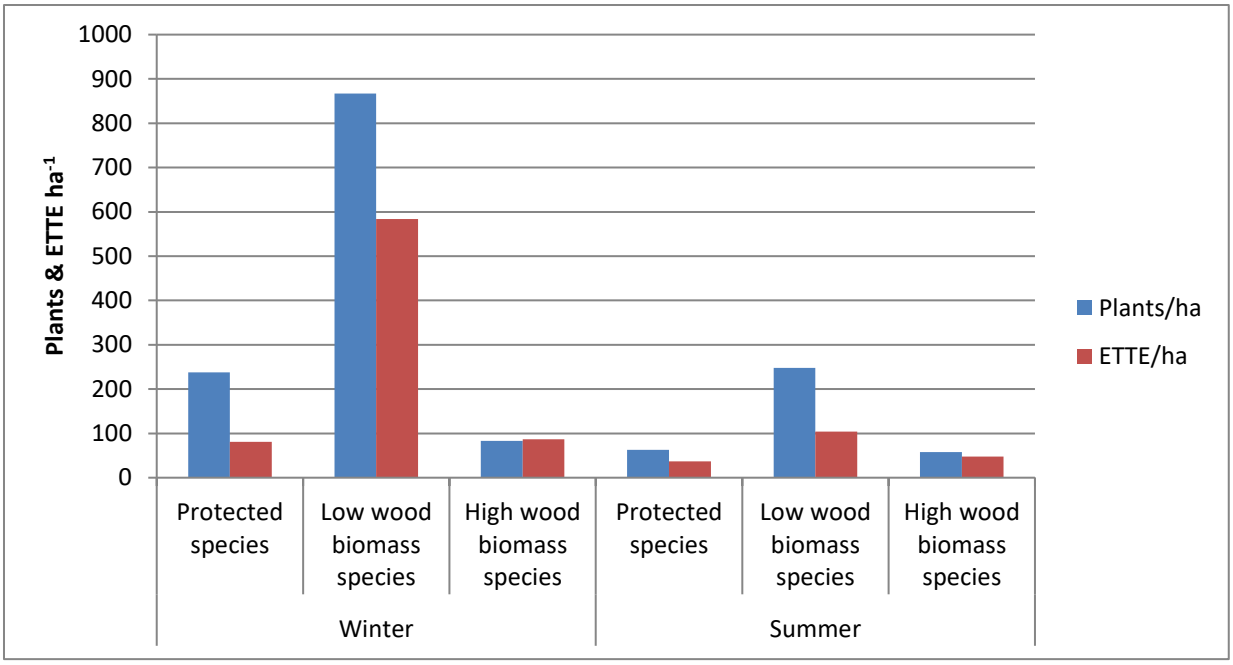


Figure 6.3: Plant density and ETTE ha^{-1} indicating the plant size structure of the winter and summer harvested plots at the end of the data collection period (4 years)

The slow regeneration of the high wood-potential species, especially *Senegalia mellifera*, is also reported by Joubert *et al.* (2017). Based on general observations, other high wood-potential species in the study area, such as *Vachellia reficiens* and *Vachellia tortilis*, are also slow growers, an observation that is supported scientifically by Cunningham and Detering (2017). The shift in dominance from high wood-potential species to low wood-potential species is a concern for savanna biodiversity. Lykke (1998) also reported that disturbances such as fire and logging for building materials changed tree-dominated vegetation to shrub-dominated vegetation in Senegal. Tredenick and Hanan (2015) further reported that forests can become savannas with continuous disturbance. This similar shift is already evident in Namibia, where savannas are shifting to bush-thickened-shrublands.

6.4. Conclusion

Following non-selective cutting/harvesting of all woody plants, regeneration in the form of coppice and sapling establishment was found to be high, regardless of harvesting having been done in winter or summer. Summer harvesting favoured the coppice probability of *Senegalia mellifera*, whereas winter harvesting favoured *Vachellia reficiens*. These trends can be used for the management of these plant species, whether for suppression or encouragement of coppice.

There was a clear shift in vegetation dominance from high wood-potential to low wood-potential species. This shift is deemed undesirable for plant diversity, species richness, and wood biomass regeneration. Generally, the 4-year post-harvest data, therefore, show differences between these two treatments, which were, however, more influenced by time as opposed to the treatments.

CHAPTER 7: THE IMPACT OF ONCE-OFF SELECTIVE AND GRADUAL SELECTIVE THINNING OF WOODY PLANTS

7.1. Introduction

Savanna ecosystems evolved with woody plants as a prominent component, which, in optimum condition, complement the herbaceous component in terms of soil nutrient enrichment and sub-habitat differentiation (Bosch and van Wyk, 1970; Kennard and Walker, 1973; Tiedemann and Klemmedson, 1973; Kellman, 1979; Bernhard-Reversat, 1982; Belsky *et al.*, 1989; Smit and Swart, 1994; Hagos and Smit, 2005). Disturbance events such as continuous overgrazing (Sebata, 2017) and incorrect bush control practices can lead to the increase of woody plants at the expense of the grasses. This phenomenon is known as bush thickening, and therefore, an understanding of the factors that influence woody plants is critical for the optimal management of African savanna ecosystems (Smit *et al.*, 1999; Joubert, 2014).

In mesic savannas, herbaceous plants can coexist with relatively high woody plant densities (Smit and Rethman, 1999). Woody plant thickening is not only detrimental to grazers but also to browsers (Smit, 2004). This is because of the inter-tree competition for resources, which affects the growth and phenology of plants, resulting in a shortening of the leaf carriage period of winter-deciduous woody species. Bush control typically causes an immediate shift in the dynamics of competition between woody and herbaceous plants, resulting in a sharp rise in herbaceous production as a result of reduced competition and the release of nutrients from the removed woody plants (Smit, 2004).

The removal of woody plants in Namibian savannas, either for direct use or during woody plant control measures, has become common practice. Smit (2004; 2005) advocates bush thinning as opposed to clearing for long-term restoration from bush thickening. It is hypothesized that a more stable environment can be created by maintaining or restoring savanna structure by preserving the large trees. 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. Although bush thinning will reduce the browse biomass at its peak, the woody plants often display a better distribution of browse at lower tree densities with leaves in comparatively younger phenological states over an extended period (Smit, 2004). The open areas in the vegetation as a result of bush thinning will lead either to neighbouring individual woody plants growing bigger and becoming more competitive or to the establishment of new individuals (Teague and Smit, 1992).

Rangeland restoration studies have been done on once-off thinning of woody plants to a pre-determined density (Smit, 2004; 2005). The effect of gradual thinning of woody plants to a pre-determined density has not been investigated. It is expected that, if thinning of woody plants takes place gradually over time, the rangeland may become more resilient (i.e., it may or may not be stable, but remains attracted towards its equilibrium) without sudden changes that might react toward "negative stability" (i.e., reverting back to woody thickening as opposed to higher grass production).

The objective of this study was to investigate and compare the response of woody plants to once-off selective, and gradual selective thinning. The effect of the season (actively growing or dormant) of once-off selective thinning on the response of woody plants was also investigated. The specific objectives of this study were to determine and assess the effect of once-off as opposed to gradual thinning of woody plants to a pre-determined density on:

- Response of cut plants through coppice regeneration,
- Growth rate of the woody plants, and
- Species composition change and recruitment of plants.

7.2. Procedure

7.2.1. Study area

The study was conducted on farms Arcadia and Omatjenne, located northwest of Otjiwarongo in an area described as the North-Central Plateau of Namibia, in vegetation classified as Thornbush Savanna (Giess, 1998). A detailed description of the study area is presented in Chapter 3.

7.2.2. Site selection and trial layout

The different treatments were conducted on plots of 50 x 30 m (1 500 m^2), located in a homogeneous, densely wooded area on the farms. Detailed information on the determination of plot sizes and target species is presented in Chapter 4, Section 4.2.2.

7.2.3. Treatments

The treatment trial layout consisted of twelve 50 x 30 m (1 500 m^2) plots. Four treatments were applied, with two replications for each treatment and four control plots. The treatments were: (i) once-off thinning in summer, (ii) once-off thinning in winter, (iii) gradual thinning over a three-year period, and (iv) non-selective harvesting. The determination of pre-determined

densities is discussed in Section 7.2.4. The study was conducted on two separate farms, each trial layout included control plots, resulting in four control plots.

The number and size class of *Senegalia mellifera* and *Vachallia reficiens* plants to be monitored, the fixed point survey for biomass quantification in the various plots, and the use of the BECVOL-3 model are discussed in detail in Chapter 4, Sections 4.2.3 & 4.2.4.

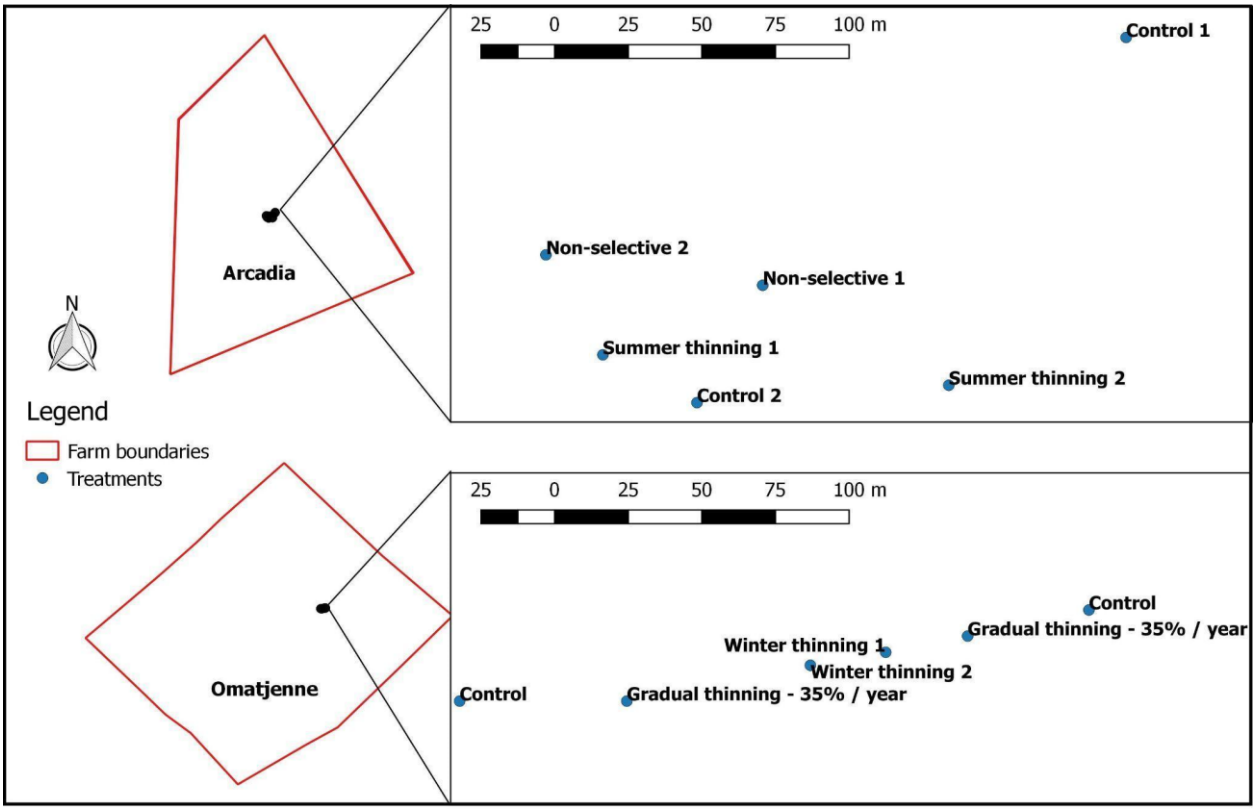


Figure 7.1: Trial layout showing the different once-off thinning in summer and winter, gradual thinning, non-selective harvest and control plots

7.2.4. The concept of bush thinning

The decision on the ideal number of woody plants that should be retained during selective bush control operations 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 areas 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 and 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 Evapotranspiration Tree Equivalents (ETTE) ha^{-1} that can be supported in a specific rainfall region without adversely affecting the grass layer should not exceed 10 times the mean annual rainfall of the area. Removing woody plants to a pre-determined density ("the general rule of thumb") based on aridity will increase herbaceous production. Studies by

Teague and Smit (1992) and Smit (2004; 2005) indicate that, in time, the competitive ability of the woody plants remaining after thinning will gradually increase and reduce the impact of re-infestation. The long-term average rainfall for the study area is 450 mm (CV = 15.14%), and therefore, the threshold ETTE ha^{-1} that can be accommodated without negatively influencing the herbaceous layer is 4 500 ETTE ha^{-1}.

7.2.5. Harvesting

Harvesting was done non-selectively and selectively. The selective harvesting was done by means of once-off selective thinning, and gradual selective thinning. The methods of harvesting and data collection dates are presented in Table 7.1.

Table 7.1: Details of bush harvesting, date of data collection, and study sites

Method of harvesting	Time of harvesting	First data collection	Final data collection	Farm
Non-selective harvesting	February 2018	February 2018	May 2021	Arcadia
Selective thinning - Summer	February 2018	February 2018	May 2021	Arcadia
Selective thinning - Winter	June 2018	June 2018	May 2021	Omatjenne
Gradual selective thinning	June 2018 **(35%)**	June 2018		
	June 2019 **(35%)**			
	June 2020 **(35%)**		May 2021	Omatjenne

For selective thinning, a BECVOL-3 survey (Smit, 2014) was conducted at fixed point transects within each plot to determine the total ETTE ha^{-1} (see in Chapter 4, Sections 4.2.3 & 4.2.4). The BECVOL-3 model was then further used to calibrate the number of ETTE per plant height class. Therefore, plant height - which is easy to determine from field measurements - and can be used to determine ETTE, which is much harder to determine - was used as the guide for the removal of trees up to a pre-determined density (4 500 ETTE ha^{-1}). The concept of bush thinning to a pre-determined density is discussed in section 7.2.4.

Harvesting was then done, targeting the pioneer, low wood-potential encroacher species first (see Chapter 4, Section 4.3.1). These invariably involved small plants. Additional bigger plants were only harvested after all the pioneer low wood-potential species had been removed and the pre-determined density had not been reached. No big trees or protected species were harvested in the selective thinning plots.

The non-selective plots were harvested in the active growing season. All plants, including the few plants of protected species, were harvested. This was done to ensure that regrowth from

coppice or sapling establishment had the same regeneration conditions without the potential influence of competition from undamaged plants.

Harvesting in all treatment plots was done mainly with chainsaws and some other hand tools such as axes.

7.2.6. Data analysis

A generalized linear model (GLM) was used for the modeling task to investigate the impacts of treatments on the vegetation structure (Venables and Ripley, 2002). The ETTE and plants ha^{-1} were used as the response variables, whereas the explanatory variables were treatment type (non-selective harvesting, selective once-off thinning, and gradual selective thinning). The control, plant species response, and the year since treatment application (2018 and 2021) were also used as explanatory variables.

A binary GLM was also used to investigate the effect of treatment on the coppicing of woody species. For each woody species, the response variable was coded as 1 where coppicing had taken place (yes) and 0 otherwise (no). The explanatory variables used for coppice analysis were also treatment type (non-selective harvesting, selective once-off thinning, and gradual selective thinning). Other explanatory variables incorporated to determine reaction towards coppice were stem diameter, number of stems, distance to the nearest plant species neighbour, and the year since treatment application (2018 and 2021).

Model fit was examined graphically by evaluating the trends and homoscedasticity of the Pearson residuals, and non-constant residual variance was modeled by updating initial models with a weighted variable (Mehtatalo and Kansanen, 2020).

The Jaccard similarity distances were calculated to determine how close treatment plots were in species composition by exploring the number of species shared between two sites divided by the total number of species (Oksanen *et al*., 2022).

Species richness and diversity were calculated using the package Vegan (Oksanen *et al*., 2022). Richness was calculated as the total number of species represented in a sample; diversity was calculated using the Shannon-Wiener diversity index (H'). These analyses were performed using R (version 4.1.2; R Core Team, 2021).

The wood biomass and ETTE were obtained from the BECVOL-3 data collection procedure (Chapter 4, Section 4.2). Species composition was calculated as the proportion of each woody

species in relation to the total number of individuals in each sample plot. The final composition estimates per treatment type were expressed as percentages (%) averaged across the plots for each area. All the descriptive statistics, such as graphs and tables, were generated using Microsoft Excel (Microsoft, 2010).

7.3. Results and Discussion

7.3.1. Response of cut plants through coppice

Generally, the coppicing and survival rates for *Vachellia reficiens* were relatively low, whereas they were relatively high for *Senegalia mellifera* (Table 7.2). Both species had a much higher coppicing rate and survival in the non-selectively harvested plots as opposed to the selectively thinned plots.

Table 7.2: Coppicing rate and survival (%) of *Senegalia mellifera* and *Vachellia reficiens* in non-selectively and selectively harvested plots

			Season		
Treatment	**Species**	**n**	**Season 1 % Coppice**	**Season 2 % Coppice**	**Season 3 % Coppice**
Selective thinning	*Senegalia mellifera*	20	70	25	15
	Vachellia reficiens	20	45	10	5
Non-selective harvesting	*Senegalia mellifera*	40	90	43	43
	Vachellia reficiens	40	65	28	13
Annual rainfall (mm)			218	475	483
Standard deviation			(± 22.8)	(± 63.44)	(±65.0)

The low coppicing and survival rate of *V. reficiens* is largely a result of the season of harvest (See Chapter 6, Section 6.3.1). The high coppicing rates in the non-selectively harvested plots are a result of drastically reduced competition, whereas the lower coppicing rates in the selectively thinned plots were a result of competition from the undamaged plants. It also appears that regrowth in the form of coppice for *V. reficiens* is much lower than that of *S. mellifera.*

The general linear model (GLM) used to assess the results presented in Table 7.2 confirmed a highly significant ($P<0.001$) reduction in coppice regrowth for each year post-harvest in both treatments (non-selective harvesting and selective harvesting through thinning) (Table 7.3).

Table 7.3: GLM showing the effect of treatment, number of stems, stem diameter, distance to nearest plant/neighbor, and nearest neighbor/plant species on the coppicing probability of *Senegalia mellifera* and *Vachellia reficiens*

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept: (Non-selective (1))	0.9765955	0.1189087	8.213	4.67E-15	***
Treatment: Non-selective (2)	-0.425	0.0655194	-6.487	3.13E-10	***
Treatment: Non-selective (3)	-0.4998952	0.0655201	-7.63	2.43E-13	***
Treatment: Selective thinning (1)	-0.1776672	0.0842245	-2.109	0.0356	*
Treatment: Selective thinning (2)	-0.5879236	0.0842245	-6.98	1.57E-11	***
Treatment: Selective thinning (3)	-0.6648467	0.0842245	-7.894	4.16E-14	***
Number of stems	0.0083879	0.0249808	0.336	0.7373	
Stem diameter	-0.0311772	0.0067192	-4.64	5.00E-06	***
Distance to nearest neighbor	0.0006175	0.0003283	1.881	0.0609	.
Neighbour: *Boscia albitrunca*	0.0627676	0.156666	0.401	0.6889	
Neighbour: *Catophractes alexandri*	-0.0092875	0.1260225	-0.074	0.9413	
Neighbour: *Commiphora* spp.	-0.1725885	0.1820668	-0.948	0.3438	
Neighbour: *Dichrostachys cinerea*	0.1530395	0.1333734	1.147	0.252	
Neighbour: *Grewia flava*	-0.0373151	0.0871109	-0.428	0.6687	
Neighbour: *Grewia flavescens*	-0.0938501	0.0988036	-0.95	0.3429	
Neighbour: *Grewia retinervis*	0.1103617	0.088626	1.245	0.2139	
Neighbour: *Senegalia mellifera*	-0.0830785	0.0847257	-0.981	0.3275	
Neighbour: *Vachellia reficiens*	0.1221145	0.111519	1.095	0.2743	
Neighbour: *Vachellia tortilis*	-0.5401697	0.2722269	-1.984	0.048	*

The number of stems and distance to the nearest plant neigbour had no significant influence ($P>0.05$) on coppice regrowth. However, stem diameter positively influenced coppicing regrowth with a high significance ($P<0.001$). The smaller the stem diameter, the higher the coppicing regrowth. The coppicing regrowth of the cut plants was negatively ($P<0.05$) affected by the presence of *Vachellia tortilis.* Although not significant ($P>0.05$), nearest neighbour species such as *Boscia albitrunca, Dichrostachys cinerea, Grewia retinervis,* and *Vachellia reficiens* positively influenced the coppicing regrowth of *Senegalia mellifera* and *Vachellia reficiens.*

The high coppicing rates in the non-selective thinning treatment plots were due to less inter-tree competition (Table 7.2). The cut plants in the selectively thinned plots had more competition from the undamaged plants and therefore lower coppicing rates. According to Moyo *et al.* (2016), the ability of a woody plant to coppice and remain vigorous largely depends on the severity of disturbances, resource availability and the mobilization of stored reserves. The resource availability such as soil water played a definite role (see Chapter 4, Section 4.3.1) in coppicing rates.

