THE RELATIONSHIP BETWEEN SIZE AND DENSITY OF *ACACIA MELLIFERA* IN THE HIGHLAND SAVANNA OF NAMIBIA, AND ITS INFLUENCE ON THE GRASS SPECIES COMPOSITION AND SOIL NUTRIENTS

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Abstract

The Size-density relationship may be a valuable tool to reveal the extent of competition and mechanisms for distribution patterns, structure and functioning of woody species in savanna vegetation types. A study on the relationship between size and density of Acacia mellifera in the highland savanna of Namibia was carried out to try to facilitate an understanding of the development of stand density in relation to size (height) of *A. mellifera*. Data was collected at Neudamm farm in three camps that are inhabited by pure stands of *A. mellifera*. A total of ten clumps in each camp were selected, and the following recordings were made: Height (size) of the selected reference tree within the clump, crown diameter and crown form, and the distance to its two nearest neighbors. Another approach to data collection was the use of the nearest neighbor method, where every *A. mellifera* at every fifth point along a transect line was selected, its height, distance to nearest neighbor as well as the height of the neighbor were recorded. The results were analyzed with a linear model test to investigate the size-density relationship. The result from the test indicated that there is no significant relationship ($P>0.05$) between the two. Significant relationship ($P<0.05$) could only be found between crown diameter and height as well as between crown form and height. The influence of *A. mellifera* clumps on grass species composition and soil nutrients was also investigated, and there was a significant ($P<0.05$) difference between grass species composition under and outside canopies. The study concluded that tree density does not affect tree size in *A. mellifera* species in the highland savanna of Namibia; hence no evidence of competition or self-thinning in *A. mellifera* stands yet. Therefore, competition may not the sole determinant of distribution and structure of wood species in savannas.

Key words: Self-thinning, bush encroachment, competition, savanna, clumps, rangelands.

Dedication

I wholly dedicate this work to my late mother and father, **Augusta Karinamuua Mupaine-Hamutenja**, and **Manuel Ueriruka Kaunatjike-Ngaruka** respectively. I still feel your love and support from you resting places. May your soul remain rested in eternal peace.

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Declaration

I, Erastus Ngaruka, declare hereby that this study is a true reflection of my own research, and that this work, or part thereof has not been submitted for a degree in any other institution of higher education.

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Erastus Ngaruka

Chapter 1

1.1 Introduction

A savanna is a tropical vegetation type co-dominated by woody plants and grasses (Cowling *et al*., 1997). Savanna vegetation occupies the broad region between dry deserts and humid forests in the tropics and subtropics (Huntley & Walker, 1982). They are part of the continuum that includes arid shrublands, lightly wooded grasslands, deciduous woodlands and dry forest (Cowling *et al*., 1997). Savannas are one of the world's major biome, and are dominant vegetation types of Africa (Scholes & Walker, 1993); they also occur in India, South America and Australia. They have an important economic role in terms of livestock and crop production (Grouzis & Akpo, 1997). In Africa, much of the savanna is of the woodland type with tall grasses forming the ground cover beneath a discontinuous canopy of deciduous trees (Archibold, 1995). Savannas occupy 54% of Southern Africa, and 60% of sub-Saharan Africa (Scholes & Walker, 1993).

The key feature common to all savannas is a climate that has a hot wet season of four- to eight- month duration and a warm dry season for the rest of the year (Nix, 1983). In southern African savannas, the wet season is uni-modal, and rain falls in the summertime, between October and April (Cowling *et al*., 1997).

In South Africa and Namibia, savannas are referred to as Bushveld and/or Bosveld (in Afrikaans language), and there are many other vernacular names (Scholes & Walker, 1993). In Namibia, it is the most representative type of vegetation (Okitsu, 2004b) occupying approximately 64 % (about 53 million ha) of the country's land area (FAO, Undated), and forms the basis for the county's livestock industry.

One of the most intractable problems in savanna management is the thickening up or invasion by trees (bush encroachment), which then suppress productivity of the grass layer (Cowling *et al*., 1997). Understanding the mechanism of co-dominance between trees and grasses, and the factors that determine their proportions has been a major challenge in savanna ecology (Cowling *et al*., 1997). An understanding of the processes of establishment and growth of woody plants and the factors which influence these processes is integral to the development of management plans for savanna communities (Tainton, 1999).

Competition between (Inter) and within (intra) species has long been regarded as a significant determinant of the structure and function of woody plant communities in African savannas (Shackleton, 2002). The main controls on recruitment of woody plants are imposed by the interactive effects of fire, herbivory and competition with grasses while the tree is still within the grass layer (Frost, 1985). Plant competition starts when any of the resources (water, soil nutrients or sunlight) becomes available in insufficient amounts for individuals, and as stated by (Archibold, 1995), the most successful competitors become the common members of the community. Hence, the domination of some savanna communities by problematic woody species (e.g. *Acacia mellifera*) which may have been favored by the present conditions. The growth and subsequent size that any individual tree can achieve is dependent on the resources to which it has access. This, in turn, is a function of available water and nutrient levels but also of the proximity and size of neighboring individuals. The larger the tree, the larger the area (volume) of resource depletion around it, and the greater the competitive effect it may have on its neighbors (Smith & Goodman, 1986). As individuals die, due to competition or to factors extrinsic to the population such as fire, herbivory, drought, or even old age, the resulting gaps will allow either the increased growth of neighboring individuals or the establishment of new individuals (De Klerk, 2004).

According to Tainton (1999), the distance between a tree and its nearest neighbor of the same type is not determined purely by chance, but that tree spacing is evenly distributed. The larger the individual, the greater is the distance between it and the nearest individual of the same type. Spacing in acacia communities has been influenced by roles of Inter- and intra-specific competition (Smith & Walker, 1983).

The encroaching woody species would be referred to as Unapparent species, from Feeny (1976 as cited in Archibold, 1995) classification, since they tend to exploit a number of habitats, and so, their distribution is patchy and unpredictable. The encroachment or the distribution of *A. mellifera* in Namibia for example, is rapidly widening over a range of habitats, and as stated by Joubert *et al.* (2008), this encroachment of Namibian rangelands by *A. mellifera* is partially resulting from a poor understanding of vegetation dynamics.

Therefore, the approaches towards managing woody species densities, or bush encroachment in savanna vegetations, would be to understand their mechanisms for their establishments and distribution, and to be able to predict their dynamics. This prediction can be deduced from determination of the relationship between size and density of trees, which, according to Woodall & Westfall (2009), has long provided a framework in understanding and predicting stand dynamics in forests. Long (1985) stated that, stand density indices that are based on size-density relationships constitute a valuable tool in translating management objectives into practical density management regimes. To develop indices of tree size-density attributes, the theoretical basis for that is the concept of self-thinning, which is based on the premise that as mean plant size per unit area increases, the number of individuals per unit area decreases (Enquist *et al*., 1998). It quantifies the reduction in tree numbers due to density-dependent mortality (Vanderschaaf, 2006), which may arise from competition between individuals within a dense stand or a clump.

Competition between trees is an important mechanism controlling not only the size and density of trees but also grass production (Smith &Walter 1983). From a theoretical point of view, there are two main mechanisms that allow competitors to coexist: equilibrium theories based on niche separation; and disequilibrium theories, in which disturbance prevents competitive exclusion from proceedings to its logical conclusion (Cowling *et al*., 1997). Trees and grasses may co-exist for example, due to their morphological differences and manner of resource use. Trees have root systems reaching deep in soils to extract water or nutrients, whereas grasses are shallow-rooted and can subsist on surface or sub-surface soil moisture. As stated by Treydtea *et al*. (2007), the varying rainfall patterns and soil fertility are the main determinant of the tree-grass interactions. In arid and semi-arid zones, trees may have negative and positive effects on their immediate environment (Abdallah *et al*., 2008), and create, under canopy, a sub-habitat that differs from the open grassland and exerting different influences on the herbaceous layer (Smit, 2004). According to (Treydtea *et al*., 2007), large savanna trees are known to modify soil nutrient condition, but whether that has an impact on the quality of herbaceous vegetation is unclear.

Wiegand & Maloney (2004) suggested that, if spatial processes have a strong influence on spatial patterns of plant distribution, then these spatial patterns necessarily contain information of population dynamics. Then it is possible to study population processes by investigating spatial patterns of plants distribution.

Investigating spatial patterns of woody species distributions may provide valuable approaches in managing woody invasion or bush encroachment in savanna vegetations. Bush encroachment in Namibia is a big concern to most livestock producers in that it is a threat to the availability, quantity and quality of forage materials. One of the main species causing the problem of encroachment is *Acacia mellifera*. Joubert *et al*. (2008) estimated that nearly 50% of the commercial ranching areas of Namibia are affected by bush thickening, mainly by *A. mellifera*. As stated before, such a continual increase in invasive species' densities and widespread distribution is due to poor understanding of vegetation dynamics, in particular, the mechanisms of establishment and pattern of distribution of *A. mellifera.*

This particular study's main focus is on the investigation of the size-density relationship of *Acacia mellifera* tree (commonly known as Black thorn (English), Swaarthaak (Afrikaans), or Omusaona in Otjiherero) in the highland savanna of Namibia. *A. mellifera* is one of, and most widely distributed woody specie, aggressively invading and degrading Namibia rangelands. Amongst the other encroachers, *A. mellifera* is seen as the most problematic. Despite the use of bush control methods, in most cases, it continues to establish and re-establish itself.

As a general description, from Roodt (1998), *A. mellifera* is a small-sized tree, with more or less rounded-shaped canopy, pairs of strongly re-curved thorns, creamy-white flowers, and papery pods that make it easy to recognize in the field. It occasionally grows up to nine meters tall, but is usually only about three meters high. Other encroaching species in the Namibia are: *Acacia fleckii* (Blade thorn), *Acacia reficiens* (False umbrella thorn), *Colophospermum mopane* (Mopane), *Dichrostachys cinerea* (Sickle bush), *Rhigozum trichotomum* (Three thorn), *Terminalia sericea* (Silver Terminalia), and *Terminalia prunoides* (Purple-pod Terminalia).

