QUANTIFICATION AND CHARACTERISATION OF ENCROACHER BUSHES TARGETED FOR CONVERSION INTO LIVESTOCK FEED AT NEUDAMM FARM, KHOMAS REGION, NAMIBIA

A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENVIRONMENTAL AND NATURAL RESOURCES MANAGEMENT (BY THESIS)

OF

THE UNIVERSITY OF NAMIBIA

BY

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MARCH 2020

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ABSTRACT

Bush encroachment is a serious problem in Namibia leading to significant reduction in livestock production and biodiversity. Harvesting encroacher bushes for conversion into livestock feed is a practice becoming more common. Every encroached area is unique in species composition and density of encroacher bushes and hence characterisation of such bushes is essential prior to laying out harvesting strategies. The main aim of this study was to determine the species composition and estimate the amount of feed-suitable biomass of the dominant species constituting encroacher bushes in Block G of Neudamm Farm. Landsat images (Landsat 5 TM and Landsat 8 TM) of the study site were used to stratify the area into low, medium and high bush density classes to assess how encroachment changed between 1989, 2000 and 2017. In the high bush density areas, bush densities, species composition, diversity and similarity were analysed in relation to site, topographical positions and soil properties. Data were gathered from 27 sample plots (2 x 50 m). There was a 14% increase in area covered by high bush density between 1989 and 2017. *Senegalia mellifera* had the highest density and biomass across all sites and at all topographical positions. Bush density differed significantly only between sites. Site 2 had significantly higher bush density than Sites 1 and Site 3. This higher bush density in Site 2 was contributed by presence of high numbers (in excess of 10000 plants/ha) of small sized trees and shrubs. Only Sodium had a negative correlation (Pearson correlation) with bush density at different topographical positions (p=0.3888), this could be because Na increases osmotic tension, by which water is held in the soil and as result the plant die-off. The total biomass of bushes varied significantly across sites (Kruscal Wallis Test, P=0.024 and biomass fit for animal feed varied significantly across Sites Kruscal Wallis Test, P=0.027). This variation is linked to variation in bush density since Site 2 which had the highest bush density also had the highest biomass. It is concluded that 4.8 tonnes/ha can be harvested by selectively removing *S. mellifera*. The study recommends harvesting of only *S. mellifera* as this would yield large amounts of uniform feed and preserve other rare species especially those being given special protection like *Boscia albitrunca*, *Searsia lancea* and *Ziziphus mucronata*. Similar studies are recommended for other areas where encroacher bushes are to be harvested.

Keywords**:** ***Bush encroachment, Namibia, Senegalia mellifera, Species composition, diversity and density of encroacher bushes.***

List of conference proceedings

Shilume, K.T., Njunge, J.T., Angombe, S., & Ndeunyema, E. (2018). *Quantification and characterisation of encroacher bushes targeted for conversion into livestock feed in Neudamm Farm, Khomas region, Namibia*. Conference proceedings of International Conference on Agriculture and Natural Resources (ICANR 2018). UNAM Neudamm Campus: Khomas Region, Namibia

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LIST OF ABBREVIATIONS

AGB	Above Ground Biomass
ANOVA	Analysis of Variance
BE	Bush Encroachment
BECVOL	Biomass Estimates from Canopy Volume
EC	Electrical Conductivity
ETTE	Evapotranspiration Tree Equivalent
IVI	Importance Value Index
OC	Organic Carbon
OM	Organic Matter
SPSS	Statistical Package for Social Sciences
UNAM	University of Namibia

ACKOWLEDGEMENTS

My utmost appreciation goes to the Almighty God. If it was not for Him I could not have finished this research project. Secondly, my sincere gratitude goes to the Finnish Embassy for supporting me financially and Neudamm-UNAM Campus transport department for providing transport during the data collection around the farm and data analysis, at Windhoek. Many thanks to the staff Mrs Albertha Sipapa, Ms Negamba Sheya and Mr Japhet Mbusisi at Ministry of Agriculuture, Water and Forestry for helping me with soil analysis.

Much gratitude goes to my supervisors Prof Joseph Njunge, Dr Simon Angombe and Dr Elizabeth Ndeunyema, for being understanding and were able to guide me until the end of my study. I would not want to forget Mr Edward Muhoko, from the Ministry of Agriculture, Water and Forestry and Mr Edward Kuliwoye, from Communal Land Development Project for helping me with the Geographical Information System (GIS) and remote sensing components. More appreciation goes to Dr Axel Rothauge for training me on how to collect the right data for the BECVOL Model. Gratitude is also expressed to Mr Kudakwashe Hove of Crop Science Department, UNAM for assistance with data analysis.

My sincere appreciation also goes to my field assistants Christophina S.N Malakia, Dorthea Shiimi, Nobuhle R Chimwaza, Kangootui Kavezemburuka, Herman Nelson, Absalom Kasenanye, Seuakouje Kazao, Karlin Hamwenye and Ndinomuwa Hikevali-UNAM Students-Neudamm Campus, for being so helpful during the data collection, surely your sweat watered my results.

Lastly, I would thank Dr Simon Kamwele Awala, Mr George Khowa, Mr Cecil Togarepi and Dr Jesaya Nakanyala for your powerful words of encouragement and

everybody who helped me in one way or the other and has not been mentioned, thank you a lot and God bless you all.

DEDICATION

This thesis is dedicated to my daughter Tendaishe Cecilia Magano Khowa and my grandmother Ndeuhala Kashiimbindjola Munodumbo who had always been on my side, not all people understand the importance of studying. M'kwanekaa! your support and endless prayers have yielded into a rewarding future.

DECLARATION

I, Kaino Temapo Shilume, hereby declare that this study is my own work and is a true reflection of my research, and that this work, or any part thereof has not been submitted for a degree at any other institution.

I, Kaino Temapo Shilume, grant The University of Namibia the right to reproduce this thesis in whole or in part, in any manner or format, which The University of Namibia may deem fit.

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Name of the Student Signature Date

CHAPTER 1: INTRODUCTION

This section outlines the background of the study, problem statement, objectives of the study, significance of the study, limitation of the study and delimitation of the study. The genera names *Vachellia* or *Senegalia* were used throughout the thesis instead of genus *Acacia.* This format follows recommendations by the 17th International Botanical Congress of 2011 on the revision of *Acacia* Genus (Kyalangalilwa, Boatwright, Daru, Maurin & van der Bank, 2013).

1.1 Background of the study

Bush encroachment is defined as the thickening of bushes of woody species and the suppression of herbaceous species which include grasses and other herbs (de Klerk, 2004). It is considered to have occurred when the canopy cover for woody plants is 40 % and above (A. Rothauge, personal communication, 16 October 2017[1]; Venter, Cramer & Hawkins, 2018). Bush encroachment is considered to be one of the most widespread forms of degradation in rangelands in arid and semi-arid areas of the globe (de Klerk, 2004; Joubert, Zimmermann, Nathanael, & Hugh, 2013; Kgosikoma, 2012) According to de Klerk (2004), Smit (2004) and Karuaera (2011), communal lands and commercial farms in southern Africa can no longer optimally cater for the livestock owing to grazing lands being overtaken by encroacher bushes. Bush encroachment results in an imbalance of biodiversity and reduction of stocking rates (Alison & Karuaera, 2011; de Klerk, 2004; Sandhage-Hofmann, *et al*., 2015). Several studies have indicated that the causes of bush encroachment are not

[1] An agricultural consultant in Namibia (Agriconsultant Namibia)

explicitly known (Kgosikoma & Mogotsi, 2013; Kgosikoma, Harvie & Mojeremane, 2012). However, the major assumed causes include climatic factors such as persistent drought (rainfall below average), poor rangeland management such as over grazing or replacement of browsers with grazers and environmental factors (soil moisture and nutrients). These factors cause trees and bushes to outcompete grasses, owing to their rooting zone differences (de Klerk, 2004; Smit, 2004; Ward, 2005). One hypothesis expounds causes of bush encroachment in two models (Walter's Two-layer Model and the State-and-Transition Model) (de Klerk, 2004), which are explained in section 2.4.