Apart from once-off selective thinning (Tables 7.2 & 7.3), the option of thinning to a pre-determined density over time was also investigated (Figure 7.2). The non-selectively harvested plots had a significantly higher ($P<0.05$) coppicing rate from cut stumps as opposed to the once-off thinning and gradual thinning over time to pre-determined density treatments. Although the gradual thinning treatment (35% over 3 years) had a lower coppicing rate, there were no significant differences ($P>0.05$) in coppicing rates between the two selectively thinned treatments.

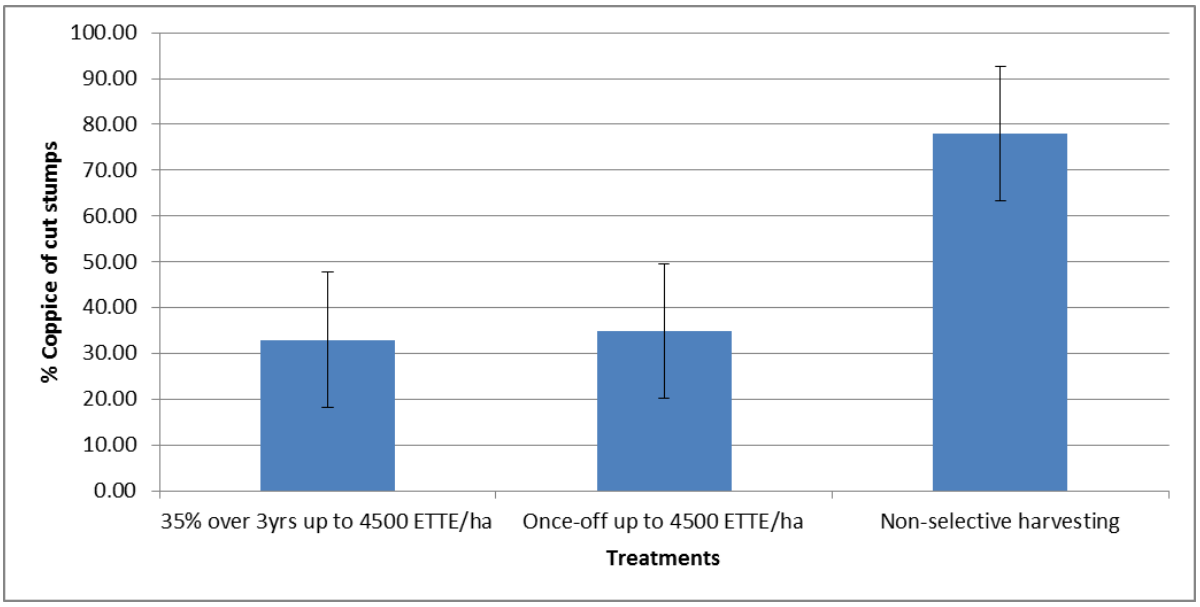


Figure 7.2: Comparison in coppice percentage of cut plants in selectively versus non-selectively harvested plots. Error bars represents standard error (SE)

Bush thickening is a slow, gradual process and takes place over several years to decades (Joubert *et al.*, 2014; O'Connor *et al.*, 2014). The gradual restoration of bush thickened rangelands has not been documented in the literature. Smit (2014) conducted thinning experiments to different tree densities, but they were once-off and not over time. Similarly to this study, Smit (2014) reported higher re-establishment of woody plants either through coppice and/or sapling establishment in the higher as compared to the lighter intensity thinned plots.

7.3.2. The growth rate of the woody plants

There was no significant difference ($P>0.05$) in growth in terms of ETTE ha^{-1} for both the non-selectively and selectively harvested plots (Table 7.4). The only significant difference ($P<0.05$) in ETTE ha^{-1} was the non-selective plot before harvesting (year 2018). Thereafter, there was no significant ($P>0.05$) regrowth for ETTE ha^{-1} for both treatments. However, although not significant ($P>0.05$), selective thinning showed a faster recovery in terms of ETTE ha^{-1}.

There was no significant difference (P>0.05) in plant density (plants ha^{-1}) before harvesting (year 2018) for both treatments compared to the control (Table 7.4). However, after harvesting (year 2021), selective thinning had a significantly (P<0.05) higher plant density than the rest of the treatments.

Table 7.4: Change in ETTE ha-1 and plants ha-1 for both selectively and non-selectively harvested plots compared to the control, before harvesting (2018) and three years after harvesting (2021). The selective thinning is a combination of gradual and once-off thinning

1. ETTE ha^{-1}	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept (Control)	628.29	307.22	2.045	0.0452	*
Treatment: Non-selective (2018)	909.29	434.47	2.093	0.0405	*
Treatment: Non-selective (2021)	-484.29	452.21	-1.071	0.2884	
Treatment: Selective thinning (2018)	359.51	427.17	0.842	0.4033	
Treatment: Selective thinning (2021)	17.35	463.15	0.037	0.9702	
2. Plants ha^{-1}					
Intercept (Control)	182.14	94.26	1.932	0.058	.
Treatment: Non-selective (2018)	139.29	133.31	1.045	0.3002	
Treatment: Non-selective (2021)	63.69	138.75	0.459	0.6479	
Treatment: Selective thinning (2018)	81.19	131.07	0.619	0.5379	
Treatment: Selective thinning (2021)	372.4	142.11	2.621	0.0111	*

The different harvesting regimes ensured interesting results three years after initial harvesting. The regrowth responses of important variables measured for different harvesting regimes over a three-year period are presented in Table 7.5.

As expected, all treatment plots had a sharp decline in ETTE ha^{-1} and leaf mass (kg DM ha^{-1}) over the three-year period after initial harvesting (Table 7.5). A sharp increase in plant densities (plants ha^{-1}) was measured in the non-selectively and once-off selectively harvested plots. The increase in plant density (plants ha^{-1}) in the once-off selectively harvested plots was significantly higher (P<0.05) compared to the control and non-selectively harvested treatment plots (Table 7.4).

The gradual thinning treatment plots had a lower (1 695) ETTE ha^{-1} , measured three years after harvesting, as opposed to the target pre-determined ETTE ha^{-1} (4 500). This result was obtained from the BECVOL-3 measurements taken in the fixed transects set out in each plot (see Chapter 4, Section 4.2.3). The lower measured ETTE ha^{-1} (1 695 as opposed to the target 4 500) three years after initial harvesting in the gradually thinned plots (35% per year over three years) (Table 7.5) may not necessarily be a true representation of the plot's plant density, as more plants could have been harvested from within the fixed transects as opposed to outside the

transect, although still within the plot. Therefore a new transect laid out representatively within the plot may have yielded the target 4 500 ETTE ha^{-1} measurement.

Harvesting was done, targeting the pioneer low wood-potential encroacher species first (see Section 7.2.5). This harvesting strategy ensured a better control of the low wood-potential species, while encouraging the growth of the high wood-potential species (Tables 7.7 and 7.8). The effect of this harvesting strategy on species composition, richness and diversity is discussed in Section 7.3.3.

The only treatment in which an increase in wood production (kg DM ha^{-1}) was measured is the once-off selectively harvested plots (Table 7.5). Considering the time frame of this study (3 years), and below average rainfall in the first year of harvesting (see Chapter 3, Section 3.2), recovery was particularly slow, especially in the non-selectively harvested plots. The logical explanation for the slow recovery of ETTE ha^{-1} in the non-selectively harvested plots is the replacement in dominance of high wood-potential species by low wood-potential species that are generally smaller and shrubby by nature (Table 7.6). The slower recovery in ETTE ha^{-1} for the once-off and gradually selectively thinned plots was mainly due to competition amongst the remaining undamaged plants, coupled with rainfall and time of recovery from initial harvesting.

Table 7.5: Quantitative data on the woody plants measured before and after harvesting in the different harvesting regimes

Treatment plots	Variable	Before initial harvesting	Three years after initial harvesting
Non-selective harvesting	ETTE ha^{-1}	10 763	864
	Plants ha^{-1}	1 475	2 250
	Leaf mass (kg DM ha^{-1})	2 419	196
	Wood mass (kg DM ha^{-1})	46 950	374
Once-off selective thinning to 4500 ETTE ha^{-1}	ETTE ha^{-1}	7 685	5 669
	Plants ha^{-1}	975	1 375
	Leaf mass (kg DM ha^{-1})	1 775	1425
	Wood mass (kg DM ha^{-1})	37 573	40 983
Gradual thinning over three years to 4500 ETTE ha^{-1}	ETTE ha^{-1}	9 544	1 695
	Plants ha^{-1}	1 425	725
	Leaf mass (kg DM ha^{-1})	2 208	395
	Wood mass (kg DM ha^{-1})	25 279	2 828

The higher increase in plants ha^{-1} in the non-selectively as opposed to the selective once-off and gradually selectively thinned plots was as expected (Table 7.5). This was most likely due to the elimination of competition from undamaged plants (Smit, 2014).

7.3.3. Species composition change and recruitment of plants

The control, and all treatment plots before initial harvesting (2018), were very similar in terms of plant species richness (Table 7.6). A decline in plant species richness after harvesting was measured in all treatments (2021), except for the non-selective harvesting treatment plots. The gradual thinning plots were the only treatment that experienced a percentage increase in high wood-potential species such as *Senegalia mellifera* and *Vachellia reficiens.*

The protected species remained relatively constant before and after harvesting in the summer and winter once-off thinned plots. There was, however, a substantial increase in *B. albitrunca,* a protected species, in the gradually thinned plots. These *B. albitrunca* plants are slow growers and were still saplings at year three (negative response on ETTE ha^{-1} (Table 7.7) and positive response on plants ha^{-1} (Table 7.8)). Along with an increase in aggressive, pioneer woody species, a general increase in protected species, especially *Albizia anthelmintica,* was also observed in the non-selectively harvested treatment plots.

Table 7.6: Plant composition (%) before and after wood harvesting, using different harvesting regimes

Species	Control	Winter thinning		Summer thinning		Gradual thinning		Non-selective harvesting	
		2018	2021	2018	2021	2018	2021	2018	2021
Protected species									
Albizia anthelmintica	7.0	2	3	3	7	–	–	11	15
Boscia albitrunca	5.0	18	15	3	–	9	75	4	2
Boscia foetida	1.0	–	–	1	2	–	–	1	2
Ziziphus mucronata	–	4	3	–	–	–	–	–	–
Low wood-potential species									
Commiphora spp.	–	2	–	–	–	–	–	1	–
Grewia flavescens	12.0	2	–	6	–	–	–	24	–
Grewia retinervis	4.0	4	13	–	7	–	–	–	15
Grewia flava	13.0	20	26	23	17	12	250	6	17
Catophractes alexandri	–	–	–	–	–	–	–	–	–
Dichrostachys cinerea	21.0	9	5	25	59	5	–	14	44
High wood-potential species									
Senegalia mellifera	25.0	20	18	24	6	51	225	29	2
Vachellia reficiens	9.0	1	18	8	2	18	175	9	2
Vachellia tortilis	1.0	–	–	3	–	–	–	–	2
Vachellia hebeclada	2.0	–	–	5	–	–	–	–	–
Senegalia erubescens	–	2	–	–	–	5	–	–	–
Species richness	**11**	**11**	**8**	**10**	**7**	**6**	**4**	**9**	**9**

The low wood-potential species also remained relatively constant in all treatments, except for the gradual selective thinning plots where there was a substantial increase in *Grewia flava* (Table 7.6).

The increase in low wood-potential species, especially after non-selective wood harvesting, caused a shift from a thickened savanna to shrubland (Table 7.6). These shrubs are aggressive, fast growers and are normally difficult to control in the short term. Control through the removal of these shrubs (low wood-potential species) will have to be selective and a long-term commitment (Smit 2004; 2005). In fact, these low wood-potential species (Table 7.6) are known to be involved in the thickening of savannas (O'Connor *et al.*, 2014), and the control of these species often leads to further increases in these shrubs (Lykke, 1998; Tredennick and Hanan, 2015). Importantly, Eldridge and Soliveres (2015) argue that the effect of shrub removal on ecosystems is strongly scale-, species- and environment-dependent and, therefore, no standardized management can be applied to every case.

There were very few differences in the effect of selective harvesting in terms of both plant densities (plants ha^{-1}) and leaf volume (ETTE ha^{-1}) for the season of harvesting and time after harvesting (Figure 7.3). These results were expected in thinned plots as competition from the remaining undamaged plants reduced the regrowth of saplings and/or coppice. The three-year time period was too short for the remaining woody plants to grow noticeably bigger in size, emphasizing the slow growth rate of these mature plants.

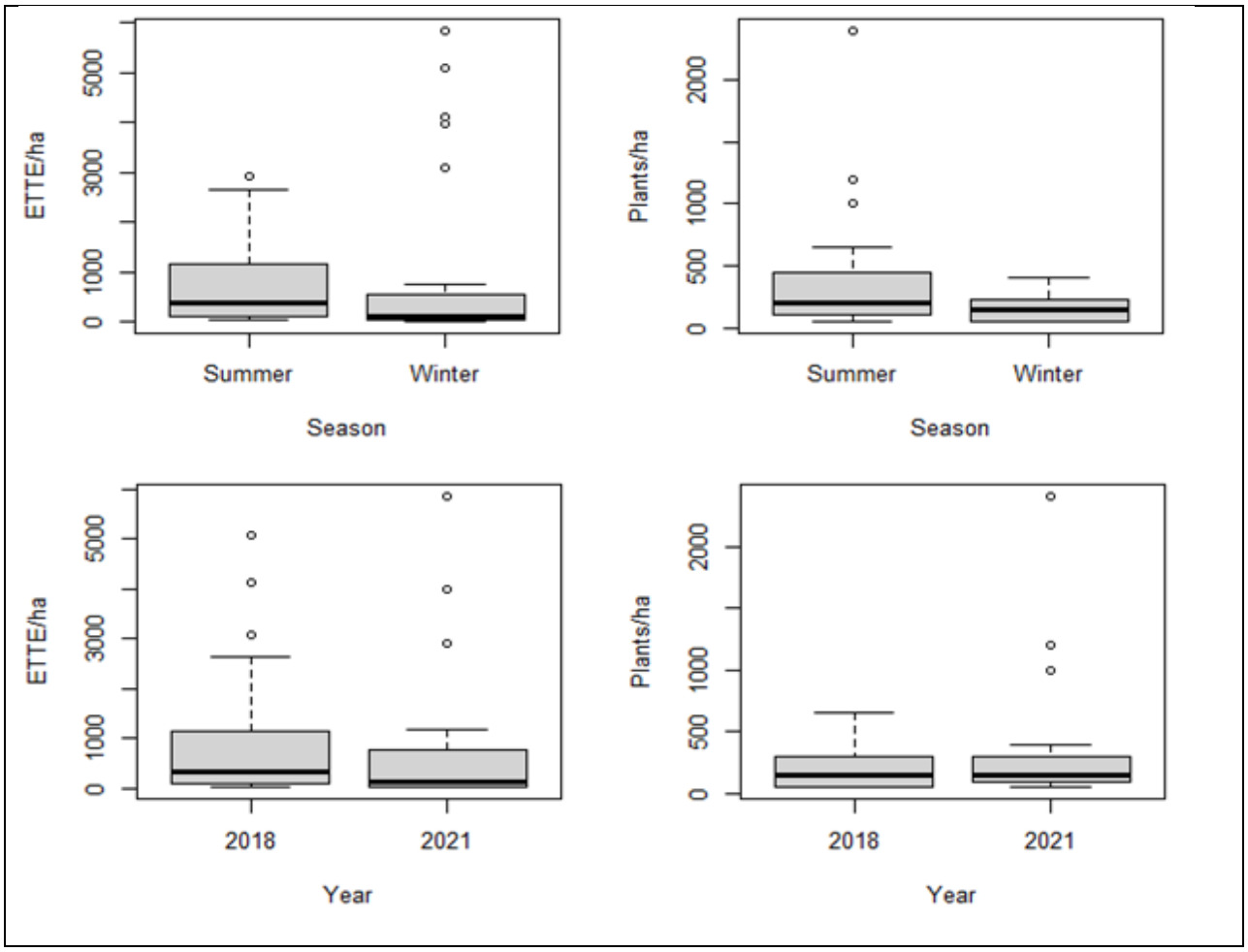


Figure 7.3: Comparison of plant densities (plants ha-1) and leaf biomass (ETTE ha-1) in once-off selectively thinned plots to a predetermined density of 4 500 ETTE ha-1 during winter as opposed to summer as well as before harvesting (2018) compared to 3 years post-harvest (2021)

In order to further analyze the plants and ETTE ha^{-1} measurements presented in Figure 7.3, two GLMs were used for detailed statistical analysis (Tables 7.7 & 7.8). It is clear that there is no significant difference ($P>0.05$) in ETTE ha^{-1} between treatments and years' post-harvesting. However, *S. mellifera* and *V. reficiens*, regardless of treatment, both displayed statistically significant growth increases ($P<0.05$). This growth is assumed to be mainly from undamaged *S. mellifera* and *V. reficiens* plants (Table 7.7). Other species that showed growth after initial selective thinning, although with no statistical significance ($P>0.05$), were *D. cinerea*, *G. flava*, *G. flavescens*, *V. hebeclada*, and *V. tortilis*.

Table 7.7: GLM indicating the difference in ETTE ha^{-1} for the season of thinning, year, and plant species

	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept: (Summer thinning)	13579	240691.6	0.056	0.95528	
Season: Winter thinning	159.996	363.455	0.44	0.6621	
Year	-6.663	119.183	-0.056	0.95569	
Species: *Boscia albitrunca*	-173.498	825.938	-0.21	0.83466	
Species: *Boscia foetida*	-63.002	1071.512	-0.059	0.9534	
Species: *Commiphora* spp.	-279.492	1386.722	-0.202	0.84127	
Species: *Dichrostachys cinerea*	445.927	765.129	0.583	0.56321	
Species: *Grewia flava*	423.875	746.697	0.568	0.57336	
Species: *Grewia flavescens*	28.839	950.32	0.03	0.97594	
Species: *Grewia retinervis*	-101.903	825.806	-0.123	0.90239	
Species: *Senegalia erubescens*	-255.492	1386.722	-0.184	0.85473	
Species: *Senegalia mellifera*	1648.626	748.033	2.204	0.0332	*
Species: *Vachellia hebeclada*	2483.504	1387.088	1.79	0.08077	.
Species: *Vachellia reficiens*	2084.627	749.39	2.782	0.00813	**
Species: *Vachellia tortilis*	302.504	1387.088	0.218	0.82844	
Species: *Ziziphus mucronata*	-225.496	950.64	-0.237	0.81368	

The plots selectively thinned in winter had a significant increase ($P<0.05$) in plant density (plants ha^{-1}), but no statistically significant difference ($P>0.05$) in terms of time (years) after initial harvesting (Table 7.8). *Dichrostachys cinerea* had a significant ($P<0.05$) increase in plant density (plants ha^{-1}) after initial harvesting.