In the end, this study intends to suggest alternative or additional approaches towards controlling *A. mellifera* with an understanding of the processes that governs its invasive establishment and distribution. Other components included in the study are the investigations of the spatial pattern of the specie, using the one-nearest-neighbor method, and as well determining the influence of the *A. mellifera* clumps on the grass species composition and some soil nutrients.

1.2 Statement of the problem

In Namibia, the increased bush densities, referred to as bush encroachment, is one form of land degradation, and its adverse effects are loss of rangeland productivity, displacement of most valuable browse and grazing resources, lowering the carrying capacity of farm lands, and consequently poor animal production, economic losses, and harsh farmers' livelihoods.

Bush control methods (biological, chemical and mechanical) have been used for long, and remain the main options to farmers to control, circumvent or minimize the consequences of bush encroachment. Although they have shown success in some parts, overall, the problem of bush encroachment is still persistent. In particular, *A. mellifera* continues to establish and re-establish itself, and its distribution is conspicuously widening, especially in the Thornbush, Highland, Camelthorn and Tree-shrub savanna, and even in the dwarf-shrub savanna, making it the most problematic specie.

In order to be able to control the aggressive invasion of rangelands by *A. mellifera*, it is necessary to understand the natural system's processes under which it thrives, and as to how the system may be managed to control the worrisome densities of the specie in order to regain healthy and balanced rangelands in Namibia. Understanding and explaining the underlying processes of the observed spatial patterns of plant individuals have long been an interesting question in plant ecology (Wiegand and Maloney, 2004). Therefore, as an effort, this research intends to determine the relationship between the density and size of *A. mellifera*, to facilitate an understanding of the development of stand density in relation to size (height), and the mechanisms for its distribution. The research also includes components of grass species composition and soil nutrients, as to investigate the influence of the tree on the two.

The knowledge of this research may bring an understanding in the establishment, distribution, structure and density of the specie, to help in devising bush density management strategies with an understanding of the natural processes functioning. The research would also trigger further or in depth research on issues of bush encroachment.

1.3 Objectives

The overall objective of this study is to understand the distribution and structure (size, crown form and crown diameter) of *A. mellifera* so as to incorporate it in bush management plans.

More specifically, the study aims to:

- Determine the relationship between the size and density of *A. mellifera* in the highland savanna of Namibia
- Determine the distribution/spatial pattern of *A. mellifera*
- Determine the influence of *A. mellifera* clumps on grass species composition, and
- Determine the influence of the specie on soil nutrients

1.4 Literature review

1.4.1 Bush encroachment in Namibia

The problem of bush encroachment has been noticed by the Namibian government and is reflected in several new policies and laws, namely the National Agricultural Policy, the National Drought Policy and Strategy, the Soil Conservation act, the Namibian Forest Development Policy, and the Poverty Reduction Strategy of Namibia (De Klerk, 2004).

De Klerk (2004) reported that bush encroachment of approximately 26 million ha of savannas in Namibia resulted in a loss of land productivity, and the carrying capacity declined from 1 Large Stock Unit (LSU) per 10 hectares (ha) to 1 LSU per 20 or 30 ha. According to Bester (1999), bush densities in affected areas varies between 2500 and 10000 bushes per ha.

Bush encroachment has adverse effect on the economy and livelihoods of farmers, for which De Klerk (2004) also reported that, economic losses of more than N$ 700 million per annum had directly impacted on the livelihoods of 65 000 households in communal areas and 6283 commercial farmers and their employees. In communal areas, bush encroachment exacerbates prevailing problems like lower food security and nutrition, increased efforts to maintain living standards, and higher demands on wages and income transfers (De Klerk, 2004).

1.4.2 Management issues of woody species

The reasons for bush encroachment in savannas are diverse and complex (Smit, 2005). Range scientists have over the years tried to identify and understand the causes of bush encroachment, but up to now, there still exist contrasting opinions. Bush encroachment would result from interactive effects of fire, herbivory and plant competition but there may be underlying causes or factors exacerbating the problem which may be influenced by natural functioning processes which is poorly understood. For example, overgrazing has been said to be the main cause, but according to Teague & Smit, (1992), mitigation protocols based on the two-layer theory, e.g. reducing livestock densities in years with below-average rainfall have fail to reduce bush encroachment, indicating that the causes of the problem are poorly understood.

Heady et al. (1994) questioned if brush is really a problem, and suggested that why not alter objectives and production procedures to take advantage of natural systems rather than alter the systems to meet objectives. Graz (2008) stressed that it is important to develop management regimes that consider the economic sustainability of grazing enterprises, with the assumption that sustainability is only achieved if the resource base continues to exhibit good condition. The author also maintained that it is equally important to consider the future development of the rangelands that are already encroached to assess the possibility that the problem might 'solve itself' given time, or to identify possible remedial interventions. Such interventions would include, mechanical thinning and selective chemical application amongst others.

Tainton (1999) stated that the aim of management may either be to maximize the production of the woody component of the community so as to provide forage for browsing animals, or to limit the density of the woody plants so as to stimulate grass production for grazing animals.

According to Smit (2004), it is a fact that bush encroachment is still not well understood at a fundamental level, both by scientists and land owners who have to deal with the problem in a practical manner. In view of the poor understanding of savanna ecosystem functioning, finding solutions to the problem, especially long-term solutions, is often difficult.

1.4.3 Tree-grass interaction

In semi-arid systems, rainfall gradients can cause plan-plant interaction to shift from positive to negative or vice versa (Riginos *et al.*, 2005). As stated by Smit (2004) that the soil enrichment under canopy sub-habitats of trees may have positive effects on grass growth, Stuart-Hill *et al.* (1987) demonstrated a consistent pattern of grass production around isolated *Acacia karoo* trees in the false thornveld of the eastern cape in South Africa, where high yields were recorded under and immediately to the south of the canopy, whereas the north had low yields. The high yields were attributed to the favorable influence of trees on the microenvironment such as leaf litter deposition and shading, whereas the low yield was due to the reduced water input associated with physical redistribution of rainfall by the trees.

In another study done in Kenya by Belsky et al. (1989), significantly higher production of herbaceous plants under canopies of both *Acacia tortilis* and *Adansonia digitata* than outside their canopies were also recorded.

1.4.3 Competition between woody species

There is competition between woody plants themselves, presumably causing density-dependent mortality and leading towards regular spacing between individuals (Skarpe, 1991). Beh-shahar (1991) viewed that the distinct transition of dominance between species indicated that competition between woody species might have been the cause behind the changes in their abundance and spatial distribution during succession.

With time, tree growth and inter-tree competition will convert the bush-encroached patch to an open savanna (Scholes & Archer, 1997). This prediction, according to Ward (2005), is supported by observations on bush-encroaching *Acacia reficiens* in Namibia, where mean distance between nearest neighbor increases with increasing tree size and trees become more evenly spaced with increasing size. By implications, weaker trees that are close to stronger neighbor are eliminated.

Doughil *et al*. (1999) stated that bush encroachment is not a permanent phenomenon, and a savanna could be changed to its grass-dominated state by favorable management or environmental conditions

1.4.4 Spatial pattern of plants

Plants are not evenly distributed in nature. Differences in environmental conditions, resources, neighbors, and disturbance are but a few of the factors that influence the population dynamics and spatial distribution patterns of plants (Barbour *et al*., 1987). Plant distribution patters may be used to identify and understand underlying processes responsible for woody species establishment. Any population is a community, at a given scale of observation, presents one of the three distribution patterns: aggregated (clumped), random, or regular, depending on the underlying processes (Fangliang *et al.*, 1997). Aggregate patterns have been explained in terms of regeneration ecology such as regeneration close to seed sources, vegetative regeneration or the occurrence of safe site. Aggregated patterns may also be the result of disturbance (Harpe, 1977). Regular spacing of even-sized individual of the same species has been interpreted as a result of density dependent mortality caused by intra-specific competition for evenly distributed resources (Philips & McMahon 1984).

Since invasive species can be distributed in any of the three patterns, which may also play a role in their recruitment and abundance or densities, understanding these plant arrangements may be an important tool in managing bush encroachment in savannas. According to Fangliang *et al*. (1997), spatial patterns shift from high clumping to looser intensity or random distribution when moving from juveniles to adult trees of the same species. Meaning large trees are less aggregated. This is due to elimination of a neighboring tree through intra-specific competition. This is an indication that the system, through plant competition, can manage itself by self-thinning, and thus, reducing bush densities. This will result in an open savanna comprise mostly of large trees. This can be comprehensively researched and monitored over a longer time.

Chapter 2

2.1 Materials and Methods

2.1.1 Description of the study area

The study was carried out at the University of Namibia's Neudamm agricultural campus (30 km east of Windhoek), and at farms Otjinakwi and Dooringboom, owned by the university as well. These two farms are situated in the Otjiwarongo district, and the vegetation is characteristic of the Thornbush savanna. Neudamm, which is also a research/teaching facility, lies between 22^{o} and 23.30^{o}S and 15.30^{o} and 18.30^{o}E in the Highland savanna of Namibia. This vegetation is in the central part of Namibia within the Tree and shrub biome, and occupies approximately 45 000 km2 or 5.5% of Namibia's land area (Coetzee, 1998 as cited in Joubert et al., 2008).The activities on the farm are a combination of small stock (goats and sheep) and large stock (Beef and dairy) farming, as well as poultry, pig and game production. The area receives an annual rainfall of about 350 to 400 mm (Mendelsohn et al., 2002).

Precipitation is highly variable and seasonal, 80% of the annual rainfall occurring from January to March. Windhoek's long-term mean annual rainfall (1892-2003) is 361 mm (CoV = 40%). The annual water deficit is approximately 2000 mm. In summer, average maximum temperatures are lower (about 29^{o}C) than in lower-lying savannas while winters are fairly cold (minimum temperature averages 3^{o}C) (Mendelssohn et al., 2002).