Bush encroachment is not merely affecting African rangelands, but it has been reported in Latin America (Fensholt *et al*., 2015), North America (Van Auken, 2000) and Australia (Fensham, Fairfax & Archer, 2005). Namibia's grazing lands have been over-taken by the encroacher bushes for decades; therefore, it is not a new problem. The first estimate of encroached areas in Namibia by Bester & van Nieker in 1979 (as citied by Bester, 1996) reported an area of approximately 8 million hectares, of which 5.3 hectares were heavily encroached. The second estimate by Bester in 1996 was at 17.5 million hectares (Rothauge, 2014; Bester, 1996). By 2014, the estimate for encroached area was at 45 million hectares of land (Rothauge, 2014).

Although BE is a big problem in Namibia, there is neither a precise definition of what an encroacher bush is nor a nationally agreed definition of encroacher species (DECOSA, 2015). DECOSA (2015) defines BE as increase of bush density and significant decrease of grasses. This definition does not fix a figure as to how much bush density would be considered as an "increase". Venter, Cramer & Hawkins (2018) puts the figure at 40% or more woody species canopy cover. DECOSA further defines encroacher bushes as “bushes characterised by often multi-stemmed shrubs up to 5 m tall. Under favourable conditions (e.g. along water-courses) several species occur also as trees reaching 8 m (e.g. mopane, terminalia mesquite) or even 12 m (e.g. candle-pod acacia, umbrella thorn).” This definition does not specify what species should constitute the bushes for the bushes to qualify as encroacher bushes. There is no nationally agreed definition of encroacher species (DECOSA, 2015). In this study the bushes considered as encroacher bushes that were analysed in Neudamm Farm, were bushes occurring in Block G in areas that were classified through satellite imagery techniques as having high bush densities in a scale of low, medium and high density (Edward Muhoko, Personal communication, 3-31 May 2018[2]). All shrub and tree species constituting these bushes were recorded irrespective of whether a species is reported in literature as being an encroacher species. In Namibia, there are numerous thorny and non-thorny species that have been reported as being encroacher species. The dominant species vary from location to location (de Klerk, 2004; Fernandez, 2016; Patricia & Beltr, 2015; Joubert *et al.*, 2013).

De Klerk (2004) stated that several studies have been carried out to determine the best ways to remove encroacher bushes by using chemical, mechanical and biological methods. At Neudamm Farm, bush encroachment has been controlled on a smaller scale using chemicals (arboricides) and mechanical methods (A. Johannes, personal communication, 5 May 2017[3]). However, bush control methods often fail since bushes regenerate abundantly after the control because of no aftercare practices (Smit, 2004; Smit, de Klerk, Schneider & van Eck, 2015).

[2] GIS and Remote sensing expert at MAWF (DoF) Head office, Windhoek
[3] Head of the security at Neudamm Unam Campus

De-bushed biomass can be turned into various commercial benefits ranging from charcoal, firewood, poles and droppers to conversion into animal feeds. The idea of utilizing the de-bushed biomass as livestock feed is not a new concept in Namibia. However, in the recent past more and more farmers are converting encroacher bushes into livestock feeds (Pasiecznik, 2016; Fernandez, 2016). De-bushed biomass can be processed into fibre or pellets that can be an alternative feed for livestock during the long dry seasons and during droughts that the country frequently experiences.

The most important bushes for feed stocks in Namibia are; *Dichrostacys cinerea, Vachellia hebeclada,* and *Senegalia mellifera* (Fernandez, 2016). The advantage of using encroacher bushes as livestock feed has positive effects on controlling the bush density. Continuous or periodical harvesting of the bushes will control the offshoot and regeneration of bushes. The feed can either be made from the first de-bushed bushes or from the coppices owing to their high nutritional content (A. Rothauge, personal communication, 16 October 2017). The encroacher bushes are then mixed with various supplements to improve the palatability and protein content. The additives include molasses to improve palatability and nutritional content, urea for additional protein, polyethylene glycol (PEG) as a tannin binding agent, sodium hydroxide (NaOH), biochar and wood ash to help break down the lignin and cellulose into digestible forms which improve the palatability and intake" (Pasiecznik, 2016; Fernandez, 2016).

The use of Geographic Information System (GIS) and remote sensing tools for mapping of species and their spatial distribution is of paramount importance before de-bushing commences (Schröter *et al*., 2009). The distribution of species varies owing to climatic attributes as temperature and rainfall, edaphic factors, topographical positions, environmental management and competition within species

(Kaholongo & Mapaure, 2014; Narayan & Anshumali, 2015; Kumar, Patel, Kumar & Bhoi, 2011; Smit, 2004).

Two harvesting methods are mostly practiced for harvesting bushes; selective in which case only some target bushes or species area removed and clearing. Clearing involves complete removal of all bushes. Clearing makes the environment prone to all types of degradation including increased soil erosion and carbon dioxide in the atmosphere. Moreover, it reduces species diversity, since some niches and species that occupies those niches will be lost for example, cavity users (Bunnell, 2012; Coockle, Bodrati and Martin, 2017).

Selective harvesting reduces competition between the herbaceous and woody species, allowing more grasses to grow. The remaining woody species grow until they reach another state of equilibrium, where the bush growth will stagnate owing to inter-bush competition. The big bushes suppress the new seedlings (Smit, 2004; Smit, de Klerk, Smit *et al*., 2015). Although selective harvesting is more recommended for conservation purposes, the quantification of biomass before harvesting has to be carried out before onset of harvesting to have an idea of quantity and quality of feed to expect. In this study, the Biomass Estimates from Canopy Volume (BECVOL) 3-Model (Smit, 2014; Smit *et al*., 2015) was used to estimate biomass of all plant portions, that can be utilized as animals' feed and other uses.

The aim of the study was to quantify and characterize the encroacher bushes in Block G of Neudamm Farm, Khomas Region, where the bushes are targeted for conversion into livestock feed. The ultimate goal was to generate baseline information that can give an indication of quantity and quality of bushes available in the study site.

1.2 Statement of the problem

Bush encroachment studies in Namibia have mainly focused on mapping spatial coverage of BE, documentation and estimation of the costs associated with BE control, and rarely assess the quality and quantity of encroacher bushes available for conversion into animal feed. In Namibia (for example at Dordabis, Otavi area and Omatjene Research Station), encroacher bushes are being converted into livestock feed (Fernandez, 2016). Such a conversion needs to be tried out in other places like Neudamm Farm that is bush encroached and has shortage of livestock feed. Detailed characterization of bushes in terms of species composition and biomass partitioning in terms of leafy and woody biomass is rarely carried out before harvesting of encroachers bushes starts. This makes it difficult to come up with harvesting strategies that yield high quality feeds and preserve woody species among the bushes that may have been recommended to be conserved.