Table 7.8: GLM indicating the difference in plants ha^{-1} for the season of thinning, year, and plant species.

	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept: (Summer thinning)	-56582.67	66437.39	-0.852	0.3993	
Season: Winter thinning	-238.41	100.323	-2.376	0.0222	*
Year	28.151	32.898	0.856	0.3971	
Species: *Boscia albitrunca*	109.968	227.981	0.482	0.6321	
Species: *Boscia foetida*	-194.205	295.766	-0.657	0.5151	
Species: *Commiphora* spp.	61.432	382.773	0.16	0.8733	
Species: *Dichrostachys cinerea*	519.795	211.196	2.461	0.0181	*
Species: *Grewia flava*	225	206.109	1.092	0.2814	
Species: *Grewia flavescens*	-47.508	262.314	-0.181	0.8572	
Species: *Grewia retinervis*	8.505	227.945	0.037	0.9704	
Species: *Senegalia erubescens*	61.432	382.773	0.16	0.8733	
Species: *Senegalia mellifera*	148.057	206.477	0.717	0.4774	
Species: *Vachellia hebeclada*	-26.978	382.874	-0.07	0.9442	
Species: *Vachellia reficiens*	52.858	206.852	0.256	0.7996	
Species: *Vachellia tortilis*	-126.978	382.874	-0.332	0.7418	
Species: *Ziziphus mucronata*	33.281	262.402	0.127	0.8997	

Other species - although with no statistical significance (P>0.05) - that increased in plant density after initial selective thinning were *B. albitrunca, Commiphora* species, *G. flava, G. retinervis, S. erubescens, S. mellifera,* and *V. reficiens.* Species such as *D. cinerea* and *G. flava* had the highest plant densities post-harvest.

The Jaccard similarity specifically indicates the dissimilarity of the gradual thinning plots after harvesting (2021) in relation to the rest of the treatments (Figure 7.4). The summer thinning and non-selective harvesting plots had a high similarity three years after initial harvesting. The winter thinning treatment after harvesting shows similarity to the rest of the treatments before harvesting.

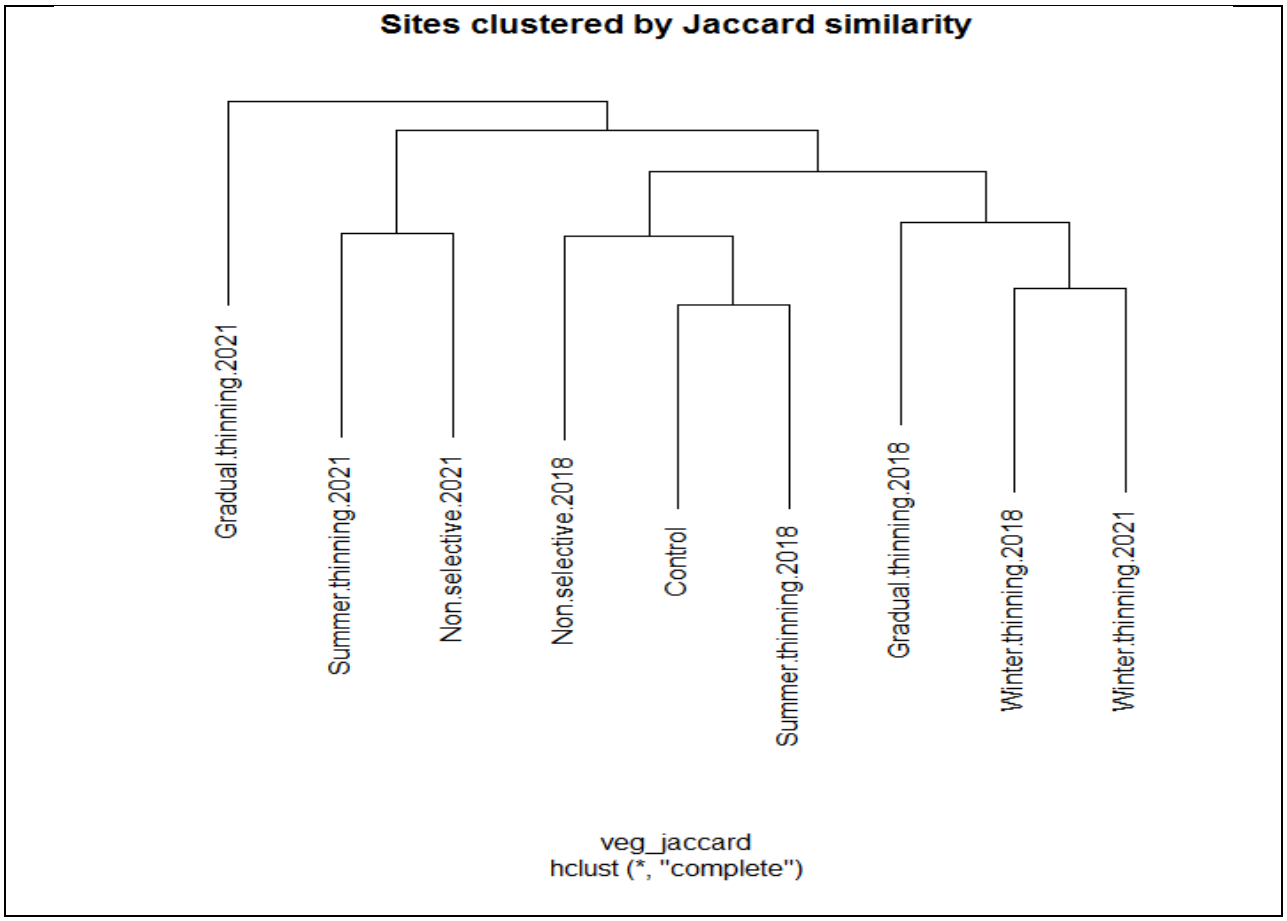


Figure 7.4: Jaccard similarity model showing similarities and differences between the different treatments and years

The dissimilarity of the gradual thinning treatment three years after harvesting was further investigated, using a general linear model (GLM). The GLM specifically indicates a significantly lower (P<0.05) species richness for the gradual thinning treatment three years after initial harvesting (Table 7.9).

Considering the dissimilarity between the treatments, especially the gradually harvested plots at year three after initial harvesting (Figure 7.3), and their significantly lower ($P<0.05$) species richness (Table 7.9), it was deemed necessary to compare the treatments in terms of the species richness and diversity on graphs for better viewing and comparison. Figures 7.5 and 7.6 illustrate the rankings of the different treatments in terms of species richness and diversity respectively.

Table 7.9: GLM showing the effect of treatment and time on the species richness

1. Species richness	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**	
Intercept (Control)	2.48491	0.28868	8.608	<2e-16	***
Treatment: Gradual thinning (2018)	-0.69315	0.5	-1.386	0.1657	
Treatment: Gradual thinning (2021)	-1.38629	0.6455	-2.148	0.0317	*
Treatment: Non-selective (2018)	-0.28768	0.44096	-0.652	0.5141	
Treatment: Non-selective (2021)	-0.28768	0.44096	-0.652	0.5141	
Treatment: Summer thinning (2018)	-0.18232	0.42817	-0.426	0.6702	
Treatment: Summer thinning (2021)	-0.539	0.47559	-1.133	0.2571	
Treatment: Winter thinning (2018)	-0.08701	0.41742	-0.208	0.8349	
Treatment: Winter thinning (2021)	-0.40547	0.45644	-0.888	0.3744	

It is evident that the control, and both winter and summer treatments before harvesting (2018), rank highest in terms of both species richness (Figure 7.5) and diversity (Figure 7.6). It is also important to note that the lost species richness was restored in the non-selective treatments within three years after harvesting (Figure 7.5), but still lagged behind in species diversity (Figure 7.6). The summer thinning treatments had a considerable drop in both species richness and diversity from before harvesting to three years thereafter. However, the winter thinning treatments had a considerable drop in species richness, but not species diversity as such. The gradual thinning treatments started off with lower species richness and diversity, and therefore the drop is acceptable, and the treatment cannot be the reason for these low species counts and index values, at least for this study.

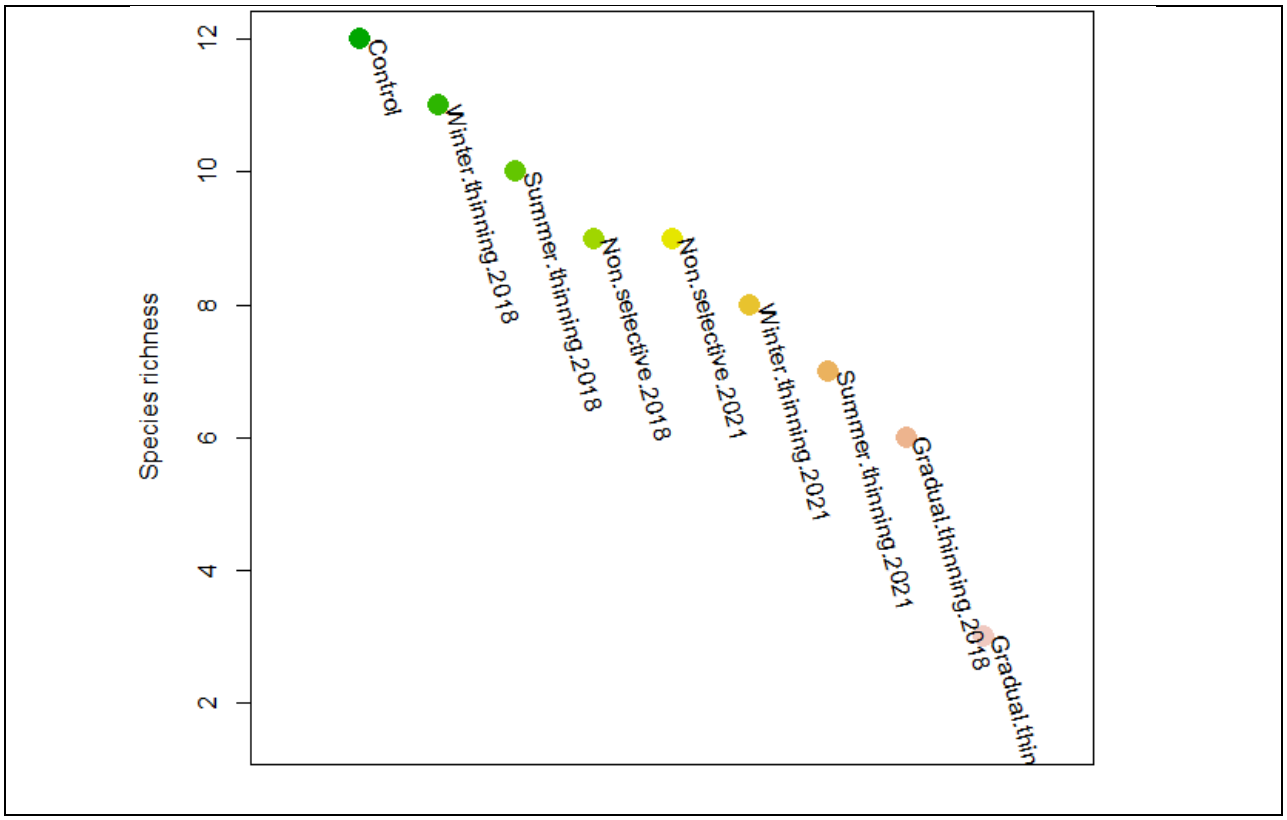


Figure 7.5: Species richness plot, calculated as the total number of species represented in a sample

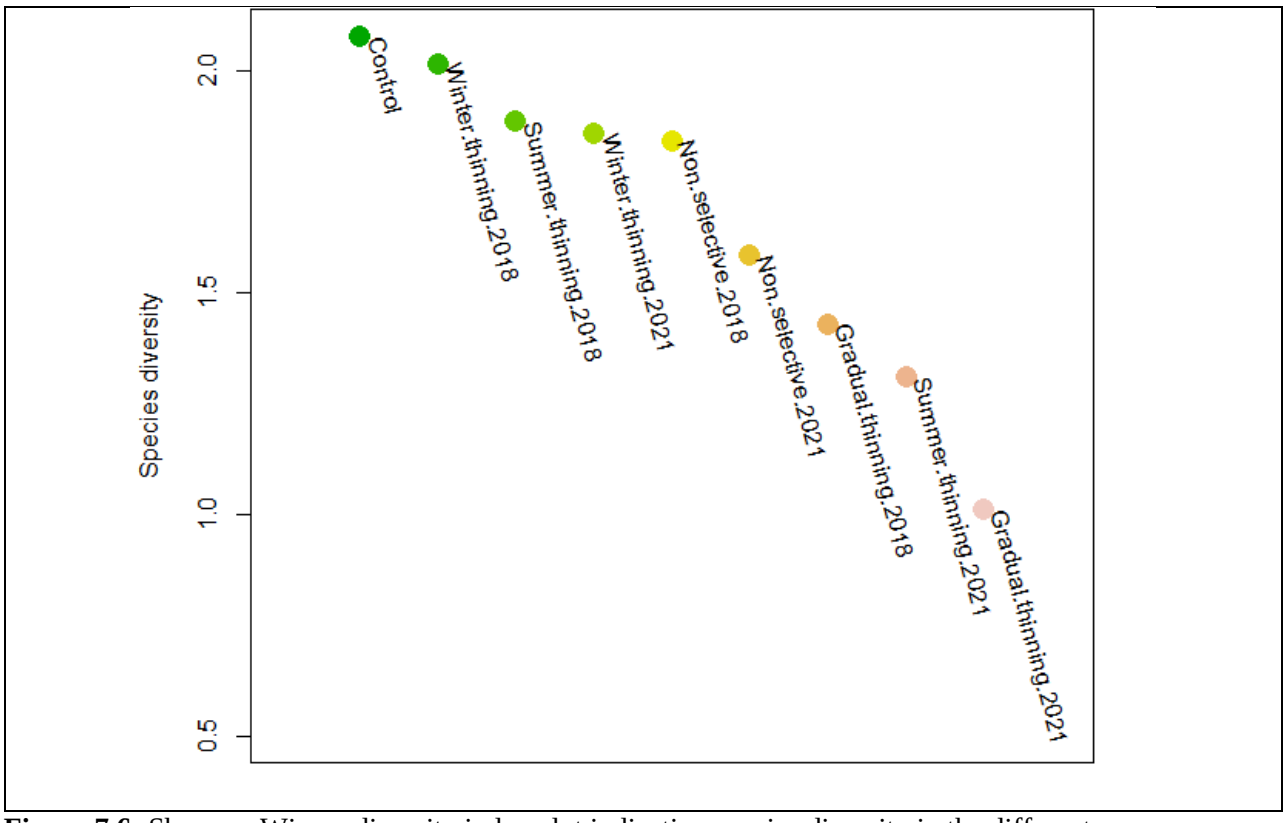


Figure 7.6: Shannon-Wiener diversity index plot indicating species diversity in the different harvesting treatments

The species diversity and richness of the control plots is a representation of species of all treatments before harvesting (2018) plus the control plots, hence the high values. The equal species richness (Figure 7.5) and difference in diversity (Figure 7.6) before and after harvesting in the non-selectively harvested plots are due to the fact that most species regrew after harvesting, but at different densities. In this regard the shift in dominance from high to low wood-potential species is noteworthy (Tables 7.6 and 7.8)

The harvesting process (see Section 7.2.5), especially for the thinning treatments (once-off and gradual thinning), contributed to the differences in both species richness and diversity (Figures 7.5 and 7.6). During this harvesting process, all the low wood-potential species were first removed, followed by a few high wood-potential species, in order to achieve the pre-determined thinning density. This caused the complete removal of some species, leaving other species basically untouched. Moreover, the undamaged plants of these untouched species exert strong competition on the cut plant species, limiting their coppicing ability and seedling establishment. This process was even up-scaled in the gradual thinning treatment plots as these low wood-potential species were repeatedly harvested.

7.4. Conclusion

From a practical land management point of view, the results of this study suggest that tree thinning is a more viable option for rangeland restoration as opposed to tree clearing.

It is evident that gradual selective thinning over time reduced plant species richness and diversity because of the continuous harvesting that prioritized small shrub species during the thinning process. These shrub species have good coppicing abilities and are fast growers, making them eligible for harvesting on a yearly basis. The yearly harvesting of these shrub species resulted in the depletion of reserves, causing them to die-off, creating a more stable rangeland with a competitive mature woody plant layer.

The gradual selective thinning treatment had two trade-offs; (a) lack of woody species diversity and richness with increased foliage production and (b) slower wood generation, but a more stable and resilient ecosystem with a reduced risk of re-thickening in the short term.

CHAPTER 8: GROWTH RATES OF *Senegalia mellifera* AND *Vachellia reficiens* IN A BUSH-THICKENED ENVIRONMENT

8.1. Introduction

Most Namibian woody plants, especially the *Senegalia* and *Vachellia* genera belonging to the Fabaceae family, are winter deciduous (Curtis and Mannheimer, 2005). According to de Bie *et al.* (1998), this shedding of leaves in the dry months is a strategy to avoid drought stress. Another strategy is to avoid drought stress through scleromorphic features and the use of water from deeper soil layers and river beds (de Bie *et al.,* 1998). Scleromorphic plants evolved in arid areas and are able to survive with limited resources.

Seasonality of rainfall strongly influences plant growth in African savannas and, therefore, plant species must be well adapted to survive in this habitat (de Bie *et al.,* 1998; Gaugris *et al*., 2007; Sebata, 2017). Most woody plant recruitment (seed production, seed germination and sapling establishment) therefore takes place in above-average rainfall years (Joubert *et al.,* 2008; 2013). There is usually an increase in woody plants with an increase in annual rainfall (Gordijn *et al.,* 2012). Joubert *et al.* (2013) argue that areas receiving 300 mm and above are most prone to woody plant thickening in Namibia. Joubert *et al.* (2017) further argue that heavily thickened areas in the Thornbush Savanna are typically found in the >400 mm annual rainfall zones and are characterized by having deeper soils. Cunningham and Detering (2017) also reported that coppice from cut woody plants survives better in deep soils with lower clay contents. This finding is supported by Sebata (2017), who reported that sandy soils tend to favour woody over herbaceous plants.

Bush thickening caused by the *Senegalia* and *Vachellia* genera is a slow process, and according to Joubert *et al.* (2017), the preventative measures for these genera are much easier than previously thought. There are recorded increases of 25-50% in bush density of the *Senegalia* and *Vachellia* genera over a 50-year period (Joubert 2014). These plants are also growing much slower than anticipated, contrary to popular perceptions (Joubert *et al.,* 2017). The recorded growth rates of *S. mellifera* in Namibia varied between 2.34 and 3.7 cm annum^{-1} in shoot length for mature plants (Joubert *et al.*, 2017). Cunningham and Detering (2017) recorded growth in shoot diameter of 2.78–3.79 mm annum^{-1}. It should be noted that the results from Joubert *et al.* (2017) were recorded from mature plants while those of Cunningham and Detering (2017) were recorded on coppice regrowth.

There is also little known about the mortality of mature plants in bush-thickened savannas. Joubert *et al.* (2017) found surprisingly high mortality rates for *S. mellifera* (61.3%) over a time span of 35 years and argued that, along with self-thinning, drought stress and fungal die-back may have contributed largely.

Given the prevalence of bush thickening and the fact that *S. mellifera* and *V. reficiens* are the most common bush thickening species in historically non-harvested areas of the Thornbush Savanna, a study was carried out to determine the mortality and growth rates of these species under bush thickening conditions.

8.2. Procedure

8.2.1. Study area

The study was conducted on the farm Arcadia, located northwest of Otjiwarongo in an area described as the North-Central Plateau of Namibia, where the vegetation is classified as Thornbush Savanna (Giess, 1998). A detailed description of the study area is presented in Chapter 3.