The terrain is broken and undulating, at altitudes of 1350-2400 m above sea level. The Highland savanna is characterized by woody species including *Acacia mellifera*, *A. hereroensis, A. hebeclada, A. reficiens, Euclea undulate, Dombeya rotundifolia, Tarchonanthus camphoratus, Rhus marlothii, Albizia anthelmintica and Ozoroa crasenervia.* (Joubert et al., 2008). Climax grasses include *Brachiaria nigropedata, Anthephora pubescens, Heteropogon contortus, Cymbopogon spp., Digitaria eriantha,* and *Eragrostis nindesis* (considered a sub-climax grass) (Joubert, 1997). Commercial ranching was initiated in the late nineteenth century in the Highland savanna. Commercial cattle ranchers maintain a fairly static stocking rate of about 15 ha/LSU on farms that are typically 5000 ha in extent. Very little of the area supports a climax grass layer today (Joubert *et al*., 2008).

2.2 Methodologies

2.2.1 Site selection

The study site was identified through field observation by selecting camps in the large-stock section of the Neudamm farm based on the state of encroachment by pure stands of *A. mellifera*. Three camps in the G-section (6, 7 and 8) and two in the C-section (C1 and C3) were selected as they were encroached by pure stands of *A. mellifera*. The three camps in G-section are divided by a dry river, into two sections or blocks. At Otjinakwi and Doringboom farming units, only one camp in each was identified for data collection.

2.2.2 Data collection procedures

Data was collected using two approaches. One was to identify ten clumps in each camp, thus five clumps in each of the two sections (blocks) of the camps (only in G-section), and as well five in one camp of each of the two farms. Even-sized clumps of *A. mellifera* were identified, and a reference tree within the clump was this tree was selected based on ease of access to collect data or take measurements from it, then the following information was recorded; its height, crown form as shown in Figure 1 (after Smit, 1989), crown diameter, distances to two neighbors of same height, and distance to a neighbor of smaller and larger size (height). Measurements were taken using a calibrated wooden pole for heights and a 50m measuring tape for distances. The clumps were selected to be a representation of the whole block or camp, and size classes of trees.

Under these clumps, soil samples and data on the grass species composition was collected. Soil samples were collected at a depth of 20cm under and outside canopies and were analyzed for Phosphorus (P), Calcium (Ca), Magnesium (Mg), Potassium (K), pH, Electrical conductivity (Ewc) and Organic matter (OM) at the Ministry of Agriculture Water and Forestry (MAWF) laboratory in Windhoek. The grass species composition data was collected using a 0.5 x 0.5m quadrat from under and from 1m outside the canopies in four compass directions around the clumps, meaning eight quadrats per clump. The composition was then determined by counting the number different species appearing in a quadrat.

The second approach used the nearest neighbor method. Four transects (50m tape measure) were laid out in each camp. Data was collected along transects as follows: any *A. mellifera* nearest to every fifth meter along a transect line was selected, and its height and canopy diameter were measured, as well as distance to its nearest neighbor, and the height of the neighbor were recorded.

Figure 1a-c: Illustrated different tree crown forms (B, C and D) of woody plants, from Smit (1989).

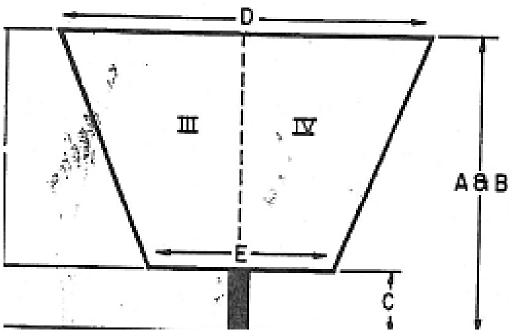

Figure 1a: Incomplete cone-shaped form (B)

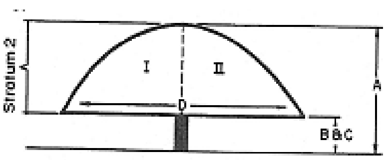

Figure 1b: Dom-shaped crown form (C)

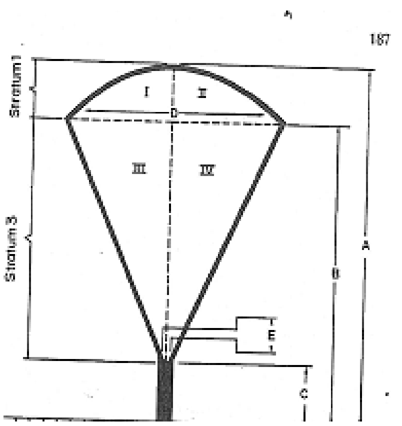

Figure 1c: Cone-shaped crown form (D)

2.3 Statistical analysis

A Shaprio-Wilk normality test was used to test for normality and transformation of data where necessary. To investigate the relationship between Size (height) and density, plants smaller than 1m in height were excluded from the data so that it could be transformed using a square root transformation (p=0.367) to achieve normality. A linear model test was used to test for the relationships between density versus height, crown form versus height, and crown diameter versus height. For crown form versus height, a Pearson's chi-square test was used. The R v2.12 program was used for grass species composition and nearest neighbor analysis. Regression for analysis of the tree height and distribution was also done. The grass species composition was analyzed by Canoconical Correspondence Analysis, and the analysis of variance.

Chapter 3

3.1 Results and discussion

3.1.1 Size-density relationship

To investigate the relationship between height and density, plants smaller than 1m in height were excluded from the data so that it could be transformed using a square root transformation (p=0.367) to achieve normality. For all the seven study sites (G6, G7, G8, C1, C3, Doringboom and Otjinakui), the analysis showed that there is no significant relationship between size (height) and density of *Acacia mellifera* ($P>0.05$),(appendix 1), but a significant relationship was found to be between size (height) and crown diameter ($P<0.05$), (appendix 2), and between size and crown form ($P<0.05$), (appendix 3), for all the sites and for both approaches used, suggesting that location did not affect these relationships. As for size and density, the results indicate that tree size is not influenced by tree density. As observed, clumps are comprised mostly of even-sized trees. With the nearest neighbor method, the analysis results ($P<0.05$, appendix 4) and the observed similarities in heights of two neighboring trees, the indication is that the heights of the two neighbors are related (generally small trees have small neighbors). This means that the seedlings of *A. mellifera* establishes in cohorts, and may eventually clump at maturity.

Self-thinning results from competition over a limited resource such as water, sunlight or soil nutrients over a particular period. Considering the similarity in plant density, it might be assumed that competition is not yet so severe as to cause visible tree mortality or retarded growths in some individuals within the clumps or stands.

Mortalities or retarded growths in *A. mellifera* might, however, be observed given a longer period of observation or may only be observed when physical disturbance such as herbivory and fire is evident. It would also be necessary to monitor trees of similar sizes but occurring at different densities, to determine what effect would different densities have on the tree size. Thus, *A. mellifera* may grow in even-sized cohorts until such time that disturbance and resource depletion take effect. In fact, arid ecosystems are characterized by slow rates of changes and thus need on average longer time periods to conclude processes than northern hemisphere hardwoods (Sankaran *et al*., 2005).

Allowing the natural system to manage itself (through self-thinning) in the absence of immediate disturbances is a longer process, therefore, it suggests that competition be directly or indirectly induced by either human interventions (e.g. use of herbivores as a means to suppressed individual trees, thus losing their competitive ability and in turn enhancing the neighbors to outcompete them) or can be induced by sudden changes in environmental or climatic conditions (e.g. drought).

As stated by Shackleton (2002), for the nearest neighbor analysis, the nearest neighbor is not necessarily the major competitor because it can be found that the nearest neighbor is a very small-sized tree while a near but not the nearest can be a larger tree. Thus, it may be that competition is not necessarily the main driving force in shaping distribution or spatial patterns of *A. mellifera* in savannas but there are other forces that may be responsible. Such forces could result from disturbances which affect individual plants' ability to establish or grow at the same rate as its neighbor. Disturbance on the soil (trampling or compaction) for example may suppress successful germination or growth of seedlings, or also, disturbance in a form of fire and herbivorous activities may suppress subsequent growths of trees, and thus resulting in retarded statures in stands, hence smaller neighboring trees, and/or mortalities.

It can further be assumed that some individual trees, due to their position, particularly along animals' pathways, succumb to constant disturbance or physical damage (apart from browsing) as animals rub against them when moving, thus disturbing the apical meristem and the potential growth of the tree. Also, trees on the edges of the clumps will be less subject to competition for water and sunlight, as they are able to spread their canopies and roots away from clumps in order to capture sufficient or additional required amounts of the limited resources for their optimum growth. They would do so without being obstructed by the other trees concentrating much of their root systems and canopies around a smaller area to access water and sunlight. These trees that are enclosed in the clumps are unable to spread their roots and canopies outward because they are obstructed by the neighbors on the edges.

Therefore, position within a clump or stand may play a role in determining the rate of growth and potential of an individual tree to survive. The result from this study agrees with the study by Shackleton (2002) on the prevalence of woody plant competition in South African savanna, that the evidence for competition as a determinant of savanna woody community is not as prevalent as may be thought.

Therefore, the distribution, structure and functioning of *A. mellifera* as a woody plant in the highland savanna may not be determined by competition alone, but a combination of factors may greatly contribute.

3.1.2 Size-crown diameter relationship

Size (height) and crown diameter showed a significant relationship ($P<0.05$), with crown diameter increasing with increasing tree height (Figure 2: crown diameter was transformed to obtain normal distribution of data). As the tree grows taller, its photosynthetic requirements increases, and an improvement in the efficiency at which the plant photosynthesizes is required, hence increasing crown diameter. The crown of a tree responds to the progressive growth of the tree by increasing the surface area for capturing sufficient amount of sunlight which is then converted to chemical energy during photosynthesis process. This energy is used to drive plant cell processes that are essential for the tree growth and survival. The process of photosynthesis in woody plants is also essential to leaving organisms requiring oxygen-carbon dioxide exchange for survival, since trees/plants take in carbon dioxide and release oxygen in the process. This makes woody species to be very important in curbing global warming through atmospheric carbon sequestration.