Before harvesting of encroacher bushes there ought to be a systematic assessment of the spatial distribution, composition and community structure of encroacher species to inform their utilization, harvesting strategies as well as encroachment control measures. Although such information exists for some parts of Namibia (De Klerk, 2004), the information does not exist for many encroached areas, Neudamm Farm included and hence there was need for this study, more so, since Neudamm Farm wants to start harvesting some bushes for animal feed. Moreover, accurate biomass estimates upon which to base sustainable harvesting of encroacher bushes into animals feed is rare. The available data on biomass of encroacher species is mainly on charcoal production. In such estimates, wood of less than 20 mm in diameter that is suitable for conversion into animal feed, is normally ignored. This is in spite of existence of biomass estimation methods like the BECVOL 3-Model which can be used to estimate both the woody and browse components of bushes separately (Smit, 2014). Such a separation of bush components is rarely done in Namibia. The lack of such information prevents the designing of comprehensive harvesting strategies that would offer flexibility on what component or portion of individual trees to convert to animal feed. A good understanding of the distribution and composition of encroacher bushes is required to ensure that investors in bush conversion to livestock feed get good returns for their investment and get nutritious feeds. Therefore, the current study endeavoured to estimate all above ground biomass of woody plants using the BECVOL 3-Model to address the aforementioned problems.

1.3 Objectives

1.3.1 Main objective

In view of the above research problem, this study seeks to (1) develop an understanding on the spatial coverage, composition and distribution of encroacher bushes in relation to edaphic and topographic factors, and (2) to estimate the amount of feed-suitable biomass of the dominant species constituting encroacher bushes in the selected block at Neudamm Farm.

1.3.2 Specific objectives

1. To assess how density of encroacher bushes (trees and shrubs) in Neudamm Farm (Block G) has changed between the periods 1989 to 2000 and 2000 to 2017;
2. To determine the trees and shrubs species composition and diversity of encroacher bushes in parts of Block G classified (in Objective 1) as having high bush density;

3. To determine the dominant (based on importance values) tree and shrub species constituting the encroacher bushes in Block G;
4. To determine if variations in densities of encroacher bushes, species composition and species diversity in Block G vary with site (geographical position of samples), topographic positions (Hill tops, Hill sides and Hill bases) and if bush density was correlated to edaphic properties; and
5. To estimate feed-suitable biomass of the dominant species constituting encroacher bushes, available in the study sites and its' partitioning into woody and browse components.

1.4 Significance of the study

This study will generate baseline information (composition, diversity and bush densities) on encroacher bushes in Block G of Neudamm Farm with intention of using the generated information to design appropriate bush harvesting strategies for this site and other similar sites. The use of BECVOL 3-Model will help the harvesters to estimate how much feed-suitable biomass (browse) is available in the study site. Moreover, information on species composition will help implement forest policies ensuring that sustainable bush harvesting is carried out without causing detrimental effects to the environment as some rangelands contain some protected species. The findings from this study will also contribute to the understanding the nature of other encroacher bushes in Namibia under similar biophysical conditions. In nutshell, the information from this study will be used in designing harvesting strategies of the encroacher bushes that ensures the site is not degraded and the harvesters get large amounts of high quality feed.

1.5 Delimitation of the study

This study was restricted to a selected Block at Neudamm Farm (Block G) that has never been assessed before and is targeted for bush harvesting trials. Vegetation characteristics are known to vary from place to place being influenced by various edaphic and biotic factors among other factors (Narayan & Anshumali, 2015). Therefore, data collected applies specifically to Block G and other similar parts of Neudamm Farm with comparable management and environmental factors.

CHAPTER 2: LITERATURE REVIEW

This chapter synthesizes issues related to bush encroachment; its distribution in southern Africa, encroacher species densities in Namibia, drivers of bush encroachment, bush encroachment control methods in southern Africa, uses of encroacher bushes in Namibia, conversion of encroacher bushes to livestock feed, mapping techniques of encroacher bushes, characterization of encroacher bushes and the use of the BECVOL 3-model for biomass estimation and species densities in relation to edaphic and topography.

2.1 Distribution of encroacher bushes in southern Africa and encroacher species.

Kgosikoma and Mogotsi (2013) described savanna ecosystems as a "continuous layer of herbaceous plants, such as grasses, and sparsely populated patches of trees and shrubs". However, most of the savanna ecosystems are being transformed into tree-dominant ecosystems (Ward, 2005), which are mostly thorny or non-thorny and palatable or unpalatable to livestock. In southern Africa, BE is a wide spread phenomenon with 3.7 million of Botswana's rangelands (Kgosikoma *et al*., 2012), about 45 million hectares in Namibia (Rothauge, 2014) and 10-20 million hectares in South Africa (Ward, 2009) being reported as encroached. Despite many studies on BE, few studies provide a definition of what encroacher bushes are. A group of consultants after extensive surveys of BE in Namibia, defined encroacher bushes as "bushes characterised by often multi-stemmed shrubs up to 5 m tall. Under favourable conditions (e.g. along water-courses) several species occur also as trees reaching 8 m (e.g. *Colophospermum mopane*, Terminalia mesquite) or even 12 m (e.g. candle-pod acacia, umbrella thorn)" (DECOSA, 2015). This definition does not specify what species should constitute a bush for a bush to be considered as “encroacher bush” The consultants concluded that there is no nationally agreed definition of encroacher species.

The National Planning Commision Secretariat (NPCS) published a list of encroacher species in 2010 which was considered by different experts, as not complete (DECOSA, 2015). In 2015 a more comprehensive list was compiled (DECOSA, 2015) based on the lists of NPCS, de Klerk (2004) and DECOSA (2013). The species considered as encroacher species were grouped into three categories (Table 1). It is worth noting that even this study did not provide the criteria used to determine an encroacher species except, the species being woody and dominant in certain areas.

Table 1: Categories of encroacher species in Namibia.

Dominant encroacher species	**Localized encroacher species**	**Alien encroacher species**
Senegalia mellifera (Black thorn) *Vachellia fleckii* (Blade thorn/Sand-veld acacia) *Vachellia erubescens* (Blue thorn/yellow-bark acacia) *Vachellia reficiens* (False umbrella thorn) *Catophractes alexandrii* (Trumpet thorn) *Dichrostacys cinerea* (Sickle bush) *Terminalia sericea*	*Vachellia hebeclada* (Candle-pod acacia) *Vachellia nebrownii* (Water thorn) *Vachellia nilotica* (Scented-pod acacia) *Senegalia senegal* (Three hook acacia) *Vachellia tortilis* (Umbrella thorn) *Combretum apiculatum* (Kudu bush) *Colophospermum mopane* (Mopane)	*Prosopis glandulosa* (honey mesquite) *Lantana camara* (Lantana) *Leucaena leucocephala* (Wonder tree) *Opuntia phaeacantha* (Prickly pear)

(Silver terminalia) *Terminalia prunioides* (Purple-pod terminalia)	*Rhigozum trichotomum* (Three thorn rhigozum)	

(Source: DECOSA, 2015).