8.2.2. Site selection and trial layout

The study was conducted on plots of 50 x 30 m (1 500 m^2), located in a homogeneous, densely wooded area on the farm Arcadia. Detailed information on the determination of plot sizes and target species is presented in Chapter 4, Section 4.2.2.

8.2.3. Treatments and data collection

The four control plots used for the larger study were used for the determination of mortality and growth rates of undisturbed *S. mellifera* and *V. reficiens* plants (See Chapter 1). Ten plants of each species were marked in each plot and four branches per plant were marked permanently with a plastic "cable tie" for shoot diameter and length measurements. The marking of plants for repeated measurements on the same plants provides a better measure of plant growth over time (Swemmer and Ward, 2020)

The number and size class of *S. mellifera* and *V. reficiens* plants that were monitored, and the use of the BECVOL-3 model for measurements on these individually marked plants are discussed in detail in Chapter 4, Sections 4.2.3 & 4.2.4.

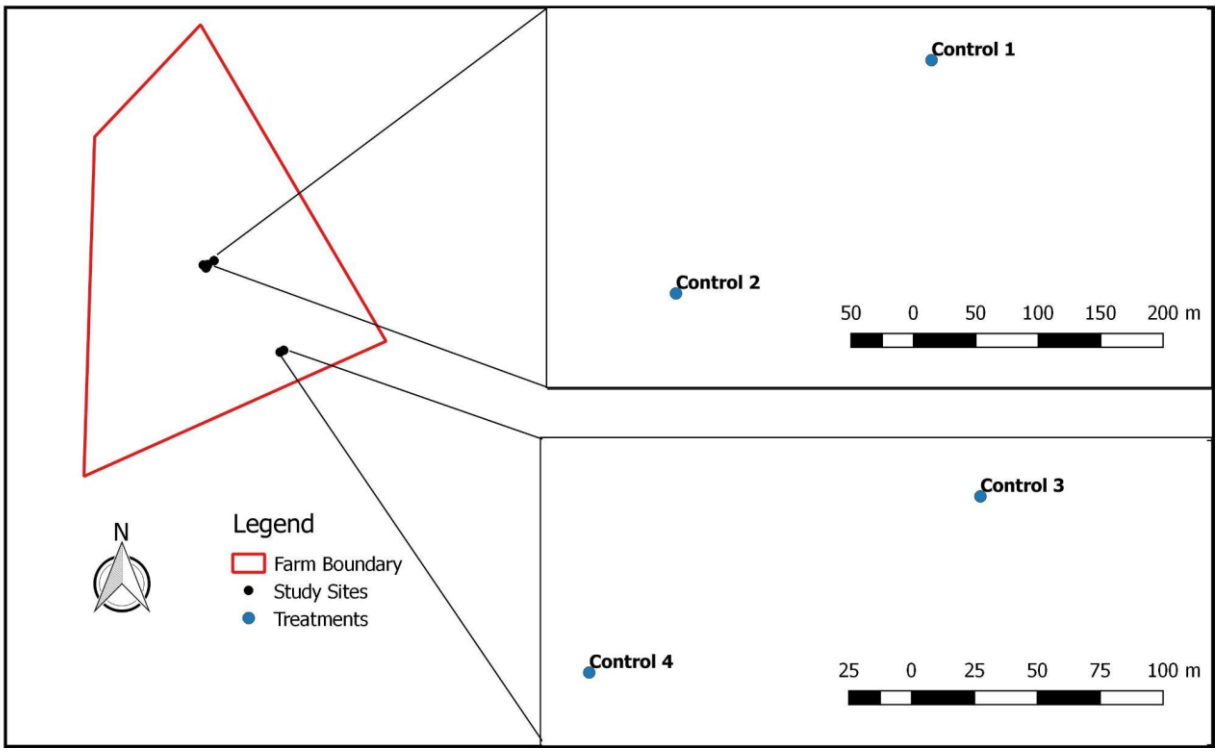


Figure 8.1: Trial layout on Farm Arcadia, illustrating the control plots in which the mortality and growth rates of *Senegalia mellifera* and *Vachellia reficiens* were measured

At the start of this research trial, four branches per marked plant were marked again with "cable ties" and the shoot length was measured with a measuring tape from the point where the cable tie was attached to the tip of the shoot. The shoot diameter was also measured with an accurate caliper at the point where the cable tie was attached. The first measurement was recorded in 2018 and growth measurements (shoot length and diameter) were recorded in 2019 and 2020. The individual plants were also measured as per the BECVOL-3 procedure (Smit, 2014) to obtain measurements such as tree height and canopy diameter, which were used for analysis in this study. The BECVOL-3 measurements are too coarse for the determination of seasonal growth of woody plants, especially only for two seasons, hence the more accurate measurements on marked tree branches.

6.2.4. Data analysis

A generalized linear model (GLM) was used for the modeling task to investigate the impacts of different variables on mortality and growth (Venables and Ripley, 2002). The mortality and growth rates were used as the response variables, whereas the explanatory variables were species, year, tree height, canopy diameter, distance to nearest neighbour and species of nearest neighbour.

A binary GLM was also used to investigate the effect of the different explanatory variables on the mortality of *Senegalia mellifera* and *Vachellia reficiens*. For each woody species, the response variable was coded as 1 where the plant remained alive (alive) and 0 if the plant died (dead) during the study period. The explanatory variables used for mortality analysis were species and year (time it takes for a plant to die). Other explanatory variables incorporated to determine reaction towards coppice were tree height, canopy diameter, distance to nearest neighbour and species of nearest neighbour.

Model fit was examined graphically by evaluating the trends and homoscedasticity of the Pearson residuals, and non-constant residual variance was modeled by updating initial models with a weighted variable (Mehtatalo and Kansanen, 2020).

The tree height and canopy diameter measurements were obtained from the BECVOL-3 data collection procedure (Chapter 4, Section 4.2). All the descriptive statistics, such as graphs and tables, were generated using Microsoft Excel (Microsoft, 2010).

8.3. Results and Discussion

8.3.1. Mortality

The mortality of *Senegalia mellifera* and *Vachellia reficiens* was surprisingly high, considering the time frame of just two years (Table 8.1). *Senegalia mellifera* had a higher mortality rate than *V. reficiens* at the end of the two year study period.

Table 8.1: Mortality rates (%) of *Senegalia mellifera* and *Vachellia reficiens* over a two year period, coupled with rainfall

Species	n	Mortality (%)		
		Start 2018	**Year 1 2019**	**Year 2 2020**
Senegalia mellifera	40	-	7.5	17.5
Vachellia reficiens	40	-	10	10
Annual rainfall (mm)		218	475	483
Standard deviation		(± 22.8)	(± 63.44)	(±65.0)

However, statistically, there was no significant difference ($P>0.05$) in mortality between the two species (Table 8.2). The year and distance to the nearest plant did contribute significantly ($P<0.001$) to the mortality of the two woody plant species. Nearest neighbour plant species did not have any statistically significant influence ($P>0.05$) on the mortality of the two woody plant

species. The tree height and canopy diameter of the monitored plant species also did not have any statistically significant influence (P>0.05) on the mortality of these two species (Table 8.2).

Joubert *et al.* (2017) reported woody plant mortalities ranging from 1.5 to 2.8 % per annum between 1972 and 2007 in the semi-arid highland savanna of Namibia. There were years of below average rainfall during the study of Joubert *et al.* (2017) and therefore the authors argue that the protracted periods of below average rainfall are likely to have been the major cause of mortality.

Table 8.2: GLM showing the effect of year, tree height, canopy diameter, distance to nearest plant/neighbour, and nearest neighbour/plant species on the mortality rates of *Senegalia mellifera* and *Vachellia reficiens*

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept: (*Senegalia mellifera*)	1.40E+02	3.99E+01	3.512	0.000537	***
Species: *Vachellia reficiens*	3.81E-02	3.57E-02	1.066	0.287473	
Year	-6.88E-02	1.97E-02	-3.484	0.000595	***
Tree height	-3.17E-02	2.53E-02	-1.254	0.211077	
Canopy diameter	-1.20E-02	1.98E-02	-0.607	0.544322	
Distance to nearest plant	-2.68E-04	8.03E-05	-3.34	0.00098	***
Neighbor: *Boscia albitrunca*	-1.39E-01	1.62E-01	-0.858	0.391588	
Neighbor: *Boscia foetida*	1.25E-02	1.79E-01	0.07	0.944463	
Neighbor: *Catophractes alexandri*	4.26E-02	1.57E-01	0.272	0.785787	
Neighbor: *Dichrostachys cinerea*	-8.47E-02	1.56E-01	-0.544	0.586681	
Neighbor: *Grewia flava*	-1.59E-02	1.52E-01	-0.104	0.917201	
Neighbor: *Grewia flavescens*	-8.13E-02	1.51E-01	-0.539	0.59025	
Neighbor: *Grewia retinervis*	4.18E-02	1.64E-01	0.256	0.798519	
Neighbor: *Senegalia mellifera*	-8.00E-02	1.52E-01	-0.527	0.598541	
Neighbor: *Vachellia reficiens*	1.68E-02	1.69E-01	0.099	0.920968	

This study was conducted under above average rainfall years and therefore the much higher plant mortalities reported by Joubert *et al.* (2017) may be as a result of competition in the thickened environment.

Considering that tree height and canopy diameter of the monitored plants did not have a statistically significant influence (P>0.05) on the mortality of the same plant species (Table 8.2), further descriptive analyses were done on the species composition, plant densities and size classes of all plants in the plots where these monitored species occurred. *Senegalia mellifera* had higher plant densities as compared to *V. reficiens* (Table 8.3). More importantly, *S. mellifera* was represented by large mature plants (see plant height and canopy diameter) as compared to *V. reficiens*, with much younger plants.

Table 8.3: Summary of plant densities and size classes of all plant species in the specific plots where mortality of *Senegalia mellifera* and *Vachellia reficiens* was monitored. Highlighted are the species of interest

Species	Plants ha^{-1}	ETTE ha^{-1}	Average plant height	Maximum plant height	Average plant canopy diameter
Albizia anthelmintica	50	191	1.63	2.13	1.01
Boscia albitrunca	50	67	0.83	1.08	0.61
Boscia foetida	38	8	0.73	0.73	0.41
Catophractes alexandri	125	113	0.89	1.08	0.48
Commiphora spp.	38	11	0.49	0.50	0.35
Dicrostachys cinerea	188	72	0.76	0.93	0.58
Grewia flava	575	1 442	1.46	1.75	1.12
Grewia flavescens	25	86	0.58	0.65	0.50
Grewia retinervis	113	161	0.25	0.28	0.35
Senegalia mellifera	263	2 483	3.01	4.08	2.93
Vachellia hebeclada	13	334	1.13	1.13	1.41
Vachellia reficiens	150	1 221	1.93	2.40	2.21
Vachellia tortilis	25	67	0.75	0.88	0.31
TOTAL	**1650**	**6253**			

The data in Table 8.3 clearly illustrate that most of the vegetation structure is mature plants (high ETTE ha^{-1} and low plants ha^{-1}) except for *Boscia foetida*, *Catophractes alexandri*, *Commiphora* species, and *Dichrostachys cinerea*. This means that the mature *S. mellifera* plants were under competitive stress from many other mature plants. According to Joubert *et al*., (2017), plants ranging from 1 to 2 m in height are about ten years old. Cunningham and Detering (2017) also reported that *S. mellifera* and *V. reficiens* woody plants commonly harvested for charcoal production (base stem diameter <18 cm) are usually in the age range of 25.5 to 32.5 years. From practical experience, plants higher than 4 m usually have stem diameters greater than 18 cm and are not to be harvested as per the Namibian forestry regulations (Forest Act 12, 2001). Based on plant size (Table 8.3) and field observations, these plants were not close to their natural senescence, and therefore, as also earlier discussed, competition for limited resources such as soil water may have caused the mortalities. Joubert *et al.* (2017) also described some causes of woody plant mortalities as self-thinning, fungal die-back and drought stress.

Although not seriously thickened, some degree of thickening was determined in the plots as per the generally accepted "rule of thumb" (Dye and Spear, 1982; Richter *et al.*, 2001; Smit, 2005). This concept, which determines whether an area is bush thickened, is discussed in Chapter 7,

Section 7.2.4. This general "rule of thumb" is based on ETTE ha^{-1} (Tables 8.3 and 8.4) and long-term average annual rainfall (see Chapter 3, Section 3.2).

8.3.2. Growth rates

The growth rates for *Senegalia mellifera* and *Vachellia reficiens* were very low, ranging from 0.02 - 0.06 cm $annum^{-1}$ and 2.85 - 8.19 cm $annum^{-1}$ for shoot diameter and length respectively, (Table 8.4).

Although the growth rates for *S. mellifera* and *V. reficiens* were quite variable for both shoot diameter and length, *V. reficiens* had on average a faster growth rate than *S. mellifera.* The better growth rate of *V. reficiens* as opposed to *S. mellifera* may be due to the fact that the *V. reficiens* plants were younger than the *S. mellifera* plants, with better growth vigour (Table 8.3).

It is also clearly noticeable that the plants had better growth rates in the plots with lower total plant densities (Table 8.4). The higher growth rate may be due to less competition. This observation may not always be the case as Prior *et al*. (2006) found that the density of the woody community reduced the growth of younger plants, but not adults, for some species, while the reverse pattern was found for other species.

Apart from specific growth rates for the two species in relation to plant densities, further analyses were carried out to graphically compare growth rate (shoot diameter and length) over time (years) and for each species.

Table 8.4: Growth of *Senegalia mellifera* and *Vachellia reficiens* in relation to total plant density measured in four different plots

Plot	Species	Plant density on plot ETTE ha^{-1}	Plant density on plot Plants ha^{-1}	Growth in shoot diameter (cm)	Growth in shoot length (cm)	Percentage change in shoot diameter	Percentage change in shoot length
Control 1	*Senegalia mellifera*			0.04	3.81	10.50	14.57
	Vachellia reficiens	8407	2250	0.05	2.87	12.83	7.11
			AVERAGE	**0.05**	**3.34**	**11.66**	**10.84**
Control 2	*Senegalia mellifera*			0.04	2.85	9.10	7.25
	Vachellia reficiens	7810	1800	0.06	7.35	16.00	20.56
			AVERAGE	**0.05**	**5.10**	**12.55**	**13.90**
Control 3	*Senegalia mellifera*			0.04	2.84	6.75	7.93
	Vachellia reficiens	4178	1400	0.02	4.02	2.81	9.74
			AVERAGE	**0.03**	**3.43**	**4.78**	**8.83**
Control 4	*Senegalia mellifera*			0.03	3.74	5.29	10.38
	Vachellia reficiens	4620	1150	0.05	8.19	14.84	23.39
			AVERAGE	**0.04**	**5.96**	**10.07**	**16.88**

It was, however, clear that shoot length increased more consistently over the years as compared to shoot diameter (Figures 8.2 and 8.3). *Vachellia reficiens* had a higher growth rate for shoot length as compared to *S. mellifera* (Figure 8.3). Neither species showed consistent growth in shoot diameter. Figures 8.2 and 8.3 illustrate visible growth in shoot length, but not necessarily in shoot diameter.

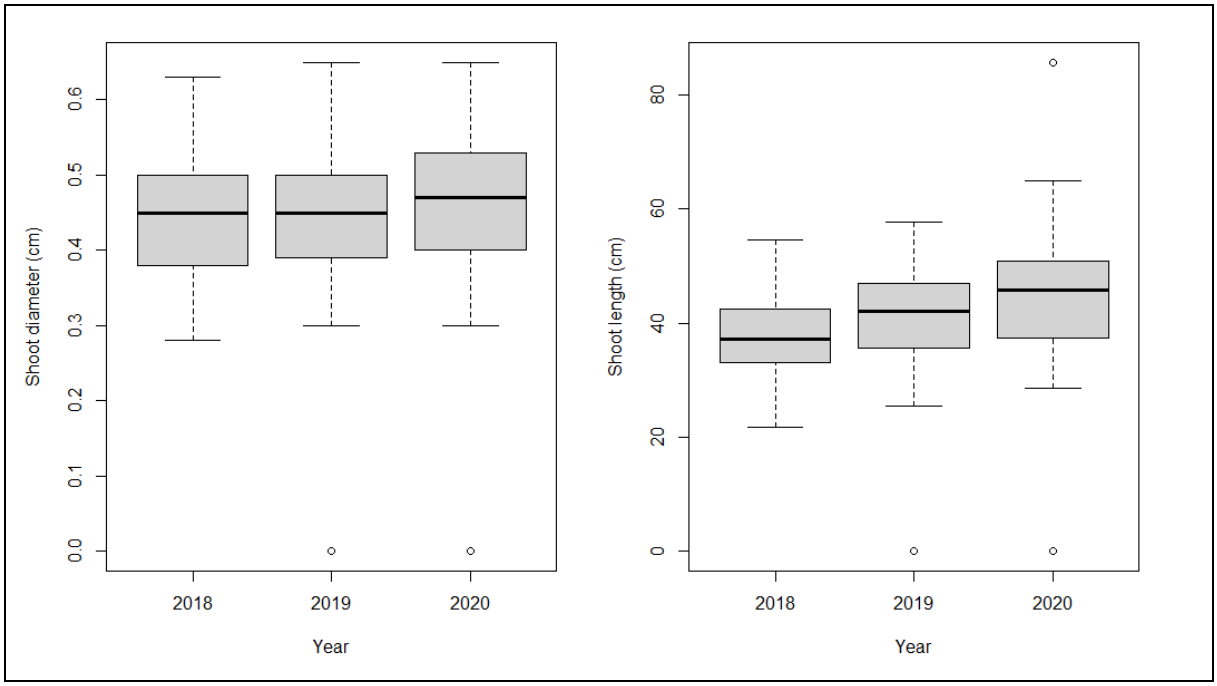


Figure 8.2: Comparison of the increase in shoot length and diameter for both *Senegalia mellifera* and *Vachellia reficiens* together, over time

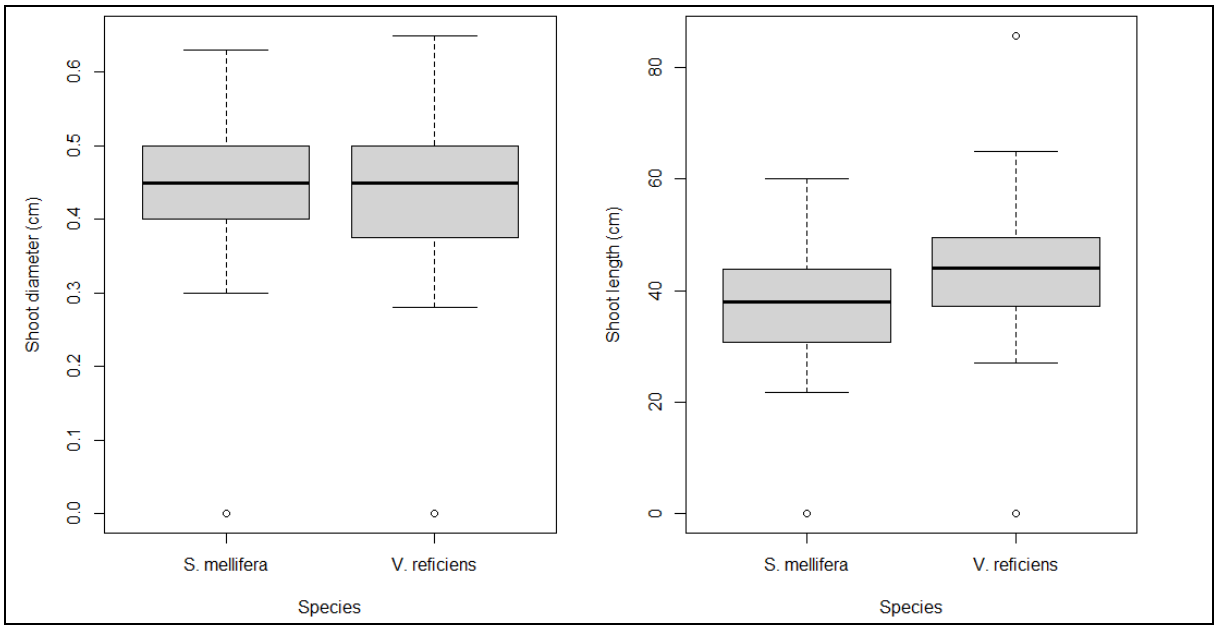


Figure 8.3: Comparison of the increase in shoot length and diameter for *Senegalia mellifera* and *Vachellia reficiens*

The general increase in shoot diameter and length per species and over time was further subjected to statistical analysis by means of a General Linear Model (GLM). The GLM indicated no statistical difference (P>0.05) in shoot diameter growth between the different species and over time (Table 8.5). However, in the case of *V. reficiens,* the GLM indicated a significantly higher (P<0.01) growth rate in shoot length only, compared to *S. mellifera*. This statistical significance supports the findings in Table 8.4 and Figure 8.3.