However, since the density of plants does not seem to change as the plant height increases the increased crown diameter leads to crowns overlapping. This in turn results in reduced light penetration and increased rainfall interception, which may cause different growth responses from different grass species. Such responses depend on particular growth requirements of different grass species. Some grasses will prefer little light and the moist cool environment under canopies while some will prefer direct sunlight. Such overlaps also results in a closing/blocking of passage ways for animals. This allows only some parts of the veld to be over-utilized since animal movement to alternative foraging sites is restricted. In turn, degradation in a form of bush encroachment in particular may result, and thus poor animals' performance.

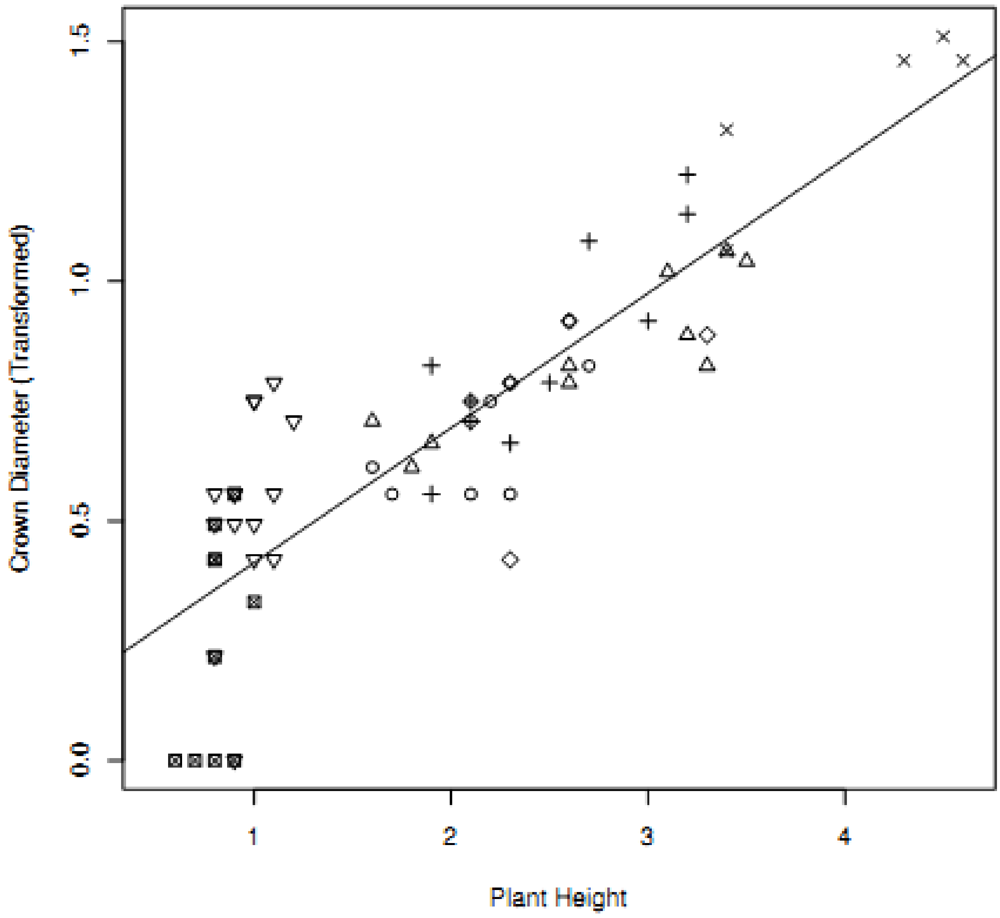

Figure 2: Height and crown diameter relationship

3.1.3 Size-crown form relationship

The study showed a significant relationship ($P<0.05$) between size (height) and crown form. Different sizes of trees have particular different crown forms. For example, as observed in most of the trees, they are most likely to develop crown form D (Cone-shape form) the taller they grow. It is an indication that sunlight becomes critical for increased photosynthetic requirements of a growing tree. Hence cone-shape crown growing upright to capture optimum light. Therefore, it may be that the height of the tree shapes the crown, suggesting that further investigations be done if the reverse could also be true.

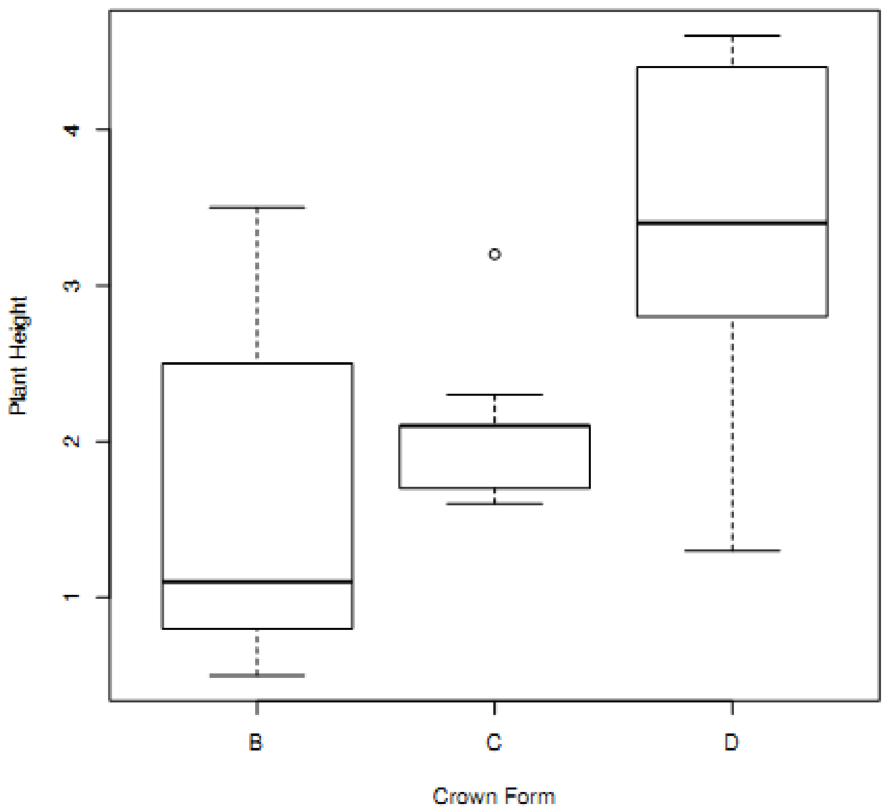

Figure 3: The distribution of plant height measurements for each crown form.

Figure 3 above shows the distribution of height measurements for each of the crown form shown in Figure 1. The indication is that trees of heights between 0.6m and 2.5 mostly develop crown form B, which is the incomplete cone-shape type, where the maximum canopy diameter occurs at the top of the tree. Trees with heights above 3m mostly develop canopy type D, which is the cone-shape type. Thus, mature or larger trees have cone-shaped canopies which is said to be an ideal form of growth. As for crown shape C, the dome-shape type, it is represented by a small number of trees that are mostly of medium-size (2m on average), but also observed in some larger trees.

Field observations revealed that crown form B appears mostly in trees of medium-size or less (≤ 2m). Such shrub-sized trees are the most problematic in encroachment since their canopies are likely to spread outwards or overlap to neighboring trees and thus closing off access, mainly for foraging animals. At the same time, trees of such a size are succumbed to disturbances due do its canopy volume mostly within the browse and fire range as compared to larger trees bearing a cone-shaped crown form (D) that are above such a range.

In bush encroachment management, thinning mostly targets size classes of 2.5 m and below, where it has been indicated in De Klerk (2004) that only a 10% of their density must be maintained, whereas larger trees are maintained at least at 90% of cover, to create open veld. That is an indication that, on average, most thickets formed are of trees mostly of 2.5m in height, or below.

3.1.4 Height-distance to neighbour relationship

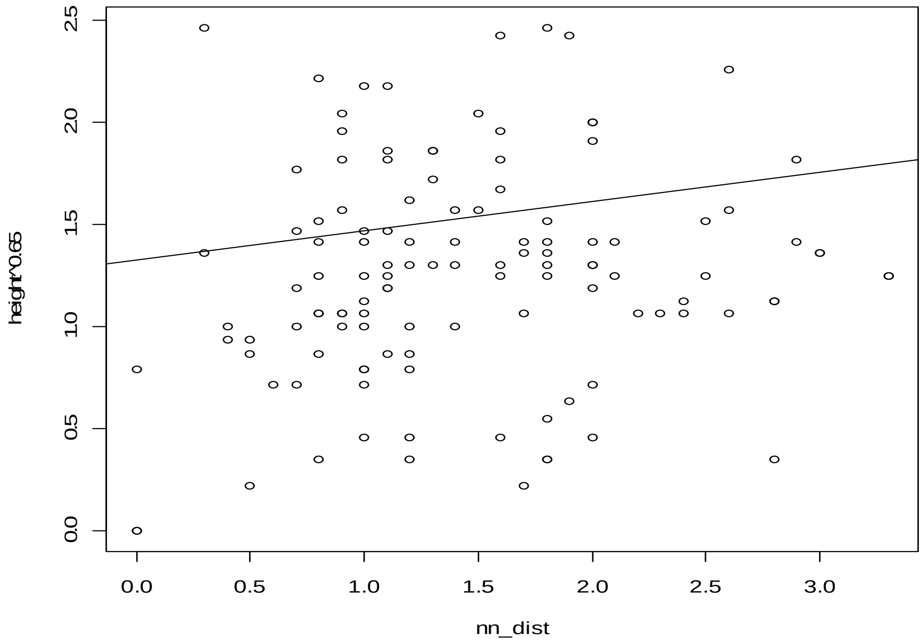

Figure 4: The relationship between height (m) of point tree and distance (m) to its nearest neighbor. The figure indicates that there is a very poor relationship (P>0.05) (R^2 -0.02522) between the heights of plants and the distance to the nearest neighbour (appendix 5). Therefore, the height of an individual *A. mellifera* tree is not influenced by the distance to its nearest neighbour or another *A. mellifera tree*. The distances between neighbours mostly range between 1m and 2m, for most tree sizes. This also means that density does not influence size, and that the presence of one tree is not influence by the presence of its neighbour, hence random distribution of *A. Mellifera* in the area.