The dominant encroacher species are stated to be the species that are known to encroach everywhere, where other species cannot survive. Localized are species that invade only certain areas owing to adaptation requirements. Aliens are exotic species which have been introduced to an area outside their native range, either purposefully or accidentally. These species become invasive in some locations, owing to the absence of natural enemies that control them in their home countries. They flourish in disturbed areas and may multiply and spread exponentially. *Prosopis glandulosa* is the worst problematic woody alien species in Namibia as it encroaches along the water courses (Strohbach, Ntesa, Kabajani, Shidolo & D'Alton, 2015).

2.2 Density of encroacher bushes in Namibia.

The density of encroacher bushes in Namibia is reported to be dependent on the climatic conditions, disruption of the competitive balance between herbaceous and woody plants, especially by fire and browsing pressure (de Klerk, 2004). Bester (1996) divided Namibia into ten bush thickening zones based on the dominant encroaching species and average bush density (Figure 1). Bester noted that there was enormous variation of bush density from 2,000 to 12 000 bushes per hectare, and therefore it must be considered that even within the different zones the density varies from patches of dense bush to more open patches with few bushes.

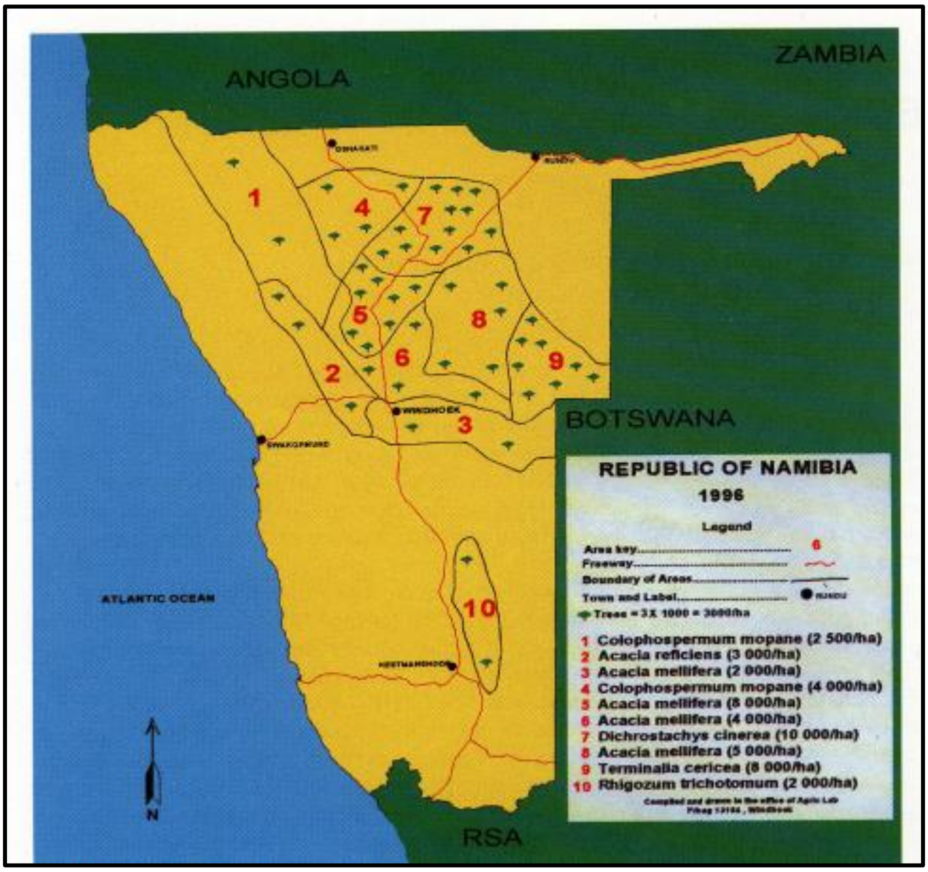

Figure 1: Bush densities for encroacher species (Sources: Bester, 1996).

In Namibia, BE is most serious in the savannah biome and rainfall is one of the key factors influencing bush density. Areas with higher rainfall generally have higher bush densities (Figure 1). Previous researchers indicated that in Namibia, Okombahe area had a "low density" - less than 1,000 bushes/ha. The areas around Omaruru, Gobabis and Windhoek are regarded as "medium to high" as the densities vary from 1,000 – 3,000 bushes/ha. Epikuro, Grootfontein, Okahandja, Okakarara, Okonjatu, Otavi, Otjinene, Otjituo, Otjiwarongo, Outjo, and Tsumeb areas are regarded as "very high density" as the density is more than 3,000 bushes/ha (Consultants, 2010).

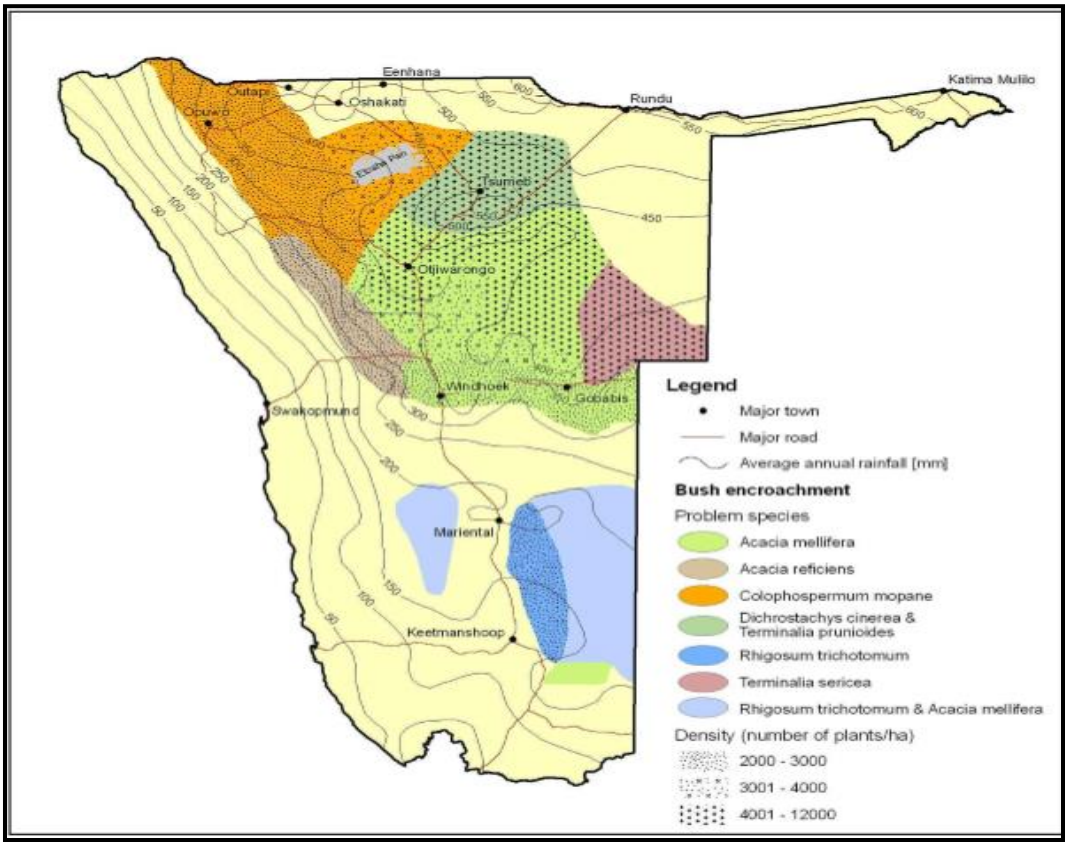

Figure 2: Encroacher bush densities in Namibia, dominant species and rainfall distribution. (Source: Rainfall map - Mendelsohn *et al*. (2002), Bush encroachment map - Consultants, (2010). It is important to note that the species with Genus Acacia in Figure 2 has changed to *Vachellia reficiens* and *Senegalia mellifera*.