Table 8.5: GLM showing the difference in growth of shoot diameter and length for *Senegalia mellifera* and *Vachellia reficiens* over a year

1. Shoot diameter	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept: (*Senegalia mellifera*)	2.04E+01	2.21E+01	0.925	0.3558	
Species: *Vachellia reficiens*	1.17E-03	1.85E-02	0.063	0.9497	
Year	-9.88E-03	1.09E-02	-0.903	0.3673	
2. Shoot length					
Intercept: (*Senegalia mellifera*)	-3.01E+03	2.08E+03	-1.448	0.14906	
Species: *Vachellia reficiens*	5.76E+00	1.74E+00	3.312	0.00107	**
Year	1.51E+00	1.03E+00	1.467	0.14367	

Growth rate studies are limited in Namibia and focuson basal stem diameter measurements whereby the plant's age was also determined (Cunningham and Detering, 2017) and tree height as a measure of plant growth (Joubert *et al.,* 2017). Generally, plant height measurements are not the best indicator of biomass growth (Hasen-Yusuf *et al.,* 2013). However, in the study of Joubert *et al.* (2017), the continued use of plant height was necessary for comparisons to earlier collected data. Nevertheless, if tree measurements are taken over a long time period, then conclusive results can be obtained. The growth rates reported by Joubert *et al.* (2017), ranging from 2.19 to 3.78 cm per annum over the long term, are in line with the more accurate measurements of shoot length ranging from 2.84 to 3.74 cm per annum for *S. mellifera* (Table 8.4) under above average rainfall conditions. The annual rainfall for the two seasons of this study was 475 mm (sd ±63.44) and 483 mm (sd ±65.0), where the long-term average is 450 mm (CV=15.14%) (see Chapter 3, Section 3.2). *Vachellia reficiens* had significantly higher shoot length growth rates (Table 8.5), varying from 2.87 to 8.19 cm per annum (Table 8.4) than *S. mellifera*.

8.4. Conclusion

Although limited literature is available on woody plant growth rates, the general conclusion is that woody plants, especially those belonging to the *Senegalia* and *Vachellia* species, are slow growers and not as invasive as generally perceived by researchers and rangeland managers.

The significantly higher growth rate, measured as shoot length as opposed to shoot diameter, was expected since the outer, peripheral branches usually concentrate on leaf and shoot growth to compensate for browsing by animals. Stem diameter growth is expected to be higher with the inner, thicker, wood-producing stems.

This study clearly shows that woody plants are continuously dying off and are replaced by others, hence the fact that a bush thickened environment continues to stay thickened. Mortalities are higher in bush thickened environments as opposed to more open savannas. It may seem that, with no drastic disturbance, mortality and recruitment take place at the same rate with more or less the same species replacing each other.

CHAPTER 9: ALLOMETRIC BIOMASS ESTIMATIONS FOR *Senegalia mellifera* AND *Vachellia reficiens*

9.1. Introduction

Despite the wide use of woody plants for animal feed (bush to feed) and wood value chains that all require an estimate of wood yields of woody plants prior to harvesting, the only viable option for a detailed estimation of the available/usable wood biomass is currently the third version of the Biomass Estimate from Canopy Volume (BECVOL 3) model (Smit, 2014). More recently, an Excel-based biomass quantification tool for the quantification of bush feed and wood - the most commonly used bush resources in Namibia - was developed by Boys and Smit (2020) as an easy to use tool for a more limited estimation of wood yields. Both these models use allometric regression equations developed from harvested woody plants that predict the biomass non-destructively from measurements of the plants.

Regarding the BECVOL 3 model, species for which regression equations were developed include *Vachellia karroo, Combretum apiculatum, Dichrostachys cinerea, Terminalia sericea, Colophospermum mopane* and *Grewia flava.* These species were selected because of their potential value as fodder plants (e.g. *G. flava* and *C. apiculatum*) or their importance as potential encroacher species (e.g. *D. cinerea*) (Smit, 2014). Predictions for other woody species were accommodated by two "general" regression models, viz. one for microphyllous species (*A. karroo* and *D. cinerea* combined) and one for broad-leaved species (*C. apiculatum, T. sericea, C. mopane, G. flava* combined).

Due to the labour-intensive nature of woody plant harvesting, there are still numerous important woody plant species such as *Vachellia reficiens, Vachellia luederitzii,* and *Senegalia mellifera* for which specific regression equations have not yet been developed. While the general regression equations may offer an acceptable compromise, it is expected that species-specific regression equations developed from harvested woody plants will provide definite benefits in terms of the accuracy of the predictions for those species.

The objective of this study was to further expand the more versatile BECVOL-3 model by developing additional allometric regression equations from harvested, undamaged *V. reficiens* and *S. mellifera* plants, relating spatial canopy volume to above-ground leaf and wood biomass.

9.2. Procedure

9.2.1. Trial layout and shrub harvesting

The method used was in accordance with Smit (1989a, 1989b, 2014). Fifteen undamaged plants from each of the species were randomly selected from all size classes typical of a savanna ecosystem. The criterion 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.

The dimensions of each woody plant, as described in the previous section, were measured prior to the plants being felled, and their spatial canopy volume was calculated (cm^3). The measurements were: (i) maximum woody plant height (A); (ii) height where the maximum canopy diameter occurs (B); (iii) height of first leaves or potential leaf-bearing stems (C); (iv) maximum canopy diameter (D); and (v) base diameter of the foliage at the height of the first leaves (E) (Smit,1989a; 2014) (Figure 10.1). After measurement, the selected plants were felled and all the leaves, branches and wood were separated by hand.

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 caliper. The shoots <0.5 cm are considered part of the browse 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 (Smit, 2014) or used for bush feed. The stems >2.0 cm constitute that fraction suitable for use in firewood and charcoal production.

Due to the extensive thorns and small, microphyllous leaves of the harvested *S. mellifera* and *V. reficiens* plants, the leaves and branches could not be hand separated in the field. The branches with the leaves attached were clipped in the field at the different stem diameters, placed into cartons and transported to an oven for pre-drying before separation took place (Figure 9.1). The drying of the plant material took place for about 24 – 48 hours after which the dry leaves could be shaken off the branches for separation. The branches were then further dried (7 – 12 days) at 70°C to a constant mass for dry matter (DM) determination of the different branch diameter size classes. The leaves had to be moistened again for the purpose of measuring leaf volume. This was done by measuring the known volume of water displaced by the leaves in a large measuring cylinder (Figure 9.2).



Figure 9.1: The felling of randomly selected trees for the hand separation of the leaves and branches. Accurate measurements were taken of each tree prior to felling



Figure 9.2: The drying of plant material, separation of leaves and the determination of leaf volume with a measuring cylinder took place in Windhoek in a controlled environment

9.2.2. Statistical analysis

Separate regression models were developed for the undamaged *S. mellifera* and *V. reficiens* plants. Regression analyses were applied, relating the calculated spatial canopy volume (cm^3) as the independent variable, and leaf volume (cm^3), as well as each of the dried shrub fractions (g) (leaves, shoots <0.5 cm, stems >0.5-2 cm and stems >2cm), as dependent variables. Three regression models were tested: linear ($y = a + bx$), exponential ($\ln y = a + bx$) and multiplicative ($y = ax^b$), where y = the estimated leaf volume (cm^3) / dry mass fraction (g), x = spatial canopy volume (cm^3), a = the intercept and b = slope. 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 (Smit 2014). This partial transformation of data did not alter the curvilinearity of the plotted lines nor the r values but was merely used to change the relationship from convex to concave. In this form the data were 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 was largely avoided (Smit 2014).

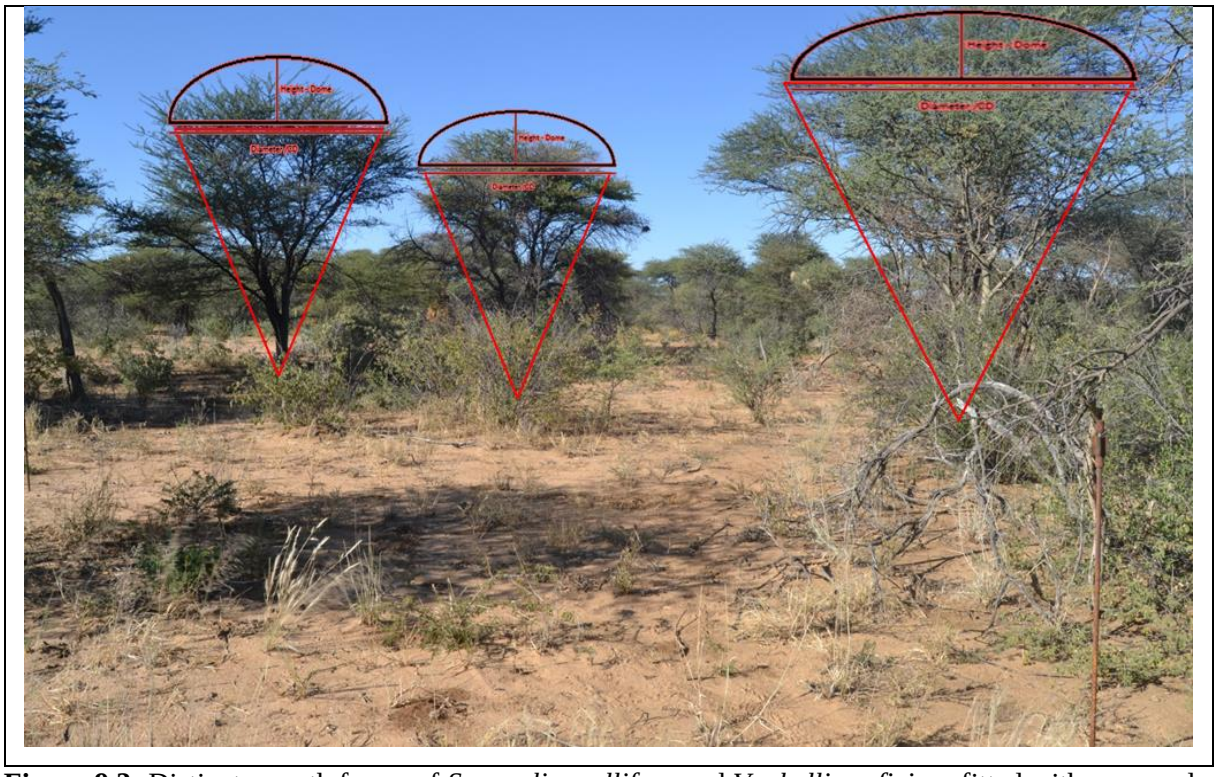


Figure 9.3: Distinct growth forms of *Senegalia mellifera* and *Vachellia reficiens* fitted with cone and dome shapes to calculate spatial canopy volume

Both *S. mellifera* and *V. reficiens* have the distinct growth form of a cone and dome (Figure 9.3) and therefore their spatial canopy volumes were calculated using the formulas of a cone

($V = \pi r^2 (h/3)$) and dome ($V = 1/3 \pi * h^2 (3r - h)$), where V = volume, h = height, and r = radius. The h for the cone = B measurement, whereas the h for the dome = A minus B measurements (see Section 9.2.1).

Evapotranspiration Tree Equivalent (ETTE) as defined by Smit (1989, 2014) as "*the leaf volume equivalent of a 1.5 m single-stemmed woody plant = 500 cm*^{3}" is calculated from leaf volume using the following standardized formula given by Smit (1988a): ETTE = Leaf volume (cm^3) / 500.

Statgraphics software were applied with the different plant dry mass fractions (g) as dependent variables (four categories: leaves, shoots <0.5 cm, stems >0.5–20 cm and stems>20 cm) and the calculated spatial canopy volume (cm^3) as the independent variable. Other descriptive analyses such as tableswere performed using MS Excel (Microsoft Offce, 2010).

9.3. Results and Discussion

Separate regression models were developed for harvested, undamaged *S. mellifera* and *V. reficiens*. The results of the regression analyses of *S. mellifera* and *V. reficiens* are presented in Tables 9.1 & 9.2. From the results, it was clear that regardless of regression model used, all yielded highly significant ($P<0.001$) results. However, in most cases, the exponential model yielded the highest coefficient of determination for *S. mellifera* and *V. reficiens*. The trend towards higher coefficients of determination for curvilinear (exponential and multiplicative) regression models compared to the linear model was also noted by Smit (2014). Similar results were found by Stehn (2020) for *Tarchonanthus camphoratus*, and Smit (1989a; 1989b; 2014) for *V. karroo*, *Combretum apiculatum*, *Dichrostachys cinerea*, *Terminalia sericea*, *Colophospermum mopane* and *Grewia flava*.

Increasing shrub size and canopy volume had an inverse relationship with leaf mass (Table 9.3), and plants had fewer leaves and shoots per unit of canopy volume. Larger stems (>2.0 cm) occupy more space in the canopy centre, giving the woody plant its characteristic structure (Van der Meulen & Werger, 1984; Bartelink, 1997; Ansley *et al.*, 2012). As also argued by Stehn (2020), the choice of regression model selected for this study depended on the required accuracy, preference, convenience and simplicity of use.

A good correlation ($r = 0.8599$) was found between spatial canopy volume and leaf volume (Figures 9.4 and 9.5) and therefore the spatial canopy volume, obtained by transforming the spatial canopy volumes to their normal logarithmic values - which is easy to determine from

field measurements - can be used to estimate the leaf volume - which is much harder to determine. The estimated leaf volume calculated from spatial canopy volume can then be used to calculate evapotranspiration tree equivalents (ETTE) (see Section 9.2.2). Not only can the developed regression equations now be used to calculate the dry mass of leaves and wood components for *S. mellifera* and *V. reficiens* plants but, by applying partial volumes as described in Smit (1989b), browse at different height strata as well as detailed information can be obtained from the BECVOL 3 model with the required measurements of the tree canopies.

Table 9.1: 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 (dependent variables) of *Senegalia mellifera* plants: 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	15	0.72	0.53	<0.01	363.313	371.458	0.000255	6.7E-06
	Exponential		0.92	0.85	<0.001	-3.29206	2.26862	0.686241	0.080955
	Multiplicative		0.92	0.85	<0.001	-18.7356*	3.00773	9.55351	1.13052
Leaf dry mass (g)	Linear	15	0.72	0.53	<0.01	188.433	192.829	0.000132	3.49E-05
	Exponential		0.92	0.85	<0.001	-3.85722	1.16812	0.686916	0.08092
	Multiplicative		0.92	0.85	<0.001	-19.4179*	3.00592	9.56322	1.12984
Shoot dry mass (shoots <0.5 cm in diameter) (g)	Linear	15	0.73	0.54	<0.01	290.47	554.683	0.000396	0.000101
	Exponential		0.93	0.87	<0.001	-4.83522	1.27674	0.811917	0.084444
	Multiplicative		0.93	0.87	<0.001	-23.3426*	3.20454	11.3468	1.2045
Stem dry mass (stems >0.5-2.0 cm in diameter) (g)	Linear	15	0.91	0.84	<0.001	-215.971	871.168	0.001296	0.000158
	Exponential		0.91	0.82	<0.001	-6.02637	1.74988	0.945276	0.121221
	Multiplicative		0.9	0.81	<0.001	-27.1333*	4.68034	13.0448	1.7592
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	15	0.85	0.74	<0.001	-1140.22	1352.28	0.001481	0.000245
	Exponential		0.96	0.91	<0.001	-25.1069	2.64945	2.1596	0.183537
	Multiplicative		0.96	0.91	<0.001	-74.1835*	6.69159	30.1242	2.51518
Total wood dry mass (all fractions) (g)	Linear	15	0.9	0.81	<0.001	-1066.01	2358.57	0.003173	0.000428
	Exponential		0.97	0.95	<0.001	-6.72663	1.00438	1.0476	0.069577
	Multiplicative		0.97	0.94	<0.001	-30.2665*	2.80903	14.5126	1.05583

Table 9.2: 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 (dependent variables) of normal *Vachellia reficiens* plants: 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	20	0.72	0.54	<0.01	496.141	458.974	0.000282	0.000072
	Exponential		0.86	0.74	<0.001	-1.44512	1.41321	0.580277	0.096186
	Multiplicative		0.85	0.72	<0.001	-13.9006*	3.59411	7.82462	1.34226
Leaf dry mass (g)	Linear	20	0.73	0.54	<0.01	227.076	210.086	0.000129	0.000033
	Exponential		0.86	0.74	<0.001	-2.21016	1.41306	0.579193	0.096176
	Multiplicative		0.85	0.72	<0.001	-14.6384*	3.59524	7.80848	1.34268
Shoot dry mass (shoots <0.5 cm in diameter) (g)	Linear	20	0.72	0.53	<0.01	413.832	355.984	0.000214	0.000056
	Exponential		0.88	0.77	<0.001	-2.1328	1.34791	0.609686	0.091741
	Multiplicative		0.88	0.77	<0.001	-15.3732*	3.36921	6.57935	1.25827
Stem dry mass (stems >0.5-2.0 cm in diameter) (g)	Linear	20	0.87	0.77	<0.001	-667.829	1315.46	0.001355	0.000207
	Exponential		0.88	0.77	<0.001	-2.1328	1.34791	0.609686	0.091741
	Multiplicative		0.88	0.77	<0.001	-15.3732*	3.36921	8.27859	1.25827
Wood dry mass (wood >2.0 cm in diameter) (g)	Linear	20	0.92	0.85	<0.001	-1641.35	1308.67	0.00178	0.000206
	Exponential		0.91	0.84	<0.001	-23.6986	3.72025	2.06895	0.253206
	Multiplicative		0.9	0.82	<0.001	-67.9249*	9.76077	27.8298	3.64527
Total wood dry mass (all fractions) (g)	Linear	20	0.92	0.84	<0.001	-1896.02	2503.59	0.003351	0.000394
	Exponential		0.95	0.9	<0.001	-6.47669	1.40331	1.02607	0.095512
	Multiplicative		0.93	0.87	<0.001	-28.3191*	3.889	13.7678	1.45239