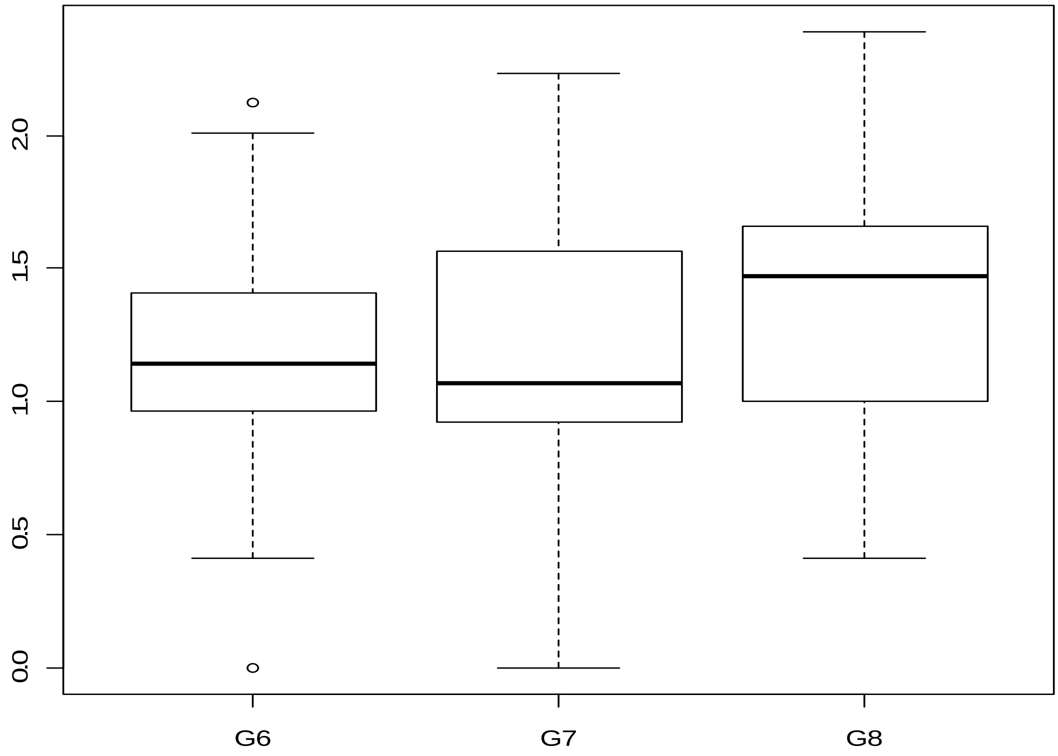

Figure 5: The distribution of plant height measurements for each of the camps surveyed.

This shows that camp G8 had taller or larger trees than the others, followed by G7, then G6 having shorter or smaller trees. The difference in heights distribution between the three locations can be attributed to management among other factors. It was confirmed that camps were treated for bush with a chemical (Molopo granules) some unspecified time back, but G6 was again treated in year 2008, hence abundance of saplings or smaller young trees, assumed to be a re-establishment or regeneration of *A. mellifera*. These camps are also routinely grazed by gestating and lactating beef cattle (Afrikaner breed) from January to August every year.

3.1.5 Grass species composition

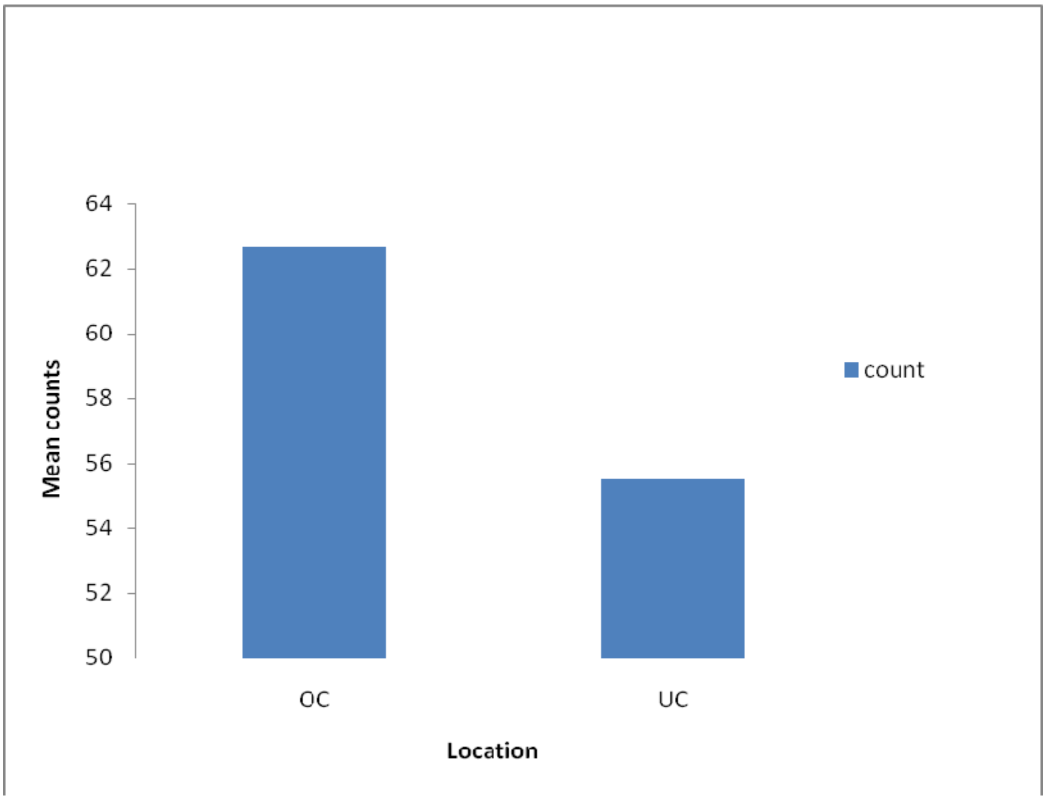

Figure 6: Grass species composition under (UC) and outside canopy (OC).

The composition survey was done by counting the number of species appearing in a quadrat. The figure above shows only result for camps G6, 7 and 8 at Neudamm. There was a significant difference in the grass species composition found under and outside canopies of *A. mellifera* (P<0.05) (appendix 6). The grass species composition outside the canopies had a higher number of species than under canopies. The reasons for lower number of species under canopies could mainly be insufficient amount of light and water as a result of interception by the tree canopies, and may be that the soil nutrients are not in sufficient amounts to support a higher composition. Also, disturbance has a role to play in a lower turnout of number of grass species under canopies; this is through trampling and grazing by animals basking under trees for shade.

The grasses under trees are mostly young and greener, and animals opt for them first. Therefore, that has led to some, amongst others, very sensitive grass species (*Anthephora pubescens and Schmidtia pappophoroides)* to escape such disturbances and establish outside canopies, leaving only some opportunistic grasses (e.g. *Porgonathria fleckii and Setaria verticilata* amongst others) and forbs, since they may be favored by or withstand the conditions. The disturbance or grazing outside canopies is not as constant and concentrated as under canopies. Outside canopies, animals mostly graze in motion because of the larger grazing radius and a greater range forages to select, whereas when under shades or canopies, they stand to graze, avoiding sunlight. Although trees are said to create favorable environments for grasses under their canopies, the case with the *A. mellifera* clumps as shown by results from the study is that such environments do not favor all grass species, but only some. The tree-grass interaction can only favor one that captures and best utilize an optimum combination of moisture, sunlight, and nutrients from the soil. Therefore, tree-grass interaction can be positive or negative to any of the two depending on the species involved.