2.3 Mapping of encroacher bush cover.

Across the globe, vegetation is mapped using geographical information systems (GIS) techniques like remote sensing backed by ground truthing. Remote sensing is the process of acquiring information, characteristics and properties of the earth's surface without being in direct physical contact with it (Campbell, 2002; Kumar, 2017; Schröter *et al*., 2009). Objects on the earth surface have uniqueness in reflectance, thus they are identified differently and that normally depends on the spatial resolution (low to high) selected to obtain the necessary data (Oldeland *et al*., 2010). The remote sensing technology presents vegetation data from present time to over a number of decades back. In addition, reseachers can describe vegetation cover from local scale to global scale by applying remote sensing imagery. The remote sensing imagery can be expensive and there are some factors such a cloud that can affect the image classification, thus results in poor quality image.

The spectral radiances in red and infra-red are vital in vegetation mapping when using remote sensing technology. The radiances are incorporated into spectral vegetation indices (VI). There are differences in spectral signitures between photosynthentically and non-photosynthetically active vegetation.

There are various sensors that are used when mapping vegetation, such as; Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) (Landsat), Satellite Pour l'Observation de la Terre (SPOT), Moderate Resolution Imaging Spectroradiometer (MODIS), IKONOS and Qiuckbird. Below are the strengths and weaknesses of these sensors (Table 2).

Table 2: Strengths and weaknesses of remote sensing sensors.

Type of sensor	**Strengths**	**Weaknesses**
Landsat TM and ETM+	• It is useful to map long-term vegetation cover and spatiotemporal vegetation changes. • The sensor map vegetation at a community level.	• The relatively low temporal resolution might restrict the application of the sensor in vegetation mapping, caused by medium spatial resolution of Landsat imagery. • It takes approximately 16 days for the satellites to revisit the last location.
SPOT	• Capable of obtaining an image of any place on earth every day. • It can map vegetation at flexible scales, either at regional, nation or global scale. • It detects large-scale change of the environment due to the sensitivity of the images to vegetation growth. • Effective in monitoring the distribution and growth of particular plants.	• Spot images can be integrated with other remote sensing images to get accurate data.
MODIS	• Able to view the entire earths' surface every 1-2 days. •	• Due to course spatial resolution, vegetation mapping at a local scale or regional scale is not recommended.

IKONOS	• Can be used to map vegetation cover at local scale or validate vegetation cover classified from other remote sensing images.	• The spectral information available from IKONOS is limited to the blue, green, red and near-infrared bands which is similar to those of Landsat TM or ETM +.
Quickbird	• Used for validation purposes.	• Impractical to apply Quickbird imagery in a large area because it has high cost.

(Sources: Banerjee & Ray, 2019; Xie, Sha, Yu, 2009).

Blaser (2013) used Landsat TM to map the changes in bush density over time in Zambia. The study revealed that woody vegetation cover increased from 26 % to 45% (1986-2010) while open areas declined from 50% to 33% during the same period. Similarly, Hudak & Wessman (2001) conducted a study in South Africa and found that there was an increase in bush density as it more than doubled from 21% (1995) to 59% (1998).

In central Namibia, Oldeland, Dorigo, Wesuls & Jürgens (2010) mapped the spatial distribution of *Senegalia mellifera* and *Vachellia reficiens* based on their different phenological behaviors. The extracted gradient reflected the relationship between species composition and cover values, and the phenological pattern as captured by the image data. However, there were errors encountered in the images.

2.4 Drivers of bush encroachment.

Several authors stress that the causes of bush encroachment in Namibian savannas are poorly understood. However, de Klerk (2004), Sheuyange, Oba & Weladji (2005), Ward (2005), Zeleke (2009) and Ward (2013) indicated that there are two postulated models which explain the cause of bush encroachment, namely; Walter's two-layer model (Walter et al., 1971; Walker & Noy-Meir, 1982) and State-and-transition model (Westoby et al., 1989) Approximately 64% of Namibias' land (824269 km²) is covered by savanna biome; however, there is an increasing competition for water between herbaceous plants (e.g grasses) and woody plants. The woody plants such *Vachellia* and *Senegalia* are tolerant to drought and browsing/grazing (De Klerk, 2014). The tolerance makes them thrive better than the other plants, which can cause the whole ecosystem to be encroached. Water is important for the survival of all living things, it is explained in Walters' two-layer model on how it hinders the woody plants and grasses coexistence. The model explains that coexistence of woody plants and herbaceous plants in the savanna biome are regulated by a natural mechanism such

as root niche-partitioning system. Plant deploy their roots at different depths; few centimetres above ground (Grasses and young shrubs) and some penetrates deeper into the ground (trees or big shrubs) and that could be the leading factor of the phenomenon. Unfortunately, the Walters' two-layer did not explicitly indicate how far the roots of this different plants are being deployed. When rainfall is below the mean annual rainfall it is more beneficial to the grasses, because they utilize the water on the top soil while, the trees and shrubs will not be able to utilize it (Ward, 2013), therefore they grasses outcompete the woody plants. However, when the rainfall is above the mean annual rainfall, the water percolates down and will be more available in the subsoil and woody plants will have more access to it because of their long tap roots (Zeleke, 2009). Therefore, due to their root niche separation, the woody plants tend to dominate the area, suppresses the grasses and cause bush encroachment (Ward, 2005). Moreover, the model also explains that overgrazing leads to the removal of perennial and annual grass species from the ecosystem. Therefore, the soil moisture becomes available to the trees and shrubs and that creating a competitive advantage for trees and forming woody-dominated biome. Therefore, the farmers need to de-stock some of the livestock during the dry seasons to avoid the phenomenon. If there was no overgrazing in the savanna biome then bush encroachment was going to be nonexistent. It must be stated that not all situations of bush encroachment may be explained by the two-layer theory. Inadequacies of this theory and other possible theories are highlighted by Ward

(2005) in his article “Do we Do we understand the causes of bush encroachment in African savannas?”

The state-and-transition model puts emphasis on vegetation dynamics and theories that bush encroachment is event-driven in savannah ecosystem and it is reversible depending on favorable management (appropriate restoration methods, balance between grazers and browsers that previously existed in the area) and environmental conditions (Bestelmeyer *et al*. 2017). The model implies that rangeland vegetation state changes through transitions which are normally caused by external factors such as suppression of fire, variability of rainfall and removal of browsers from the rangelands. The ecosystem goes in a transition from grass dominant and discontinuous woody layer to shrub dominant state which is beyond the natural density (Rothauge, 2011). Species like *S. mellifera* proliferates and starts to invade the area, the phenomenon is termed bush encroachment (Karuaera, 2011). The transition in the savanna can alter the abundance and diversity of species.