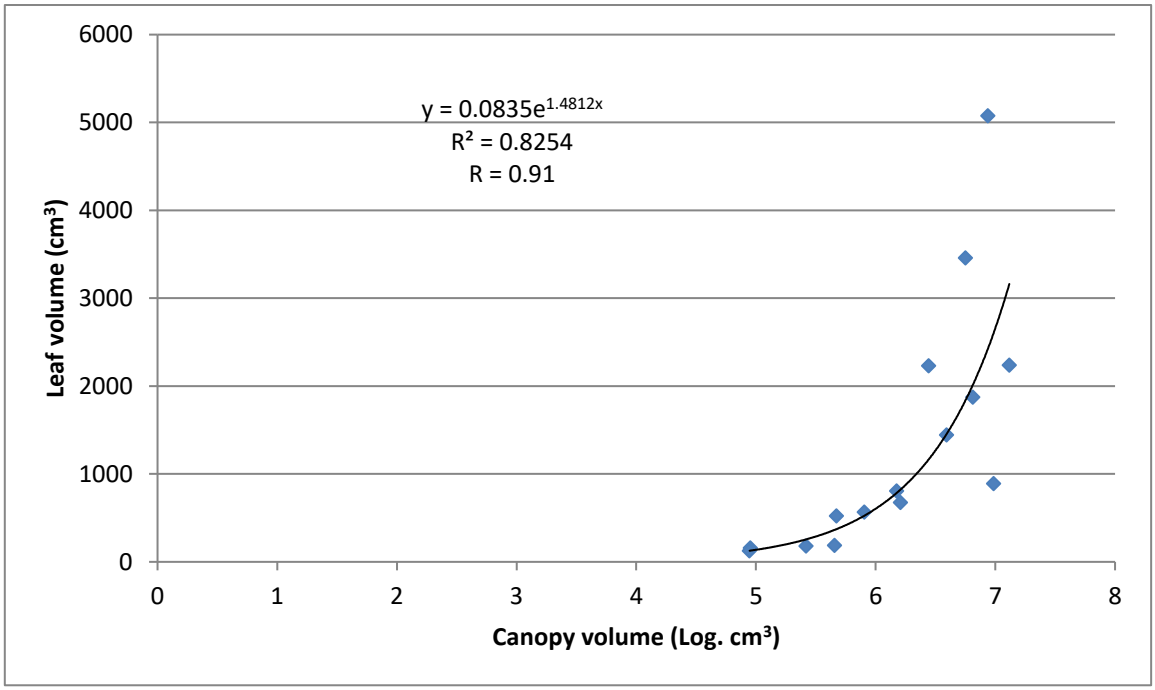


Figure 9.4: The relationship between canopy volume (cm^3) and leaf volume (cm^3) of undamaged *Senegalia mellifera*

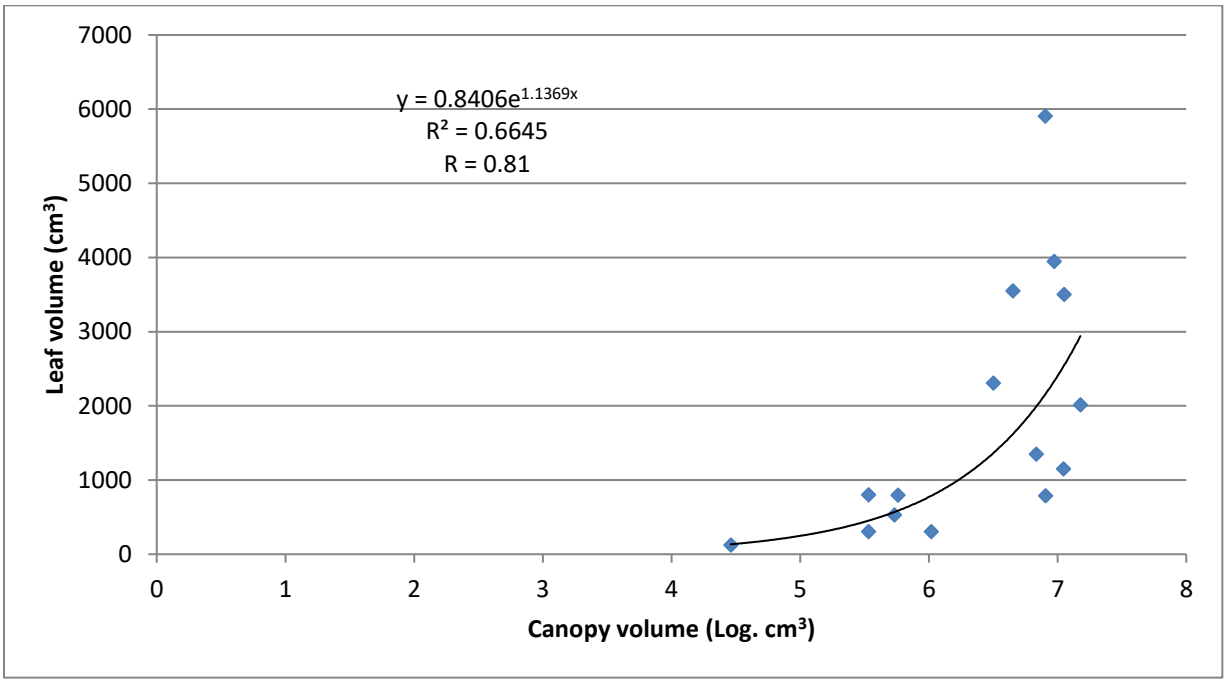


Figure 9.5: The relationship between canopy volume (cm^3) and leaf volume (cm^3) of undamaged *Vachellia reficiens*

Table 9.3: Summary of the average wood and leaf mass dry matter production per plant height and canopy diameter of *Senegalia mellifera* and *Vachellia reficiens* and the percentage that the wood and leaf mass comprised of the total plant biomass

Tree height (m)	n	Wood Mass (g DM/plant)	Leaf mass (g DM/plant)	Wood Mass (%)	Leaf Mass (%)
> 0 - 1	7	574 (±132.0)	188 (±45.2)	75.33	24.67
> 1 - 2	9	3280 (±989.9)	593 (±172.4)	84.69	15.31
> 2 - 3	5	23976 (±6262.3)	1881 (±370.5)	92.73	7.27
> 3 - 4	7	20063 (±4145.9)	983 (±220.1)	95.33	4.67
> 4	2	45171 (±435.0)	922 (±120.7)	98.00	2.00

Canopy Diameter (m)	n	Wood Mass (g DM/plant)	Leaf mass (g DM/plant)	Wood Mass (%)	Leaf Mass (%)
> 0 - 1	3	142 (±63.1)	57 (±7.8)	71.36	28.64
> 1 - 2	9	1254 (±244.9)	251 (±36.3)	83.32	16.68
> 2 - 3	7	7291 (±1692.2)	1100 (±171.5)	86.89	13.11
> 3	11	30000 (±3978.0)	1321 (±248.0)	95.78	4.22

± Denotes SE

9.4. Conclusion

This study has shown that there is a highly significant relationship between the spatial canopy volume and leaf volume, leaf dry mass, shoot dry mass for shoots ≤ 5 mm in diameter, stem dry mass for stems > 5 – 20 mm in diameter and stem dry mass for stems > 20 mm in diameter of undamaged *Senegalia mellifera* and *Vachellia reficiens*. Regression equations with high coefficients of determination have been developed for inclusion in the BECVOL 3 model. The BECVOL 3 model proved to be a handy tool for the accurate description of the woody plant layer in a savanna ecosystem for research purposes, wildlife management and wood biomass estimates, especially for the growing charcoal industry in Namibia. The ability to estimate the aboveground biomass of woody plants accurately is thus essential for the study of savanna structure, productivity, carbon sequestration, and the impact of different land-use practices (Smit, 2014).

CHAPTER 10: THE EFFECT OF DIFFERENT METHODS AND INTENSITIES OF WOOD HARVESTING ON THE HERBACEOUS LAYER

10.1. Introduction

Southern Africa, especially Namibia, has experienced recurrent droughts and increasing air temperatures over the past decades, which tend to favour woody plant growth, especially in areas where livestock numbers were not adjusted towards the reduced utilizable biomass. This general observation is largely supported by Smit *et al.* (1999), Smit (2004) as well as Britz and Ward (2007), who found that grasses are generally more severely affected by droughts compared to woody plants. This has contributed to an unbalanced, yet stable savanna ecosystem that is unlikely to return to its original state, at least in the short-term.

Many savanna areas are water-limited ecosystems and bush thickening is considered a major factor contributing towards the low occurrence or even total absence of herbaceous plants due to severe competition from the woody plants for available soil water (Smit *et al*. 1999). Earlier research showed that increasing tree densities was a sign of veld deterioration as experiments indicated that grass productivity was extremely low at high tree densities, but recovered as trees were removed (Du Toit, 1972, 1986; Teague, 1973). Aucamp *et al.* (1983) then argued that these experiments were done under extreme situations under no bush and severe bush thickened conditions and cannot be conclusive. It was later concluded that the aridity of the area needs to be borne in mind since more woody plants can be retained in wet areas than in dry areas without affecting herbaceous yields (Dye and Spear, 1982; Richter *et al.,* 2001; Smit, 2005). Removing woody plants to a pre-determined density (Dye and Spear, 1982; Richter *et al.,* 2001; Smit, 2005) based on aridity, for rangeland restoration, will increase herbaceous production. Studies by Teague and Smit (1992) and Smit (2004; 2005) indicate that, in time, the competitive ability of the remaining woody plants after thinning will gradually increase and reduce the impact of re-infestation. The concept of bush thinning is discussed in detail in Chapter 7, Section 7.2.4.

It is important to acknowledge that any bush harvesting programmme that also includes restoration of thickened areas as an objective should prioritize selective harvesting rather than total harvesting of all woody plants (Smit, *et al*. 2015). This is however, not always the situation in Namibia and harvesting is not always sustainable as it is financially driven due to the value of wood and wood products such as charcoal and biochar. Bush control measures (chemical and/or mechanical) are expensive and due to re-thickening of woody plants, it is not always effective in solving the problem. Farmers are then faced with severe re-thickening, often with aggressive pioneer woody species and a loss of biodiversity.

There are currently different harvesting practices (mechanical and manual) and intensities (clearing and thinning) of bush commonly practiced in Namibia. The effects of these bush harvesting practices are discussed in Chapters 4 - 8. However, despite claims of increased grass production following tree harvesting, the effects of these harvesting practices on the herbaceous layer are not yet adequately studied. The main objective of this study, therefore, was to provide a short-term assessment of the effects of different harvesting practices on the herbaceous layer. The specific objectives were to determine the effect of:

- Selective and gradual selective bush thinning on the herbaceous species composition and yield,
- Selective versus non-selective bush harvesting on the herbaceous species composition and yield, and
- Coppice control of woody plants on the herbaceous species composition and yield.

10.2. Procedure

10.2.1. Study area

The study was conducted on farms Arcadia and Omatjenne, located northwest of Otjiwarongo in an area described as the North-Central Plateau of Namibia, with vegetation classified as Thornbush Savanna (Giess, 1998). A detailed description of the study area is presented in Chapter 3.

10.2.2. Site selection and trial layout

The different treatments were conducted on plots of 50 x 30 m (1 500 m^2), located in homogeneous, densely wooded areas on the farms. Detailed information on the determination of plot sizes and target species is presented in Chapter 4, Section 4.2.2.

10.2.3. Treatments and trial layout

The treatment trial layout consisted of four 50 x 30 m (1 500 m^2) plots. There were two treatments for each bush control method (Table 10.1). The response of the herbaceous layer to the different wood harvesting methods was then determined (see Section 10.2.4).

Table 10.1: The different bush control methods and different treatments applied. The response of the herbaceous layer was measured under these bush control methods. The concept on bush thinning to a pre-determined density (4 500 ETTE ha^{-1}) is discussed in Chapter 7, Section 7.2.4

Study Objectives/Tested bush control methods	Treatments	Replications	Location/farm where study was conducted
Once-off selective versus gradual selective thinning	Once-off selective thinning to a pre-determined 4 500 ETTE ha^{-1}	2	Omatjenne
	Gradual selective thinning (35% / year over years to a predetermined 4 500 ETTE ha^{-1}	2	
	Control	2	
Selective versus non-selective wood harvesting	Once-off selective thinning to a pre-determined 4 500 ETTE ha^{-1}	2	Arcadia
	Non-selective wood harvesting / Clearing	2	
	Control	2	
Coppice defoliation versus no defoliation	Total annual coppice defoliation of *Senegalia mellifera* and *Vachellia reficiens* only	2	Arcadia
	No coppice defoliation	2	
	Control	2	

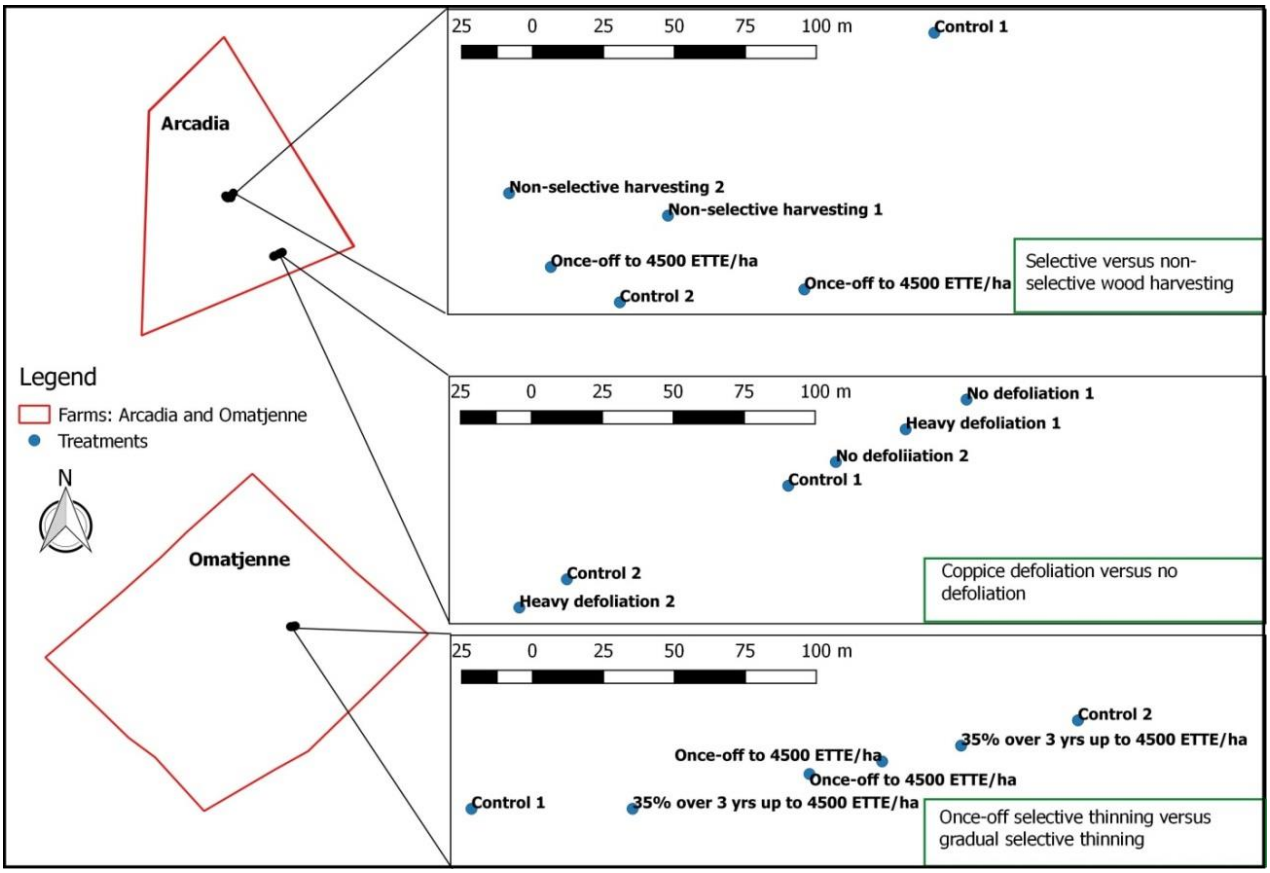


Figure 10.1: Trial layout illustrating the treatment plots in which the herbaceous biomass and species composition were measured

10.2.4. Surveys of the herbaceous layer

10.2.4.1. Species composition

The species composition of the herbaceous layer was determined, based on frequency of occurrence according to the nearest plant method (Everson and Clark, 1987; Smit and Rethman, 1999). Eighty point-observations were recorded per experimental plot. Surveys were done along parallel lines within each plot and the points were spaced 1 m apart. This approach also ensured the proportional sampling of the un-canopied (between trees) and canopied (under tree canopies) sub-habitats, as they occurred at each survey plot.

Herbaceous plants belonging to the family Poaceae (grasses) were identified on a species basis, while non-grass herbaceous plants were grouped as forbs. In all the readings a "bare patch" was recorded if no plants of the given criteria occurred within a radius of 50 cm of the point. Surveys were conducted annually at the end of the growing season (May).

10.2.4.2. Dry matter production

The above-ground dry matter (DM) production of the herbaceous plants at each experimental plot was determined at the end of each growing season (May). A harvest technique (Grunow *et al.* 1980; Catchpole and Wheeler, 1992) was used, which provided estimates of net primary production (Grossman 1982; Deshmukh and Baig, 1983) less dry matter losses due to herbivory.

All rooted herbaceous plants were harvested on a species basis in quadrates of 0.5 x 0.5 m (0.25 m^2), located within the main transect of each survey plot. In total, 20 quadrates per experimental plot were harvested. Quadrates were harvested under and between tree canopies in relation to the percentage tree canopy cover as determined during the BECVOL-3 (Smit, 2014) survey. Plants were clipped to stubble height (0.1 - 3.0 cm) using hand clippers, placed in paper bags and the clipped material dried to a constant mass (70°C) and weighed.

10.2.5. Data analysis

A generalized linear model (GLM) was used for the modeling task to investigate the impacts of different variables on herbaceous dry matter (DM) yield and species composition (Venables and Ripley, 2002). The herbaceous DM yield and species composition were used as the response variables, whereas the explanatory variables were the different woody plant harvesting treatments that included; once-off versus gradual selective bush thinning to a pre-determined density of 4 500 Evapotranspiration Tree Equivalents (ETTE) ha^{-1}, once-off selective

harvesting to a pre-determined density of 4 500 ETTE ha^{-1} (see Chpater 7, Section 7.2.4) versus non-selective bush harvesting, and annual total defoliation of coppice on *Senegalia mellifera* and *Vachellia reficiens* versus no coppice control.

Model fit was examined graphically by evaluating the trends and homoscedasticity of the Pearson residuals, and non-constant residual variance was modeled by updating initial models with a weighted variable (Mehtatalo and Kansanen, 2020).

Box plots were used to show overall patterns of response of the treatments, years and herbaceous groupings (annuals, perennials and forbs). Box plots are useful as they provide a visual summary of the data and can identify mean values, the dispersion of the data set, and signs of skewness.

These analyses were performed using R (version 4.1.2; R Core Team, 2021). All the descriptive statistics, such as graphs and tables, were generated using Microsoft Excel (Microsoft, 2010).

10.3. Results

10.3.1. Response of the herbaceous species composition to the different bush harvesting treatments

There were negligible differences in percentage species composition amongst the different treatments and between the treatments and the control (Table 10.2).

The overall dominant grass species was *Urochloa brachyuran,* which is an annual grass, but palatable with a good grazing value. The other dominant annual grasses were *Enneapogon cenchroides, Chloris virgata* and *Aristida* species. The most abundant perennial grass species were *Stipagrostis uniplumis* and *Eragrostis lehmanniana.* The non-grass herbaceous plants (forbs) were the most abundant in the non-selectively harvested plots.

The Jaccard similarity model shows a clear difference in herbaceous species composition between the selectively and non-selectively bush harvested plots (Figure 10.2). The control plot indicates a strong similarity with the once-off selectively thinned plots.