3.1.6 Mineral composition

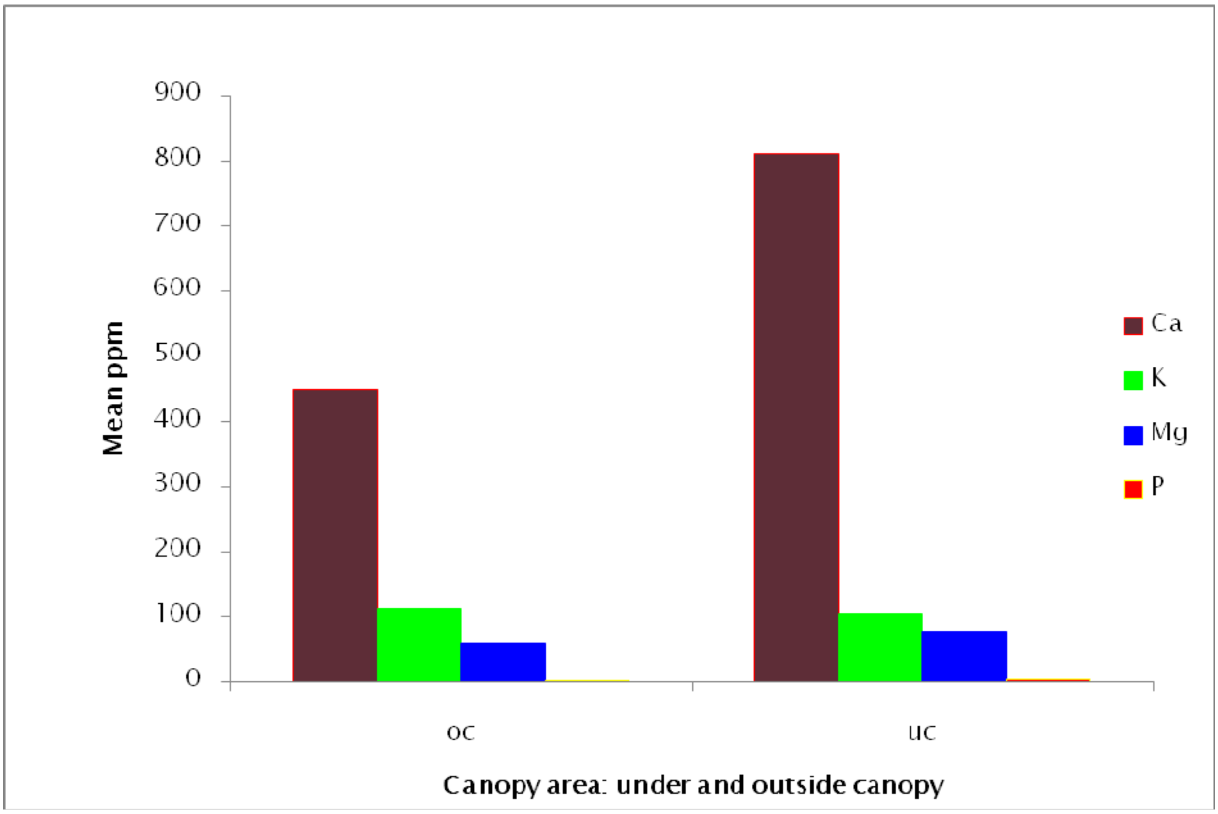

Figure 7: Mineral contents under (UC) and outside canopy (OC).

For the mineral contents mean parts per million (ppm), only Calcium and the Organic matter, amongst others, that were found to be significantly ($P<0.05$) higher under canopies than outside canopies of *A. mellifera* (table 1). For the other minerals, together with pH and electrical conductivity, there was no significant difference ($P>0.05$, appendix 7). The higher amounts of mineral (in this case only calcium) contents and organic matter under tree canopies can be attributed to manure or animals defecating under trees during resting, birds' droppings, and better nutrient cycling resulting from leaf-litter/material decomposition amongst others. The coverage of the soil surface under canopies by leaf material, and rainfall interception by canopies prevent soil nutrients to leach deep down to irretrievable depths due to minimized rate of water infiltration, whereas the nutrients outside canopies are exposed to run-offs, fast leaching, and to direct sunlight, hence the differences in contents. Location and canopy (UC and OC) does not have significant effects (P>0.05) on soil pH and electrical conductivity.

Table 1: Soil nutrient contents under and outside canopy

Element/nutrient	Under canopy (ppm)	Outside canopy (ppm)	Significance (p-value)
Phosphorus	**3.46**	**2.04**	0.2823
Potassium	**105.45**	**112.90**	0.6927
Calcium	**789.00**	**463.45**	4.22e-05
Magnesium	**83.00** o	**74.81**	0.1761
Organic matter	**2.86**	**1.76**	0.0009724

3.2 Conclusions

The study showed that there is no significant relationship between size and density of *Acacia mellifera* in the highland savanna of Namibia. Therefore, based on that result, tree density does not affect tree size. Intra- or single specie competition among woody plants is induced by an increased demand for a declining or limited resource such as water, soil nutrients and sunlight, hence self-thinning or density-dependant mortalities. In this study, there seem to be no evidence of self-thinning, or it may be that current rates of competition are as yet insufficient to result in self-thinning or for density to influence tree size. Additional time for observation and monitoring may be required so that more concrete conclusions can be made; therefore, the conclusive remarks in this study and the work done this far is groundwork.

- Generally, the size of an individual tree would not be influenced by stand density, unless disturbances and intra-specific competition (in a long-run) sets in.
- The observed similarities in heights of *A. mellifera* trees of all height classes in clumps may lead to a conclusion that the specie establishes in cohorts and grow in even-sized clumps until maturity.
- The increased abundance of pure stands of *A. mellifera* would be assumed that the rate of inter-specific competition may have been greater than the rate of intra-specific competition in savannas. Thus, assuming that *A. mellifera* may be competitively advantaged.

The poor or insignificant relationship between size and density of *A. mellifera* suggest that Intra-specific competition is less prevalent in the stands. And in particular, competition is not the sole determinant of the establishment, distribution patterns and structure of *A. mellifera*. Other factors (e.g. disturbances) may play a role.

The result from this study agrees with the study by Shackleton (2002) on the prevalence of woody plant competition in South African savanna, stating that evidence for competition as a determinant of savanna woody community is not as prevalent as previously suggested.

Based on the nearest neighbor analysis, the distribution of *A. mellifera* in the highland savanna is found to be random, thus, the presence of an individual tree does not influence the presence of another. Meaning, no evidence of competition yet. The distance separating two neighbors does not have any effluence on the two. A tree of any size can be the nearest neighbor of a tree of any size. Had intra-specific competition played a role, a regular pattern of distribution would have been realized, shown by one of the two neighboring trees being larger or smaller than the other. Retarded statures or mortalities would be noticeable as well.

Although trees in general presents favorable microenvironment to the herbaceous vegetation (grasses), and enriching the soil under their canopies, the study concludes that, under canopies of *A. mellifera* clumps, grass species composition is lower than in the open or outside canopies, whereas the soil macronutrients contents are higher under than outside canopies. The higher nutrients' contents under canopies could be attributed to herbivores droppings/feces excreted when loafing under shades, and as well, the leaf litter decomposition and minimal leaching amongst others.

The microenvironments created under tree canopies may not sufficiently support many grass species. There are pull and push factors under tree canopies, in this case, under *A. mellifera* canopies. Such factors among others include; amount of light, moisture, soil nutrients and herbivores' activities, therefore, influences of an amalgamation of such factors may either recruit or displace particular grass species, depending on species requirements for optimal establishment. Since nutrients were higher under canopies than outside, then they did not influence the lower grass composition. In this study, it seems the influences did not favor recruitment of many but only a few as compared to outside canopies. Therefore, higher grass species composition can only be achieved away or outside tree canopies, and vice versa for soil nutrients' contents.

3.3 Recommendations

The processes of the natural system and functioning in shaping savannas are slow, and yet poorly understood. Bush encroachment is a process resulting from processes of the functioning of the natural systems. Controlling *A. mellifera* encroachment is a fight against nature's complexities. Therefore, the size-density relationship requires a longer time period to investigate, and the processes that govern these relationships or interactions in savanna vegetations also need to be investigated and properly understood.

The study suggests that natural processes responsible for distribution patterns and structure of woody species are complex, and their effects are conspicuous after a protracted time period, therefore, several seasons of observations and monitoring would be recommended.

In fact, arid ecosystems are characterized by slow rates of changes and thus need on average longer time periods to conclude processes than northern hemisphere hardwoods (Sankaran *et al*., 2005).

For management, the basic control of bush encroachment, particularly by *A. mellifera* can be achieved through:

- Introduction of disturbances (herbivory and fire) from sapling stage in a controlled manner to suppress establishment and growth, or re-growth. This will result in some seedlings/trees to lose their competitive ability, and thus their potency to grow to a potential size is suppressed.

- Considerate mechanical thinning of trees. Thinning or removal of neighboring trees is a way of creating opens spaces in the veld (opening savannas) to stimulate grass production and free movement of foraging animals. Therefore, thinning must be done in a manner that considers the roles that different tree sizes play in the ecosystem. In particular, the most problematic size class (Small to medium or sapling height to about 2m tall trees), are a source of food to short browsers. Therefore, a sort of a balance should be maintained. Thinning can also be economical, where chopped trees can be used for charcoal production or as fire wood both for sale and household use.

- Stem/trunk burning. Some individual trees can be selected, and their stems burned. Wood (as fuel) can be put around the base of a tree's trunk and set alight to burn it so that the tree dies off.

- Use of chemicals (e.g. Molopo) against *A. mellifera* is common and can be recommended, but the cost must be well taken into account and the application should be targeted to the problem trees or species.

Making use of the natural system in managing bush densities means that the natural functioning of the savanna system is allowed to stimulate the development of an open savanna comprised mainly of large trees (Tainton, 1999). With the natural system functioning, inter- or intra-specific competitions among species play a role. This is where self-thinning would take place by eliminating trees that are less competitive over a limited resource such as water, sunlight and soil nutrients. Self-thinning creates open spaces, allowing the remaining trees to grow with less or no competition until potential maturity. Disturbances such as fire and herbivory may have their continued influence on vegetation dynamics, the outcome may depend on the intensity at which they act.

Generally, trees/woody plants possess ecological roles in their nature. Any form of control must be done with a mind that they are important components of the ecosystem, and their roles are needed in the ecosystem structure and functioning. Therefore, management should aim at stimulating a true savanna co-dominated by both woody and grass species, and sustaining a balanced vegetation to the benefit of all components of the ecosystem.