Other factors that have been cited as possible causes of bush encroachment include; persistent drought (rainfall below average), poor rangeland management such as over poor stocking or replacement of browsers with grazers and environmental factors (soil moisture and nutrients) (de Klerk, 2004; Devine, *et al*., 2017; Sheuyange, Oba & Weladji, 2005). The persistent drought favours more bushes than grasses. Lack of water results in most of the grass seeds (annual and perennial) grasses not germinating. Most of the grass seeds remain dormant in waiting for favourable condition in order to germinate and re-establish. In addition, feeding and supplements of livestock with the *Vachellia* and *Senegalia* species pods result in bush seeds being spread on rangelands through manure. Once the condition is right the bushes explode and this contributes drastically to bush encroachments.

Overstocking combined with lack of grass resting accelerates the rate of grass disappearing, reducing competition for the bushes and this creates favourable conditions for the bush encroachment.

Lack of soil moisture reduces the ability of the plants to uptake the nutrients from the soil, the impact is adverse to grass due to poor and shallow root systems while favouring the bushes with deep root system. Most of the seeds (grasses and bushes) geminate well under good rainfall or high soil moisture content; however due the difference in the lifeforms, bushes overtake the grasses.

2.5 Bush encroachment control methods in southern Africa

There are various methods that are being used to reduce the infestation of encroacher bushes in southern African rangelands. Chemical methods use arboricides such as tebuthiuron, ethidimuron and picloramas (de Klerk, 2004). Mechanical methods include felling or uprooting using heavy machines or manual tools. Biological method involves use of living organisms to supress the growth of the bushes (browsers and fungus) (Consultants, 2010; Lesoli, Gxasheka, Solomon, & Moyo, 2013). In Namibia, farm owners choose the method of application based on available funds, availability of farm workers and the size of the affected areas (de Klerk, 2004). A summary of the advantages and disadvantages of abovementioned methods are described in Appendix 3.

2.6 Uses of encroacher bushes in Namibia

Trede and Patt (2015) noted that the legislative framework of Namibia is a promising basis for combating bush encroachment and for developing end-use opportunities with value addition. The de-bushed biomass is processed further into various value-addition chains; firewood and charcoal (DECOSA, 2015; Joubert, Zimmermann, Nathanael, & Hugh, 2013; Muroua, 2013), fuel for kilns for example at Ohorongo Cement Factory (Joubert *et al*., 2013), briquetes (at CCF) and currently, as livestock feed (Fernandez, 2016; Pasiecznik, 2016).

In addition, wood for charcoal production is harvested manually in commercial farms. The charcoal industry started in 1990 (Joubert *et al*., 2013). Charcoal production is one of the most selective (because only a few species are utilized) and a cost-effective way of combating bush encroachment. Namibia produces about 100 000 metric tons of charcoal annually, and in return generates income of N$ 75 - 100 million per year (Muroua, 2013). The production is carried out according to the guidelines of the Namibia Agricultural Union.

The charcoal is mainly produced from *Colophospermum mopane, Senegalia mellifera.* Mopane is one of the protected species; however, there are exceptions in some areas. The trees that are cut have a diameter that ranges between 5-20 cm (DECOSA, 2015). Joubert, Zimmermann, Nathanael, & Hugh (2013) reported that de-bushing for kiln fuels production is done at Ohorongo Cement Company, north of Otavi. Energy for Future Project collects the biomass from the neighboring farms (Consultants, 2010). Ohorongo accepts wood from any species as long as it is harvested according to Namibian laws.

De-bushed biomass from bush encroached areas can also be used as a livestock feed during the dry seasons and drought years. Currently, conversion of bush to feed is practiced in Namibia by mixing the bush fibre with supplements such as molasses (palatability), coarse salt, urea (protein), dry veld concentrate, polyethylene glycol (tanning-binding agent), biochar or charcoal and sodium hydroxide or sodium chloride (NaOH or NaCI). Mixing depends on the type of the species and age (Fernandez, 2016). There is limited information on this practice; although there were feeding trials carried out in Omatjinne Research Station, a commercial farm at Dordabis and Okondjatu Conservancy. To date there are about 50 commercial farmers involved in bush to feed conversion (Dagmar Honsbein, personal communications, 2018[4]). The farmers use encroacher bushes that are eaten by livestock, however the documented ones are; *Terminalia sericea*, *Senegalia mellifera, Catophractes alexandrii*, *Vachellia reficiens* and *Combretum* species.

2.7 Estimation of above ground biomass (AGB) of trees and shrubs

Across the globe, there are two approaches that are used to estimate above ground biomass of woody plants. These are destructive (direct) and non-destructive (indirect) approaches (Vashum & Jayakumar, 2012; Cleemput *et al*., 2002). The destructive approach which is known as direct method, harvests all the trees in the vicinity and weighs various components (branches, leaves and trunks) and after they are oven dried (Kiriku, *et al.*, 2016; Vashum & Jayakumar, 2012) to come up with allometric equations. Vashum and Jayakumar (2012) further indicated that the direct method is more accurate than non-destructive methods. Despite its accuracy the method is expensive, labour intensive, time consuming and not quite applicable to

[4] Consultant on animal feed production in Namibia from iDeal-x CC.

large study areas. Kiriku *et al*. (2016) elucidated that the aforesaid method is mainly useful when developing equations to estimate biomass for individual species.

The non-destructive approach merely takes different dimensions of trees and shrubs and uses these dimensions to estimate biomass. Although, the approach does not involve felling of trees, it is time consuming and expensive, as the measurements need to be accurate, for good estimation of above ground tree biomass. This means sampling becomes necessary, especially where large areas are involved and complexity of data required. The use of non-destructive approach to estimate the biomass is more feasible for large areas (Vashum & Jayakumar, 2012). Similarly, remote sensing can also be used to estimate above ground biomass (He *et al*., 2013; Lu *et al*., 2012; Vashum & Jayakumar, 2012). There are also other studies that have used allometric equations to quantify the above ground biomass of woody species (Hunter *et al*., 2013; Lu *et al*., 2012; Smit *et al*., 2015).

The current study used Biomass Estimates from Canopy Volume (BECVOL) 2 Model and BECVOL 3 Model to estimate the above ground biomass in encroached areas of Neudamm Farm. The BECVOL Model has seven different versions, however, is rarely used in southern Africa, although it was developed for semi-arid areas of southern Africa (Smit, 2004). The BECVOL 2 Model provides estimates of the leaf volume and leaf dry mass whilst, BECVOL 3 Model is used to estimate the above ground biomass portioning into browsable (leafy) and woody components (Smit, 2014). The spatial canopy volume in the BECVOL 3 Model and BECVOL 2 Model is calculated from the following parameters; tree height, height of the maximum canopy diameter, height of the first leaves, maximum canopy diameter, and base diameter of the foliage at the height of the first leaves (Smit, 2004, Smit, 2014).

BECVOL2-Model calculates biomass at 0-1.5m, 0-2.0m and 0-5.0m levels as well as total biomass. However, BECVOL 3-Model is unique as it estimates all plant portions and all available browse at different height strata; 1.5 m, 2 m and 5m (Smit, 2014; Smit *et al*., 2015). The aforesaid heights were selected based on the African browsers as they represent the maximum browsing heights. The 1.5 m represents mean maximum browsing height for domestic goats (Aucamp, 1976) and impala (*Aepyceros melampus*) (Dayton, 1978), while 2.0 m and 5.0 m is the mean maximum browsing height of kudu (*Tragelaphus strepsiceros*) and giraffe respectively (*Giraffa camelopardalis*) (Smit, 2014). The fact that BECVOL 3 Model estimates biomass at different heights, separates leafy and woody biomass and covers the whole size range of the bush (starting with biomass of twigs < 0.5 to 2 cm and wood > 2 cm) makes the data generated by this model very versatile for management of rangelands and utilization of woody plants in rangelands. However, the method is fairly involving due to the high number (8) of measurements made on an individual bush.