Table 10.2: Percentage species composition of the herbaceous layer in response to the different bush harvesting treatments at year three post-bush harvesting

	TREATMENTS					
Species	**Control**	**Non-selective harvesting followed with: No coppice defoliation**	**Non-selective harvesting followed with: *Annual total coppice defoliation**	**Selective thinning**	**Gradual selective thinning**	**Non-selective harvesting**
PERENNIAL SPECIES						
Bothriochloa radicans	0.6	0.6	1.0	1.6	0.6	0.0
Stipagrostis uniplumis	0.2	6.9	2.5	20.2	9.0	0.0
Eragrostis lehmanniana	15.2	23.8	27.0	7.0	0.0	23.1
Panicum maximum	0.2	0.0	0.6	0.0	0.0	0.0
Tricholaena monachne	0.2	0.0	0.0	0.0	0.0	0.0
Cenchrus ciliaris	0.0	0.0	0.0	0.0	0.0	0.6
ANNUAL SPECIES						
Enneapogon cenchroides	6.7	22.0	14.4	2.5	0.6	8.8
Urochloa brachyura	55.8	20.6	35.9	55.2	83.1	33.8
Enneapogon desvauxii	0.0	1.3	0.0	0.6	0.0	0.0
Chloris virgata	5.6	0.6	1.9	3.1	0.0	15.6
Tragus berteronianus	1.0	0.0	1.0	0.8	0.0	6.9
Melinus repens	0.6	0.0	1.3	0.5	0.0	0.0
Aristida species	3.6	6.9	2.5	1.1	1.9	5.0
Setaria verticullata	1.7	0.0	0.0	0.3	0.0	0.0
Pogonarthria fleckii	0.0	0.0	0.0	0.5	3.1	0.0
Forbs	8.1	16.9	10.0	3.3	1.3	6.2
Bare areas	0.5	0.4	1.9	3.3	0.4	0.0

*Coppice control/defoliation was only done on *Senegalia mellifera* and *Vachellia reficiens*

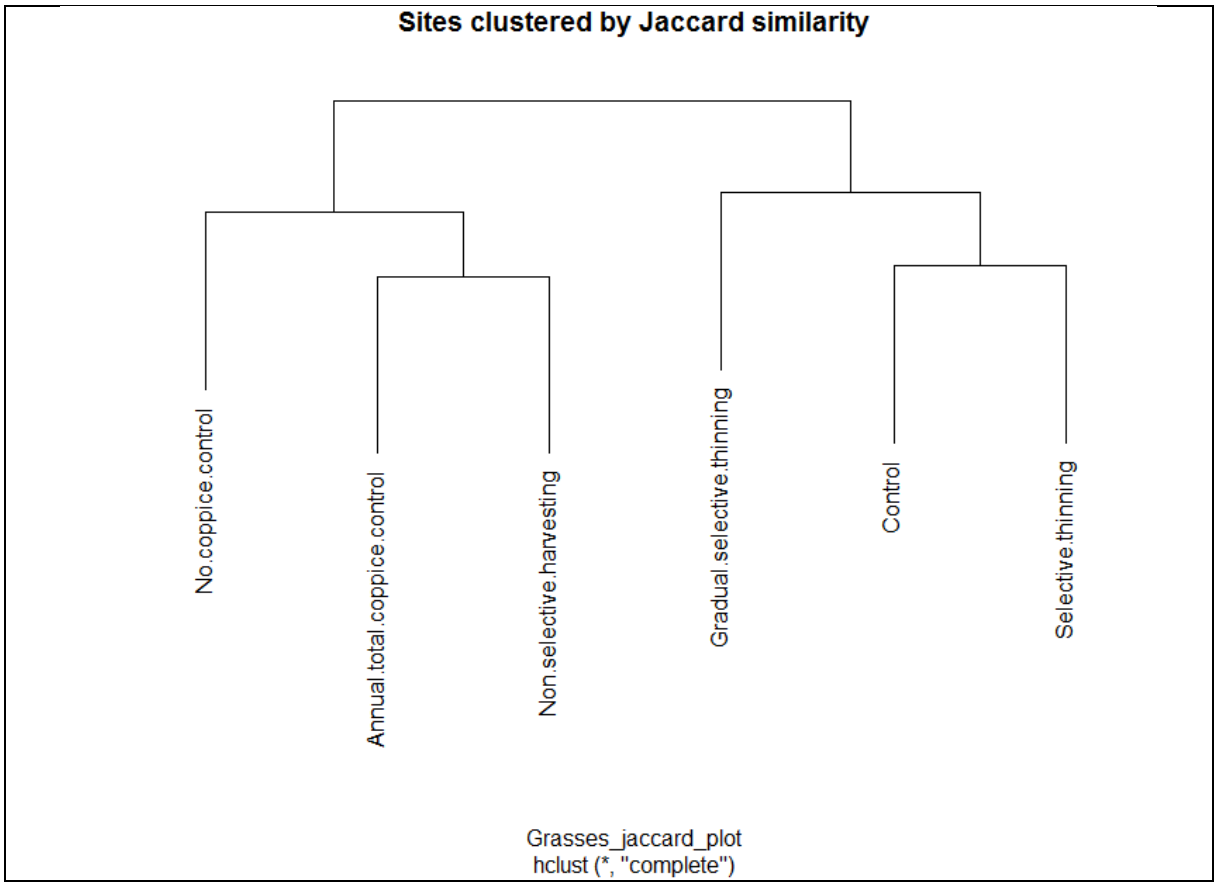


Figure 10.2: Jaccard similarity model showing similarities and differences between the different treatments. IMPORTANT: the "No coppice control" and "Annual total coppice control" plots were initially harvested non-selectively and the annual total coppice defoliation was done on *Senegalia mellifera* and *Vachellia reficiens* only

10.3.1. The response of the herbaceous dry matter yield to selective and gradually selective bush thinning

The woody plants in these plots were initially harvested, both once-off selectively and gradually selectively to a pre-determined density of 4 500 ETTE ha^{-1} (see Chapter 7, Section 7.2.4). The objectives and details from a bush control point of view are discussed in detail in Chapter 7. The herbaceous dry matter yield was subsequently measured in these bush harvested plots.

There were negligible differences in herbaceous dry matter (DM) yield between the gradual thinning (35% over three years) and once-off thinning to a pre-determined density of 4 500 ETTE ha^{-1} (Figure 10.3). The control plots had a higher herbaceous DM yield compared to the two treatments. There were also differences in the herbaceous DM yield between the years (Figure 10.4). The herbaceous DM yield increased substantially from the year 2019 to 2021 in correspondence with an increase in seasonal rainfall (see Chapter 3, Section 3.2). It was also clearly evident that the annual herbaceous plants contributed the most to the herbaceous DM yield recorded (Figure 10.4).

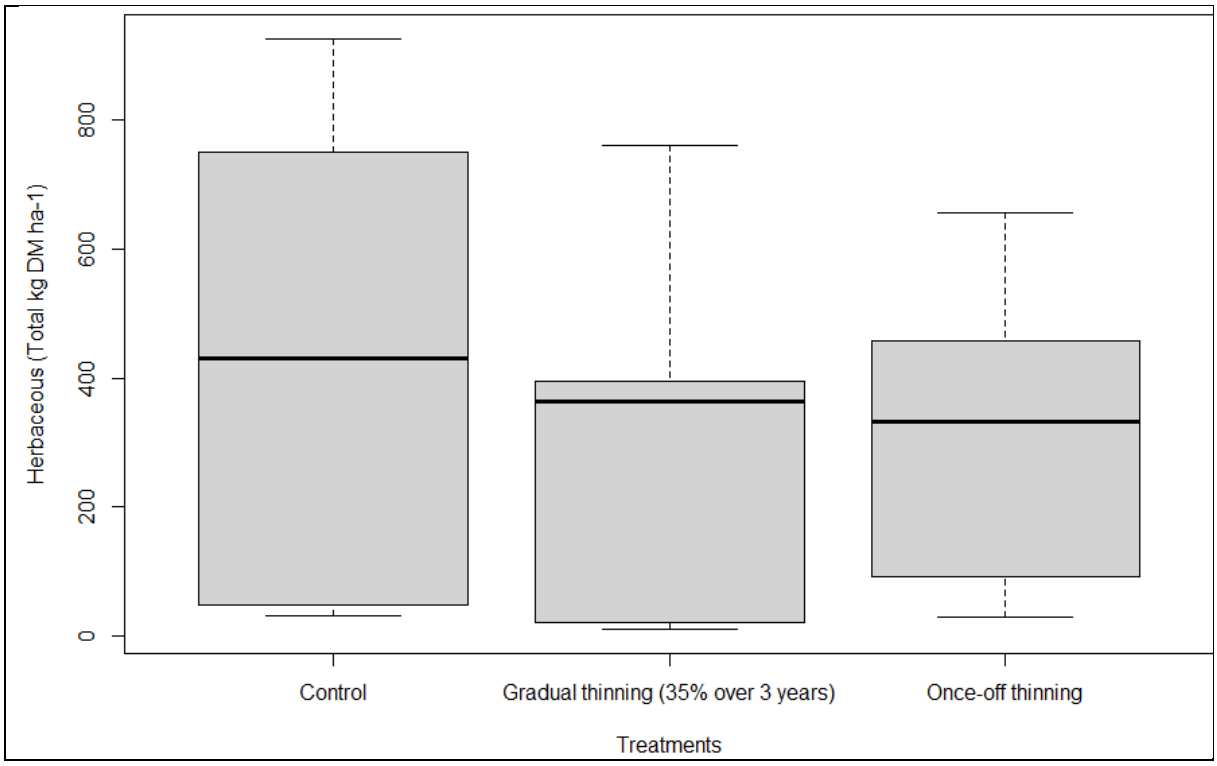


Figure 10.3: Comparison in the herbaceous dry matter yield production for the different treatments

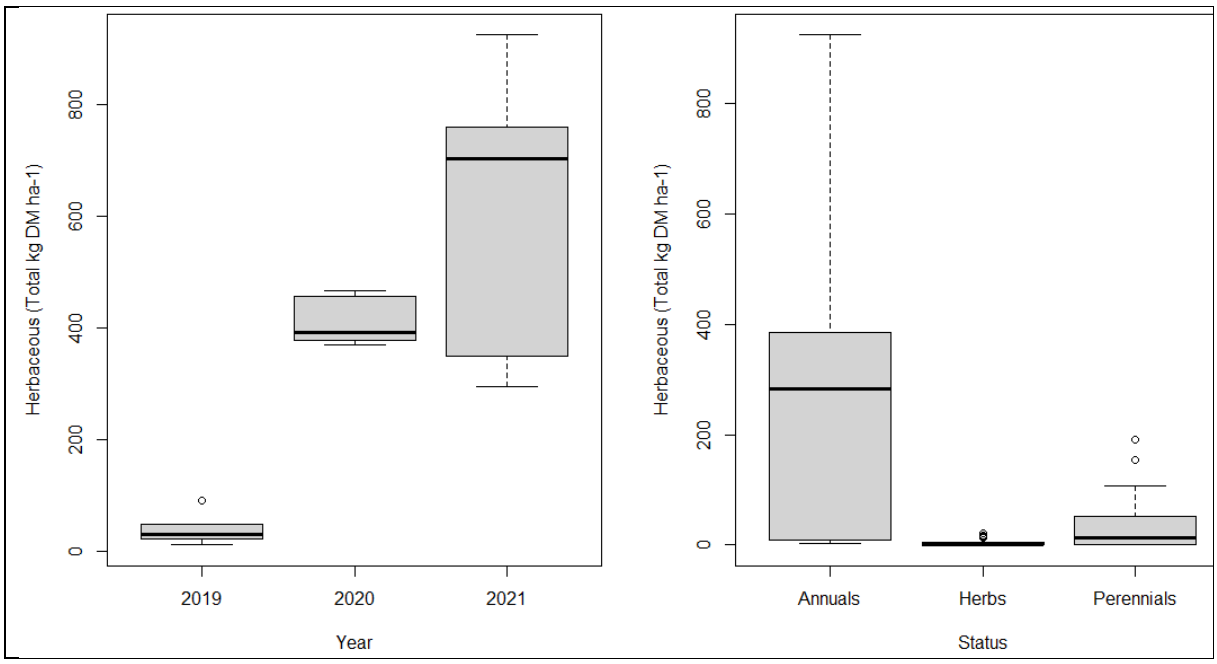


Figure 10.4: Comparison in the change of total herbaceous dry matter yield production over the years and the contribution of each herbaceous grouping to the total yield

The data presented in Figures 10.3 and 10.4 were further analyzed with a GLM. It was found that there was no statistical difference ($P>0.05$) in herbaceous DM yield between the different treatments (Table 10.3). There were, however, highly significant differences ($P<0.001$) in herbaceous DM yield between the different years and between the different herbaceous groupings (annual, forbs and perennial status) in contribution to the total herbaceous DM yields.

Table 10.3: GLM showing the effect of the different treatments, year and on the herbaceous dry matter yields

	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept: (Annuals)	-196093	51851.72	-3.782	0.000431	***
Status: Forbs	-310.74	51.34	-6.053	2.08E-07	***
Status: Perennials	-276.41	51.34	-5.384	2.15E-06	***
Treatments: Gradual thinning (35% over 3 years)	-38.78	51.34	-0.755	0.453673	
Treatments: Once-off thinning	-39.69	51.34	-0.773	0.443263	
Year	97.24	25.67	3.788	0.000423	***

10.3.2. The response of the herbaceous dry matter yield to selective versus non-selectively bush harvesting

The woody plants in these plots were initially harvested both selectively to a pre-determined density of 4 500 ETTE ha^{-1} and as well as non-selectively. The objectives and details from a bush control point of view are discussed in detail in Chapter 7. The herbaceous dry matter yield was subsequently measured in these bush harvested plots.

There were negligible differences in herbaceous dry matter (DM) yield between the non-selectively harvested and selectively thinned plots (Figure 10.5). Although with no statistical significance (P>0.05), non-selectively harvested and selectively thinned plots had higher herbaceous DM yields compared to the control plots. The herbaceous DM yield increased substantially from the years 2019 to 2021 (Figure 10.6) in correspondence with an increase in seasonal rainfall (see Chapter 3, Section 3.2). It is also clearly evident that annual herbaceous plants contributed the most to the herbaceous DM yield recorded.

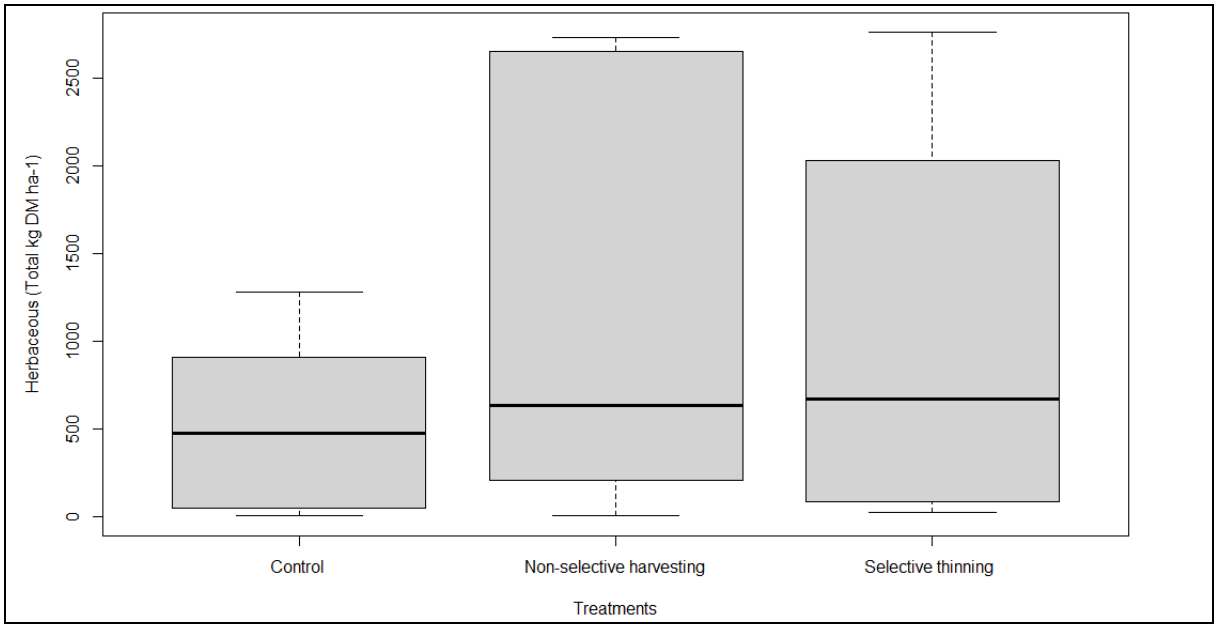


Figure 10.5: Comparison in the herbaceous dry matter yield production for the different treatments. The boxplot shows the median plant densities

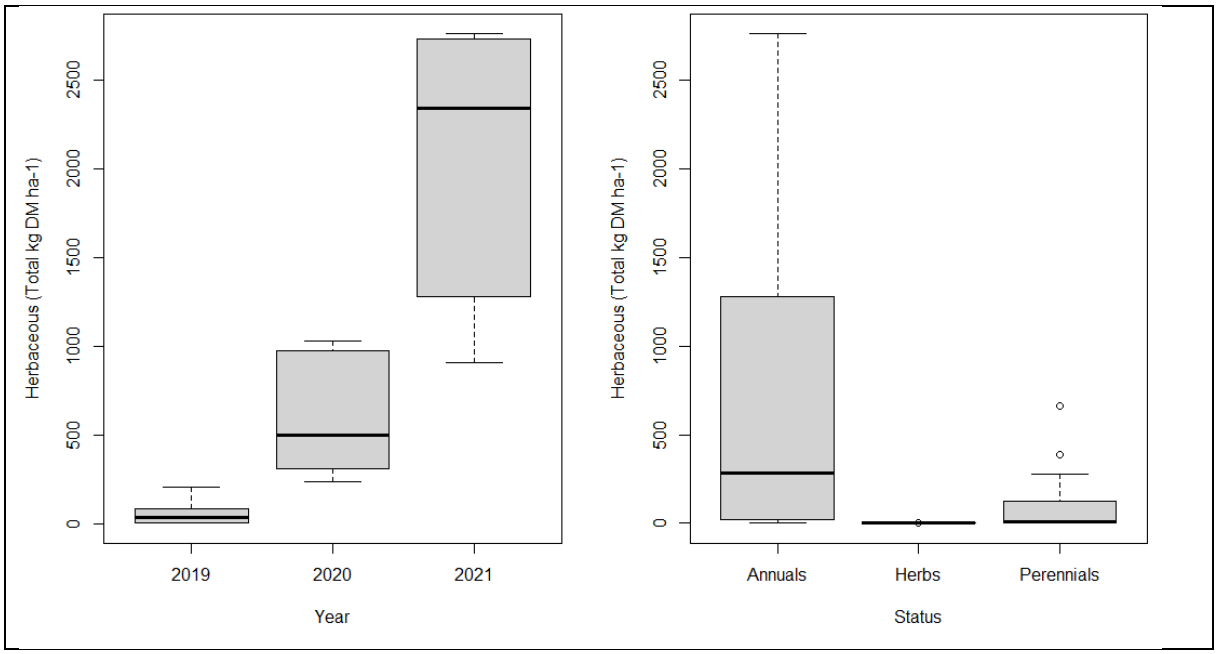


Figure 10.6: Comparison in the change of total herbaceous dry matter yield production over the years and the contribution of each herbaceous grouping to the total yield

The data presented in Figures 10.5 and 10.6 were further analyzed with a GLM. It was found that there was no statistical difference (P>0.05) in herbaceous DM yield between the different treatments (Table 10.4). There were, however, highly significant differences (P<0.001) in herbaceous DM yield between the different years and between the different herbaceous groupings (annual, forbs and perennial status) in contribution to the total herbaceous DM yields.

Table 10.4: GLM showing the effect of the different treatments, year and on the herbaceous dry matter yields

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept: (Annuals)	-672215	181919.7	-3.695	0.000563	***
Status: Forbs	-804.51	180.12	-4.467	4.83E-05	***
Status: Perennials	-704.86	180.12	-3.913	0.000286	***
Treatments: Non-selective harvesting	203.79	180.12	1.131	0.263501	
Treatments: Selective thinning	168.88	180.12	0.938	0.353132	
Year	333.12	90.06	3.699	0.000557	***

10.3.3. The response of the herbaceous dry matter yield to annual total defoliation versus no defoliation of coppice after initial non-selective bush harvesting

The woody plants in these plots were initially non-selectively harvested and only *Senegalia mellifera* and *Vachellia reficiens* were defoliated annually. The objectives and details from a bush control point of view are discussed detail in Chapter 5. The herbaceous dry matter yield was then also measured in these bush harvested plots.