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Appendices

Appendix 1: Linear model test for size- density relationship

```
Data:  tmp$height^0.5

W = 0.9724, p-value = 0.3673

Lm (formula = height^0.5 ~ dist_same1, data = tmp)

Residuals:

    Min       1Q   Median       3Q      Max

-0.50744 -0.17884 -0.02479  0.20380  0.59843

Coefficients:

               Estimate Std. Error t value Pr(>|t|)

(Intercept)  1.51657    0.08624    17.585   <2e-16 ***

dist_same1   0.01984    0.03599   0.551    0.584
```

Appendix 2: Linear model test for height-crown diameter relationship

```
Lm (formula = log(crown_diam)^0.625 ~ height)

Residuals:

    Min       1Q   Median       3Q      Max

-0.62570 -0.14602  0.02478  0.17212  0.56014

Coefficients:

                Estimate Std. Error t value Pr(>|t|)

(Intercept) 0.007984   0.068192   0.117    0.907

Height      0.283200   0.030055   9.423 4.53e-15 ***
```

Appendix 3: Pearson's Chi-squared test for height-crown form relationship

Pearson's Chi-squared test

Data: data01$crown_form and data01$height

X-squared = 90.394, df = 54, p-value = 0.001398

Appendix 4: Pearson's product-moment correlation test for Height of point tree versus height of its neighbor

Pearson's product-moment correlation

Data: height and nn_height

t = 8.4911, df = 138, p-value = 2.909e-14

Alternative hypothesis: true correlation is not equal to 0

95 percent confidence interval:

0.4651014 0.6851216

Sample estimates:

Cor 0.585803

Appendix 5: relationship between height and distance to nearest neighbour

```
lm(formula = height^0.65 ~ nn_dist)

Residuals:
      Min        1Q    Median        3Q       Max

-0.071626 -0.021808  0.000604  0.025294  0.066481

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
```

```
(Intercept)  1.0996995  0.0107460 102.335   <2e-16 ***
```

Nn_dist -0.0008766 0.0043404 -0.202 0.841

```
Residual standard error: 0.0326 on 38 degrees of freedom

Multiple R-squared: 0.001072, Adjusted R-squared: -0.02522

F-statistic: 0.04079 on 1 and 38 DF,  p-value: 0.841
```

Appendix 6: Comparing species composition of the different camps

Compare beta diversity

Response: Distances

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Groups	1	0.7049	0.70490	26.215	6.303e-07	***
Residuals	238	6.3997	0.02689			

It was found that the diversity between the locations differs. This is due to a difference in the composition of the species rather than in the proportions in which they are found. This is shown by the results of the CCA, below.

Canonical Correspondence Analysis

Comparison of the grass composition under trees and in the open.

Permutation test for cca under reduced model

Terms added sequentially (first to last)

```
Model: cca(formula = count.df2 ~ location, data = predictor.df)
          Df  Chisq      F N.Perm Pr(>F)
location   1 0.0645 2.4250   1999  0.001 ***
Residual 238 6.3264
```

Appendix 7: Soil analysis

pH

```
lm(formula = pH^2 ~ location + canopy, data = data01)
Residuals:
     Min       1Q   Median       3Q      Max
-12.1387  -1.9220   0.2905   2.6108   6.2599

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)   43.1054     1.7425  24.738  < 2e-16 ***
locationG6B1  -6.4737     2.3117  -2.800  0.00816 **
locationG6B2   4.6571     2.3117   2.015  0.05146 .
locationG7B1   0.8664     2.3117   0.375  0.71000
locationG7B2   0.1944     2.3117   0.084  0.93344
locationG8B1  -3.7537     2.1624  -1.736  0.09113 .
locationOtji   5.6276     2.3117   2.434  0.02000 *
canopyuc      -0.0532     1.2072  -0.044  0.96510
```

Ecw

Shapiro-Wilk normality test: data: ecw^0.25

W = 0.9659, p-value = 0.3939

ANOVA

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Canopy	1	1012.5	1012.5	2.9779	0.09627	.
Location	4	4471.5	1117.9	3.2879	0.02622	*
Residuals	26	8840.0	340.0			

OM

Could not achieve normality through coding – used the Kruskal Wallis test.

Kruskal-Wallis rank sum test: data: OM and canopy

Kruskal-Wallis chi-squared = 10.8793, df = 1, p-value = 0.0009724

P

Shapiro-Wilk normality test: data: P^0.2 W = 0.9469, p-value = 0.1174

ANOVA

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Location	4	0.20515	0.051287	1.4817	0.2365
Canopy	1	0.04173	0.041728	1.2056	0.2823

Residuals   26 0.89993 0.034613

K

Shapiro-Wilk normality test: data: K

W = 0.9607, p-value = 0.2873

ANOVA

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
location	4	2674	668.47	0.2629	0.8991
canopy	1	406	406.12	0.1597	0.6927
Residuals	26	66120	2543.07		

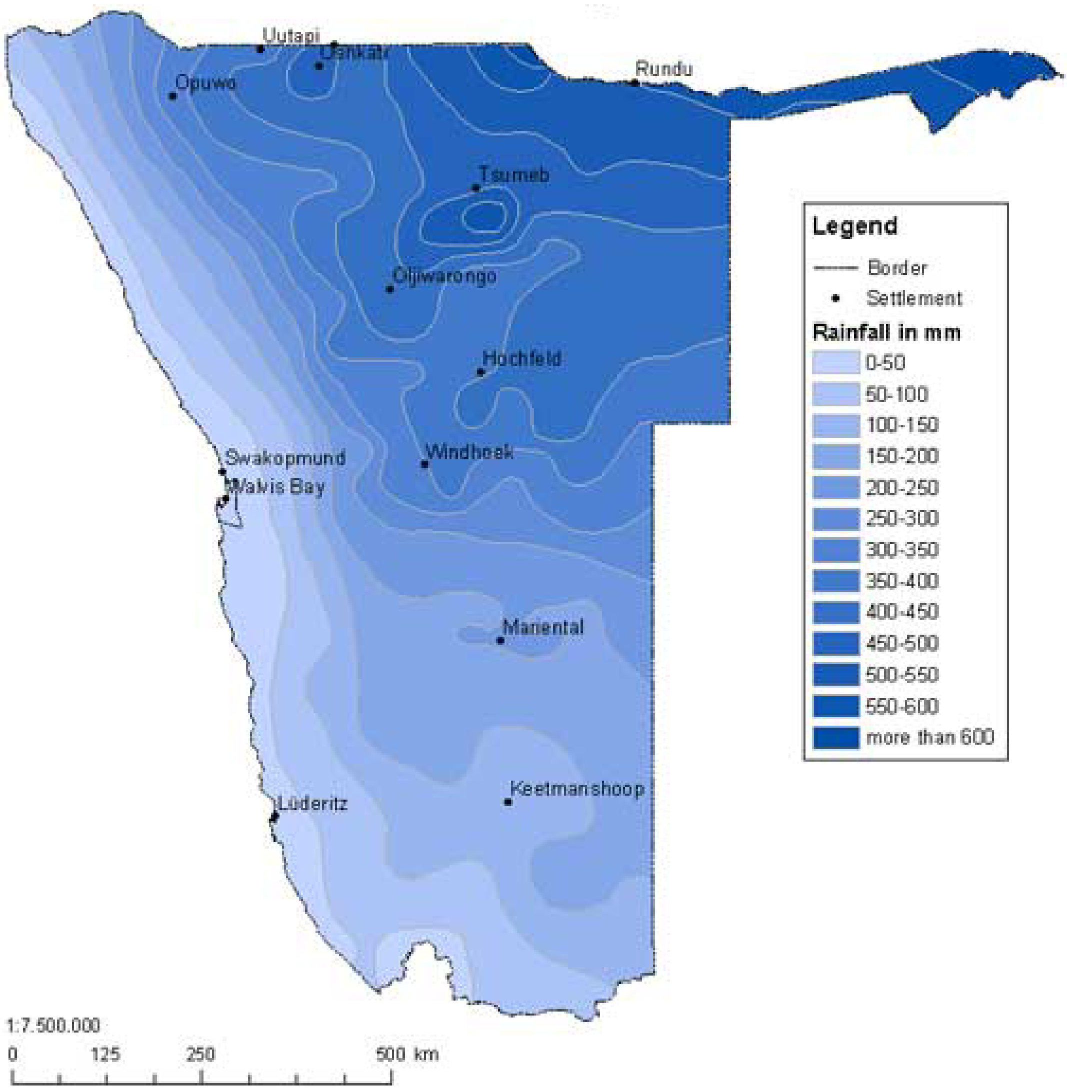
Appendix 8: Grass species appearing on sites

1	*Eragrostis superb*	*8*	*Porgonathria fleckii*
2	*Aristida congesta*	*9*	*Microchloa cafra*
3	*Aristida meridionalis*	*10*	*Melinis repens subs repens*
4	*Aristida adscensionis*	*11*	*Melinis repens subs grandiflora*
5	*Erasgrostis trichophora*	*12*	*Stipagrostis uniplumis*
6	*Eragrostis lehmaniana*	*13*	*Cenchrus cilliaris*
7	*Eragrostis scopelophyla*	*14*	*Heteropogon contortus*