2.8 Harvesting of encroacher bushes

It is vital for bush harvesters to understand that encroacher species are different in various ways. Differences in terms of livestock feed value, seed dispersal, seed establishment and coppicing abilities and conservation status as some of the species maybe legally protected. A good understanding of these differences will help with development of suitable harvesting strategies to achieve the intended goal of harvesting the bushes.

Consultants (2010) indicated that the first cut of most species has more biomass as compared to the re-cut after several years. This will certainly depend on how long it takes before re-harvesting, if the period is long enough the biomass may be the same or more. In addition, they further noted that plant species involved, soil types, and amount of rainfall determine the amount of biomass after the first cutting. Several farmers have observed that for some species, tree density per hectare increased after the first harvest due to re-generation from seed germination in addition to re-sprouting of the trees cut. A study carried out at Omarassa Farm, Namibia, *Senegalia mellifera* was recorded to get to a height of 1.5 to 2m tall after 10 years, when cut with a machine (Consultants, 2010).

2.9 Rules and regulations governing harvesting of encroacher trees and shrubs in Namibia

The legislative framework of Namibia is reported to offer sufficient basis for combating bush encroachment and for developing end-use opportunities with value addition (Trede & Patt, 2015). There are several Acts in Namibia which regulate the harvest and utilization of encroacher bushes (Trede & Patt, 2015; DECOSA, 2015).

- *Forest Act 12 of 2001 as amended by Act No 13 (2005)* (Trede & Patt, 2015; DECOSA, 2015)

Harvesting of trees and wood anywhere in Namibia is governed by the Forest Act. The Act provides a list of protected species that should not be removed when harvesting the bushes. If such species form part of the targeted biomass, permission to harvest will need to be requested for from the Directorate of Forestry. Other protected species may just be growing within the encroacher bushes in which case, care would have to be taken not to damage them during the harvesting of bushes.

- *Environmental Management Act No. 7 of 2007* (Trede & Patt, 2015; DECOSA, 2015).

Sections 27, 29 and 44 of the Environmental Management Act, 2007 (Act No. 7 of 2007) stipulates that there are certain activities that may not take place without an Environmental Clearance Certificate. In terms of bush harvesting, the certificate is only required when the area to be harvested is covering more than 150 hectares.

In general, these Acts emphasizes sustainable harvesting of encroacher species and hence the need to analyze the plant community characteristics of these bushes well in order to develop harvesting strategies that satisfies the legal and policy requirements and yet yields benefits to the harvesters.

2.10 Distribution of woody plant species in relation to edaphic factors and topography.

Topography and edaphic factors are not mutually exclusive since topography has an influence on soil factors. For example, soils on hill sides may be shallow due to erosion and low in nutrients but are generally better drained while those at the hill bottom may be deeper and higher in nutrients due to nutrients from the hill side being deposited there but may be poorly drained. Plant community structures and species composition are often results of environmental factors (climate, soil properties, topography) and competition between species for resources (either water, space and soil nutrients). A study in China Zhang *et al*. (2016) revealed that elevation has more effect on the distribution patterns of woody plants. The study was carried out in subtropical mountain forests of the Lower Lancang River Basin. The soil properties such as moisture content, electrical conductivity (Ec), soil pH, organic matter, total nitrogen, available nitrogen, total P, K and exchangeable Ca affect distribution pattern of woody plants (Ahmad *et al*., 2016); Zhang *et al*., 2016). Ahmad *et al*. study was done in Pakistan and the dominant woody species were *Capparis decidua*, *Prosopis cineraria, Haloxylon recurvum* and *Aerva javanica*. A study carrried by Hagos and Smit (2004) on soil enrichment by *Senegalia mellifera* subsp. *detinens* on nutrient poor sandy soil in a semi-arid southern African savanna found out that the occurance of trees in good soil quality is owing to existance of trees, as they can as well improve the soil quality, by littering of leaves or through nitrogen fixing processes.

The high rainfall patterns and high nutrient soils in African savannas encourage the growth of trees, hence resulting in transition from grassland to forest thickets (Devine *et al*., 2017). In Botswana, a study by Kgosikoma, Harvie & Mojeremane (2012) showed that bush encroachment is likely to occur where there is low clay soil and high sandy soil. In a similar study, Sankaran *et al.* (cited in Kgosikoma & Mogotsi, 2013) indicated that bush encroachment is observed to occur in places with low nitrogen content, although encroacher bushes are known to be good fixers of nitrogen in soils (Ward, 2005). Studies in Kruger National Park have shown that the interaction between soil properties and disturbance (herbivory) have pronounced effect of the woody density of savannah ecosystems. The current study's focus was not to investigate how and which environmental factors resulted in the formation of the encroacher bushes under study (that is "cause and effect"), rather, it only assessed whether the composition, diversity, bush density and biomass of the dominant woody species constituting the encroacher bushes were related to site (geographical position) topographic position and some selected soil properties.

CHAPTER 3: RESEARCH METHODS

3.1 Study site

3.1.1 Location

The study was carried out in Block G of Neudamm Farm of the University of Namibia. The farm is in the Khomas Region (Figure 3). Khomas region borders the following Regions; Otjozondjupa, Omaheke, Erongo and Hardap Region. Neudamm Farm is approximately 30 km East of Windhoek, along the B1 road to Hosea Kutako International Airport and Gobabis. The farm lies within the semi-arid highland savanna (Karuaera, 2011). The farm covers an area of approximately 10187 hectares, divided into nine blocks (A, B, C, D, E, F, G, H, I and J) and 210 grazing camps. The study was carried out in Block G which covers 1710 hectares. Neudamm Farm was selected because it has sections that have been encroached by bushes. Before the study, Block G had been selected by the Farm Management for encroacher bush conversion into livestock feed trials (Bush to Feed Project), because approximately 50 % of its area was observed to be covered by dense bushes, mainly of *Senegalia mellifera*, a species good for livestock feed. In addition, the Block is flat enough to allow the conversion machinery (bush processing) to be based there and easy movement of machinery when harvesting. Since the study was also funded by the Bush to Feed Project, it was recommended that Block G should be the study site.