There were negligible differences in herbaceous dry matter (DM) yield between coppice defoliated and non-defoliated plots (Figure 10.7). Although with no statistical significance (P>0.05), coppice defoliated and non-defoliated plots had higher herbaceous DM yields compared to the control plots. The herbaceous DM yield increased substantially from the years 2019 to 2021 (Figure 10.8) in correspondence with an increase in seasonal rainfall (see Chapter 3, Section 3.2). It is also clearly evident that annual herbaceous plants contributed the most to the herbaceous DM yield recorded.

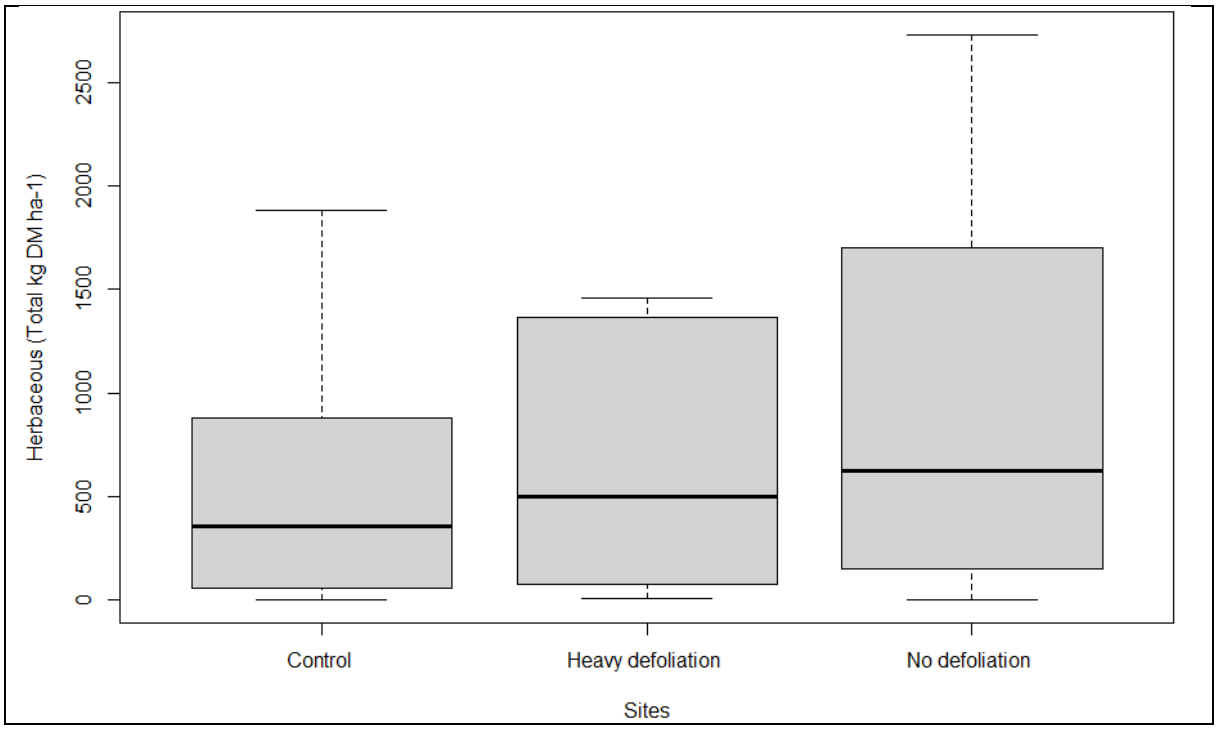


Figure 10.7: Comparison in the herbaceous dry matter yield production for the different treatments. The boxplot shows the median plant densities

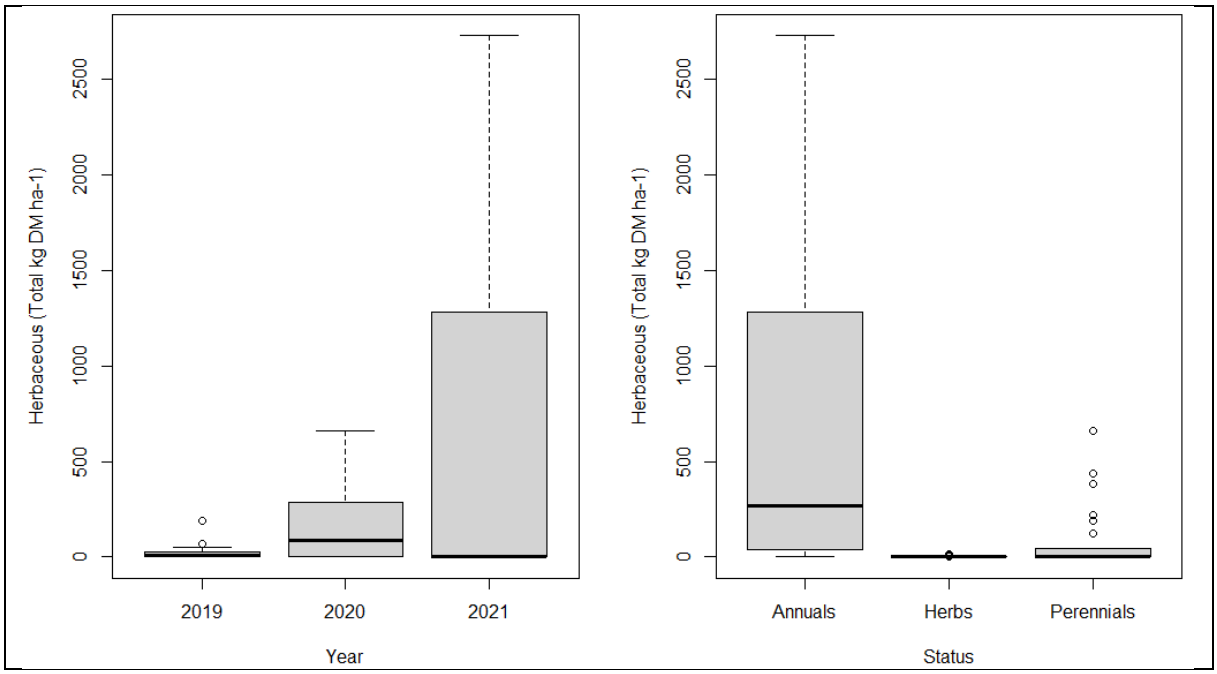


Figure 10.8: Comparison in the change of total herbaceous dry matter yield production over the years and the contribution of each herbaceous grouping to the total yield.

The data presented in Figures 10.7 and 10.8 were further analyzed with a GLM. It was found that there was no statistical difference (P>0.05) in herbaceous DM yield between the different treatments (Table 10.5). There were, however, highly significant differences (P<0.001) in herbaceous DM yield between the different years and between the different herbaceous groupings (annual, forbs and perennial status) in contribution to the total herbaceous DM yields.

Table 10.5: GLM showing the effect of the different treatments, year and on the herbaceous dry matter yields.

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	
Intercept: (Annuals)	-535807	110883.1	-4.832	6.01E-06	***
Status: Forbs	-661.3	109.79	-6.024	4.35E-08	***
Status: Perennials	-587.15	109.79	-5.348	7.53E-07	***
Sites: Annual total defoliation	32.91	122.74	0.268	0.789	
Sites: No defoliation	138.62	100.22	1.383	0.17	
Year	265.55	54.89	4.838	5.89E-06	***

10.4. Discussion

Due to extensive periods of low herbaceous cover, the soils in the study area were compacted to a large extent with little surface organic material and plant litter. There were, however, also no clearly visible signs of soil erosion at the study area. There were also observed signs of animal concentration, especially game, on the harvested plots.

Considering the similarities in herbaceous species composition and dry matter yields between the different treatments and between the treatments and control plots, it is evident that the bush control did not contribute to improved herbaceous yields as expected. In view of the costs involved in bush control measures this is an important result since it is unlikely that the reponse of the herbaceous layer to bush control will offset the cost. With the documented ample evidence that woody plants enrich the soil (Bosch and Van Wyk, 1970; Kennard and Walker, 1973; Tiedemann and Klemmedson, 1973; Kellman, 1979; Bernhard-Reversat, 1982; Belsky *et al*., 1989; Smit and Swart, 1994; Hagos, 2001), and the above average rainfall in the second and third seasons (2020 and 2021) during the study (see Chapter 3, Section 3.2), the continued dominance of annual grass species three years post-bush harvest is concerning and has serious implications for programmes intended for the restoration of a stable and productive herbaceous layer in this area of Namibia. It is possible that soil compaction, high soil surface temperatures due to a lack of surface organic material, and a possibly depleted seed bank of perennial grasses are the main contributors towards the low contribution of the perennial grasses to the total herbaceous dry matter yields. This observation is not unique since Smit and Rethman (1999) also found a dominance of annual grasses in bush-thickened and recently bush-controlled plots in the Mopani veld of northern region of South Africa, with a general lack of successional progression to perennial grasses. Schwieger (2022) also reported a lack of perennial grasses in the Thornbush Savanna, although in the communal areas.

All of the cases above are typical of non-equilibrium ecosytems. The terms “equilibrium” and “non-equilibrium” as used in rangelands, are strongly debated by scientists. The central aspect of this debate is a definition of the degree to which climate and consumers (herbivores) can influence vegetation (Illius and O’Connor, 1999). 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 & Swift, 1988). It is clear that the grass production in the study area is rainfall driven (Figures 10.4, 10.6, 10.8), and therefore, according to Ellis and Swift (1988) can be classified as a non-equilibrial pastoral system as dry material production is primarily dictated by variability in rainfall. The implication of this is that grasses have to establish from seed every year in response to rainfall, and subsequently they may be largely absent during dry seasons. The perennial grasses are also sprouting early in the season with minimal rainfall or carry-over moisture from the previous rainfall year. This makes the perennial grasses vulnerable to the grazers and therefore seed production is negatively affected. It can therefore

be expected that perennial grasses will normally be present in low numbers and their numbers will only increase during consecutive wet seasons and under sound veld management practices that ensure ample seed production to allow for any possible improvement in plants succession. In this regard the application of bush control measures appears to contribute little towards achieving rangeland restoration of the study area - at least in the short term.

10.5. Conclusion

Although surveys in all plots confirmed a state of bush thickening as per the general rule of thumb and thus the need for some form of bush thinning, the grass dry matter production did not improve as generally assumed with reduced woody plant competition. The herbaceous dry matter production showed a more pronounced positive response to increased rainfall rather than to bush thinning during the study period. No species composition successional improvements were observed during the three-year study period, although the herbaceous dry material yield increased drastically in response to the higher rainfall.

The results of this study show that bush control practices should best be timed with years of above average rainfall coupled with good rangeland management principles to achieve the maximum benefits expected from the bush control exercise. More drastic measures such as re-seeding of perennial grasses may need to be incorporated within the rangeland management principles after bush harvesting.

The recommendations would be to apply sound rangeland management principles for improved rangeland conditions over a shorter time period after initial bush harvesting. Some management recommendations include:

- Breaking up of the soil surface crust by concentrating a high animal number in a camp for short periods,
- Allowing for long and scheduled rest periods for perennial grasses to produce seed, and for the seed to germinate and seedling to establish before the area is grazed again, and
- Allowing for herbaceous litter to accumulate on the soil surface to improve the soil surface micro-climate, add organic matter to the soil, and to build soil structure and health.

Sound rangeland management principles are not limited to the above. Bush thinning, during which the large trees are protected, is recommended to maintain diversity in the savannas as clearing does not provide the benefit of significantly higher herbaceous dry material production

in the short-term. Bush cleared areas also stand a higher risk of re-thickening, whereas bush-thinned areas maintain stability between the herbaceous and woody layers in the long-term.

11. SUMMARY

The savannas of northern Namibia are prone to woody plant thickening, which involves indigenous woody species in their natural environment. Land owners, therefore, attempt to restore the rangelands through the removal of some or all the woody plants with a view to reduce the negative competition interactions with the herbaceous layer that will allow for the establishment of grasses and subsequently increase the grazing capacity for livestock. The utilization of the bush resource made available through these bush control programs has gained significant interest in these savanna areas of Namibia over the past years. This has led to the development of a lucrative bush value-chain industry (mainly wood, charcoal, biochar) which often leads to the over-exploitation of the resource for short-term financial gains. Various mechanical, as well as semi-mechanized/manual methods, are commonly used in the bush harvesting process, often resulting in soil disturbance and a change in vegetation composition, especially with non-selective harvesting. The ecological effects of the specific harvesting method and the consequent regrowth patterns of the woody plants are not well understood and greatly affect the initial purpose of wood harvesting, which is often postulated as a measure intended to improve the productivity of the rangeland for meat production.

The effect of the most common harvesting practices such as non-selective and selective harvesting on the vegetation, using a heavy bush roller (mechanical) and chainsaws (semi-mechanized/manual) were investigated over three years in an area northwest of Otjiwarongo, described as the North-central plateau of Namibia, with vegetation classified as Thornbush Savanna. The dominant woody plant species were *Senegalia mellifera* and *Vachellia reficiens*. They are also the most sought-after species for charcoal production due to their high wood yield potential and for this reason, they are also the species of interest in this study. The coppicing ability, survival of coppice, change in woody species composition, woody plant recruitment through coppice and/or sapling establishment, the rate of biomass production, the effect of annual total coppice defoliation on coppice regrowth, and growth rates and mortalities of woody plants were studied. The trial layout consisted of plots of 50 x 30 m (1 500 m2) with at least two replications of each treatment.

The rainfall was below-average in the first year of the study but increased drastically to above average in the second and third years. Preceding the study period, the area had several years of drought (below-average rainfall) and this contributed towards the urgent need for bush control for increased grass growth for livestock. This study was then specifically conducted to provide

scientifically-based guidelines for both the land owners and the biomass industry on the sustainable use of the resource.

The non-selective (bush-roller and chainsaw) harvesting showed no significant differences ($P>0.05$) in coppice regrowth for *Senegalia mellifera* and *Vachellia reficiens*. However, although not statistically significant ($P>0.05$), the chainsaw harvested plots had higher coppice rates when considering all other woody species, in addition to the species of interest. On the contrary, the bush-roller-harvested plots had a higher sapling establishment as compared to the chainsaw-harvested plots. *Dichrostachys cinerea* was the only species that had a highly significant ($P=0.002$) increase in sapling establishment in both bush-roller and chainsaw non-selectively harvested plots. There was a general change in dominance from high wood potential (mostly *S. mellifera, V. reficiens, Vachellia tortilis, V. hebeclada*) to low wood potential (mostly all *Grewia* species, *D. cinerea, Catophractes alexandri*) in terms of regrowth in these plots. Plant density (plants ha^{-1}) had a very fast return to its original pre-harvest state, whereas Evapotranspiration Tree Equivalents (ETTE) ha^{-1} showed a very slow return to its original pre-harvest state. The ETTE ha^{-1} is projected to return to its original pre-harvest state in less than 12 years, whereas the wood biomass does not show any signs of returning to its original pre-harvest state or even to the biomass equivalent to 4 500 ETTE ha^{-1} as calculated to be optimum based on the long-term average median/mean rainfall. There was no statistically significant ($P>0.05$) regeneration in species richness over the three years after initial harvesting. The chainsaw-harvested plots had a significantly lower ($P<0.05$) species diversity compared to the control and bush-roller-harvested plots. Both species diversity and richness showed recovery with time (years), indicating positive regeneration.

Generally, the coppice of cut plants was significantly influenced ($P<0.05$) by the average basal stem diameter and distance away from the nearest plant neighbour. The smaller the stem diameter and the further the plant was from its nearest neighbour, the higher the coppicing rate. The number of stems of the cut plant and the nearest neighbour species did not generally influence the rate of coppice.

There was a highly significant difference ($P<0.001$) between the annual total defoliation and no coppice defoliation plots. Annual total defoliation of coppice proved to be effective for the control of coppicing woody plants without the need for any chemical treatment (arboricide). There was no statistically significant difference ($P>0.05$) in sapling establishment between the annual total defoliation and no defoliation of coppice plots. However, *Grewia flava* and

Vachellia reficiens showed a significant increase ($P<0.01$) in sapling establishment for both treatments. *Grewia flava* also showed a highly significant ($P<0.001$) increase in overall plant density (plants ha^{-1}) on a species basis, although there was no overall significant difference ($P>0.05$) in plant density (plants ha^{-1}) between the two treatments.

There was a highly significant difference ($P<0.01$) in the rate of coppice between the two seasons (hot wet summer and cold dry winter) as treatments. Plants initially harvested in summer had a higher coppice rate and survival than plants harvested in winter. The summer-harvested *S. mellifera* stumps coppiced more vigorously compared to *V. reficiens*. The winter-harvested *V. reficiens* coppiced more vigorously compared to *S. mellifera*. Harvesting *S. mellifera* in winter can lead to the complete die-off of the species as it coppices very poorly in the first year and stands the risk of dying in the follow-up years, regardless of the amount of rainfall. There was no significant difference ($P>0.05$) in overall sapling establishment between the two treatments. However, *D. cinerea* had a highly significant increase ($P<0.001$) in sapling densities (plants ha^{-1}) over the study period. There was a very slow regeneration in wood biomass and leaf volume (ETTE ha^{-1}) of plants in these non-selectively harvested plots regardless of the season (summer and winter) in which they were harvested.

There were highly significant differences ($P<0.001$) in coppice amongst the selectively versus non-selectively harvested plots. Plants harvested selectively, while retaining 4 500 ETTE ha^{-1}, had lower coppicing rates than those where the whole area was harvested non-selectively. The high ETTE ha^{-1} before harvesting could not be reached three years after harvesting, whereas plant density (plants ha^{-1}) in the selectively thinned plots significantly ($P<0.05$) exceeded the original plant density (plants ha^{-1}) before initial harvesting within three years. Woody species such as *S. mellifera, V. reficiens* and *V. hebeclada* increased significantly ($P<0.05$) in leaf volume (ETTE ha^{-1}) in the selectively harvested plots.

Mature *S. mellifera* woody plants had a significantly higher ($P<0.001$) mortality rate in the bush-thickened control plots. The mortality of *V. reficiens* was not as high as that of *S. mellifera*. Regarding shoot growth, the growth in shoot length was more pronounced than that of shoot diameter. *Vachellia reficiens* had a significantly higher ($P=0.001$) growth rate in shoot length compared to *S. mellifera*.

Allometric regression equations were also developed from harvested undamaged *Senegalia mellifera* and *Vachellia reficiens* plants for inclusion into the BECVOL-3 model. Highly significant relationships ($P<0.01$) were found between the spatial canopy volume and leaf

volume, leaf dry mass, shoot dry mass for shoots ≤ 5 mm in diameter, stem dry mass for stems > 5 – 20 mm in diameter, and stem dry mass for stems > 20 mm in diameter.

There were negligible differences in species composition of the herbaceous layer amongst the different bush control treatment plots. The overall dominant grass species was *Urochloa brachyura*, which is an annual grass, but palatable with a good grazing value. Although surveys in all plots confirmed a state of bush thickening as per the general rule of thumb and thus the need for some form of bush thinning, the grass dry matter production did not improve, as generally assumed, with reduced woody plant competition. The herbaceous dry matter production showed a more pronounced positive response to increased rainfall rather than bush thinning during the study period. No species composition successional improvements were observed during the three-year study period, although the herbaceous dry material yield increased considerably in response to the higher rainfall.

It was clear that bush control in rangeland dominated by annual grass species does not contribute to rangeland restoration in the short-term as the herbaceous dry material yield from the annual grasses is highly rainfall dependant for production. However, bush control by way of selective thinning of the smaller plants while protecting the large trees as opposed to clearing is recommended to maintain diversity and prevent re-thickening from pioneer, aggressively growing woody plants. Sound rangeland management principles such as resting, soil improvement through breaking up the soil surface crust, allowing for the accumulation of dead plant litter, and effective utilization of the fodder plants must accompany the bush control process. Additional pro-active management strategies must be considered such as re-seeding with perennial grasses to facilitate the successional stages towards the dominance of climax perennial grasses over a shorter period as the natural process may take too long and the initial purpose for bush control may not be realized.

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