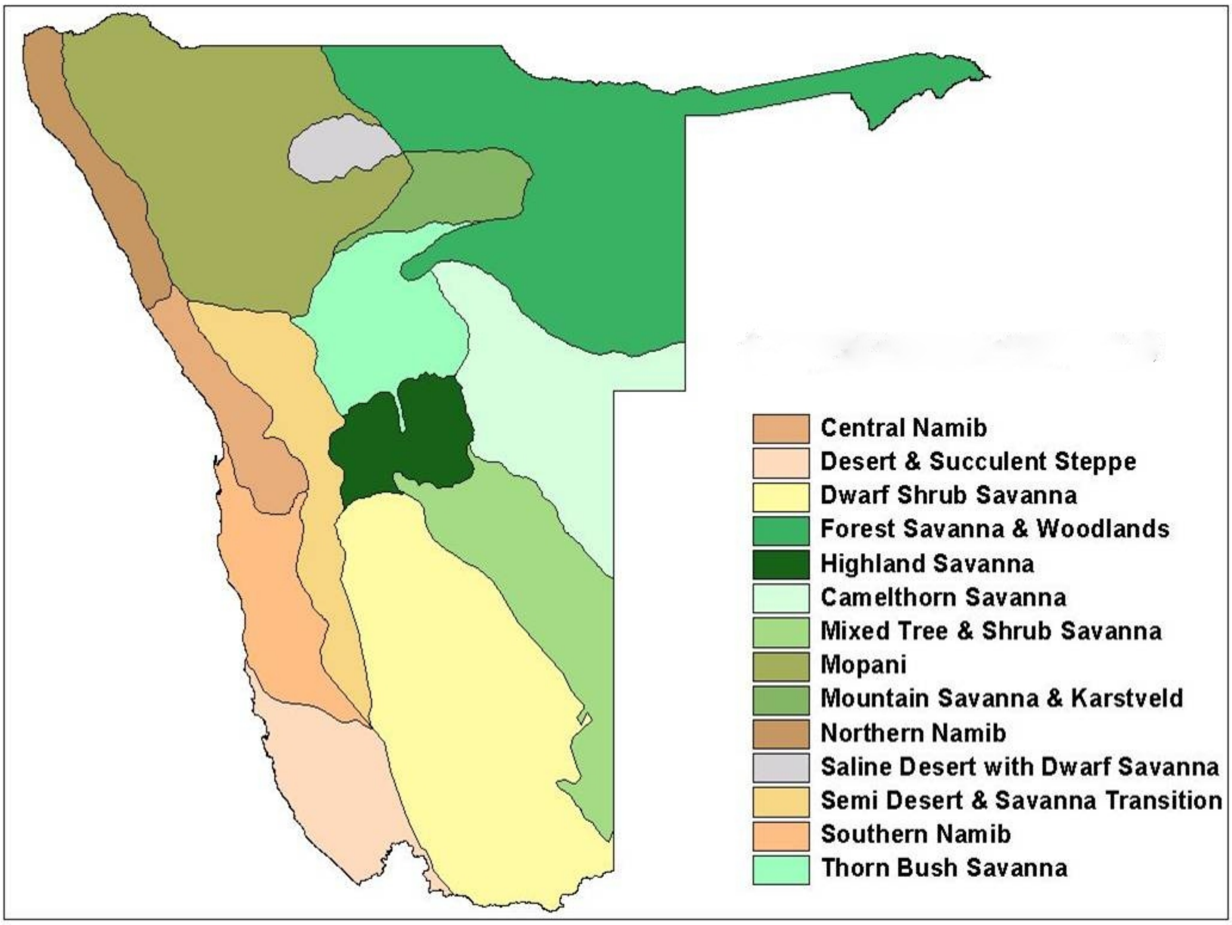
15	*Eragrostis nidensis*
16	*Fingerhuthia Africana*
17	*Setaria vercitilata*
18	*Schmidtia papophoroides*

19	*Aristida stipitata*
20	*Eneapogon cencroides*
21	*Brachiaria nigropedata*
22	*Anthephora pubescens*

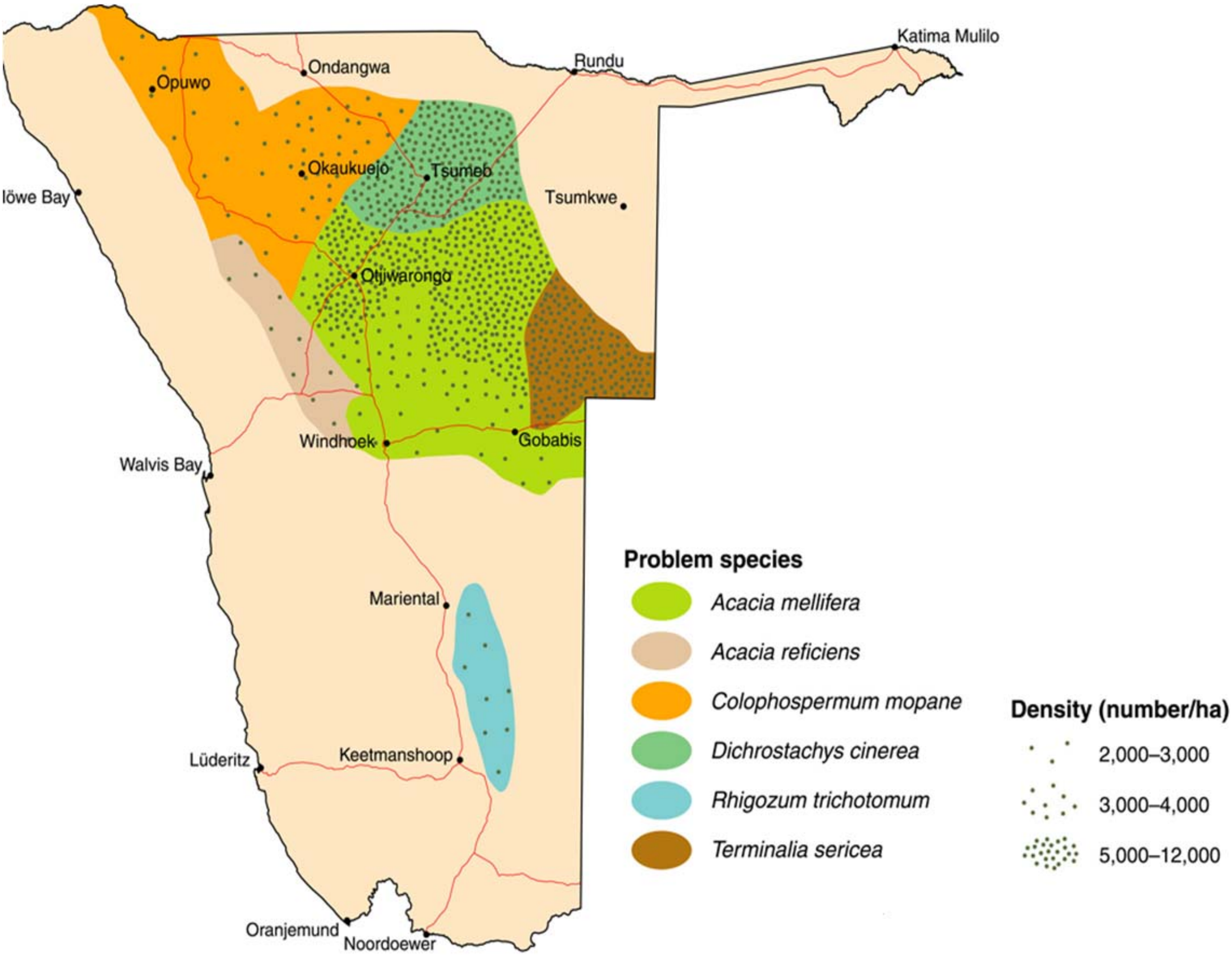
Appendix 9: Average annual rainfall in Namibia



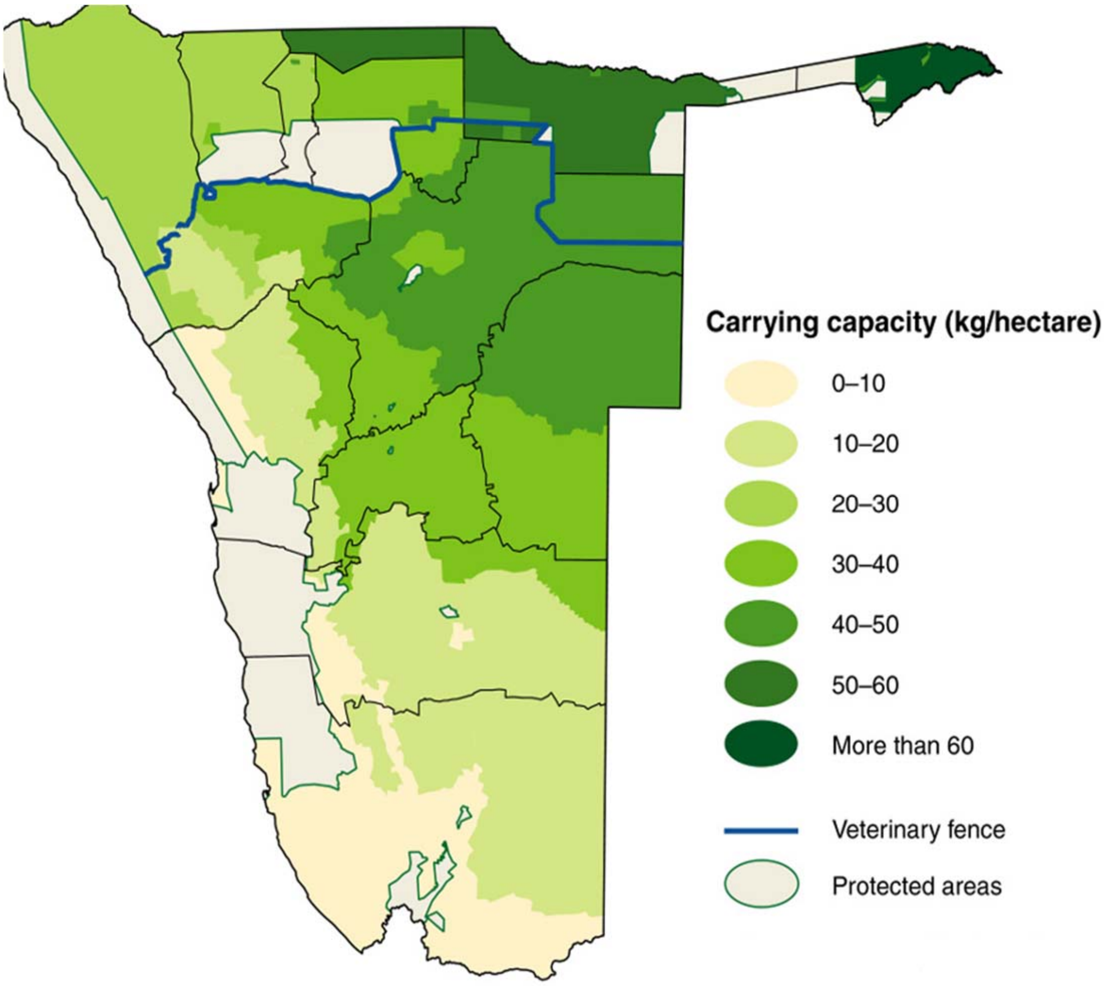
Appendix 10: Vegetation types of Namibia (Giess 1977)



Appendix 11: Problem woody species and their distribution in Namibia (Mendelsohn *et al*., 2002)



Appendix 12: Carrying capacity map of Namibia (Mendelsohn *et al*., 2002)



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