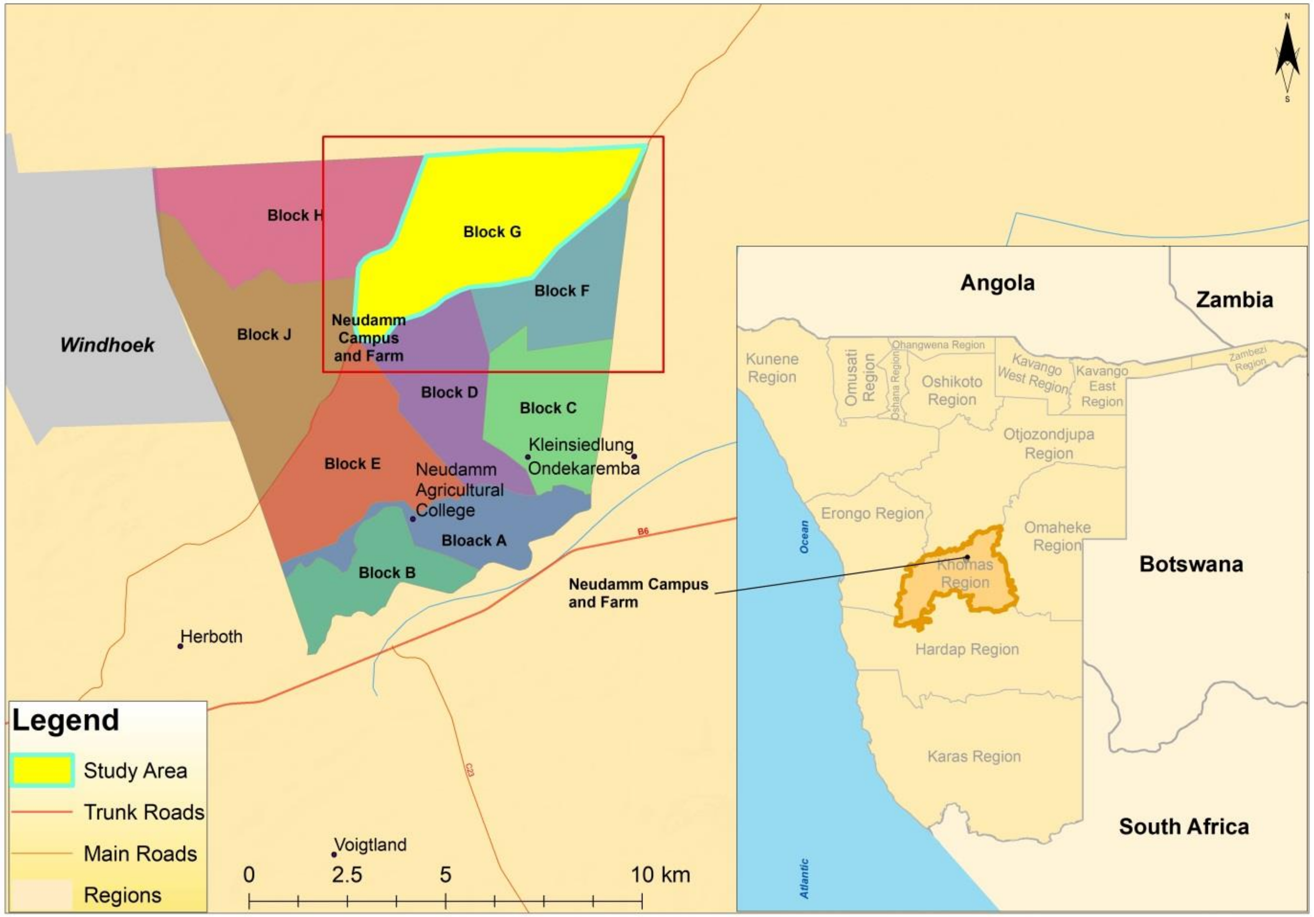

Figure 3: Neudamm Farm, in Khomas Region.

3.1.2 Climate

The mean annual rainfall at the farm is approximately 300 mm. The average annual temperature is about 19.47 ° C. It gets very cold in winter, with an average minimum temperature of 3°C and summer has an average maximum temperature of 29° C. The Khomas Region is about 1350-2400 m above sea level (Jourbert *et al*., 2008). The findings of Bertram & Bramen (cited in Karuaera, 2011) showed that some mountains found on the north-western corner of the Neudamm farm peak around 2000 m.

3.1.3 Soils

The main soil type in the area is lithic leptosols, which is homogenous and is mostly shallow. The soil is covered with quarzitic pebbles which improves soil moisture (Jourbert, 1997). According to Karuaera (2011) the soils are also skeletic on the slopes, where they can turn into blockfields and bare bedrock. The soils are rich in material derived from physical weathering (Scholz, 1973). The soils contain very little organic matter because of low litter supply and rapid mineralization (Bertram & Bramen, 1999). This results in soils with low water-holding capacity.

3.1.4 Flora

Neudamm Farm is situated within the semi-arid highland savanna (Karuaera, 2011). The Farm is known to be affected by bush encroachment for decades (Joubert *et al*., 2008). Some of the common woody species in Khomas Region include; *Vachellia hereroensis, Vachellia hebeclada, Vachellia reficiens, Euclea undulata, Dombeya rotundifolia, Tarchonanthus camphoratus, Searsia marlothii, Albizia anthelmintica* and *Ozoroa crassinervia* (Joubert *et al*., 2008). *Senegalia mellifera* is the dominant woody species in the Khomas Region. The common grasses in the Farm are *Brachiaria nigropedata, Anthephora pubescens, Heteropogon contortus, Cymbopogon spp., Digitaria eriantha, Eragrostis nindensis, Eragrostis trichophora* and *Stipagrostis uniplumis*.

3.1.5 Fauna

The Farm is housing large and small livestock. The large stock consists of Sanga, Afrikaner, Simmentaler and horses (Arabierx-Boer horse breed). The small stock has different breeds of sheep and goats (Boer goat, Kalahari red, Swakara, Dorper and Damara sheep). In addition, there are wild animals in the Farm such as kudus, oryx, red hartebeests, warthogs, waterbucks and baboons.

3.2 Determination of extent of BE and changes in bush density between the periods 1989-2017

Landsat images were used to stratify Block G of Neudamm Farm into areas of high, medium and low bush density. The images were downloaded from the United States Geological Survey (USGS) database (http://glovis.usgs.gov). The images were generated using Landsat-5 Thematic Mapper (TM) C1 level-1 and Landsat 8 OLI/TIRS C1 level-1. Images for 1989 and 2000 were acquired from Landsat 5, whilst 2017 images were from Landsat 8. Landsat-5 TM uses spectral ranges of 0.45–2.35µm (Kamwi, Kaetsch, Graz, Chirwa, & Manda, 2017). Landsat 8 has TM with spectral ranges of 0.43-12.51 µm (Barsi *et al*., 2014). The resolution and bands of the images used are shown in Appendix 1 and overviews of satellite images used in the study are presented in Table 3.

Table 3: Overview of satellite images used in the study

Year	Study Site	Landsat (Path/Row)	Acquisition date
1989	Block G, Neudamm Farm	Landsat 5 (WRS Path: 178 and WRS Row: 076)	1989-07-14
2000	Block G, Neudamm Farm	Landsat 5 (WRS Path: 178 and WRS Row: 075)	2000-06-26
2017	Block G, Neudamm Farm	Landsat 8 (WRS Path: 178 and WRS Row: 076)	2017-05-24

The images selected for use in this study were those taken during the dry season. In such images, reflectance of the herbaceous layer, which might interfere with the reflectance of woody vegetation cover, is eliminated and there is less soil and vegetation moisture and no cloud cover, hence less errors are encountered during the image classification process. After the images were obtained they were classified and analyzed as explained in the data analysis Section 3.4.1. Once Block G was stratified into high, medium and low bush density areas, 20 plots of 2 x 25 m were laid out at random 10 in each low and medium bush density strata. Trees and shrubs rooted in these 20 plots were counted without separating the species or determining there sizes. The average for 10 plots was used to calculate the average bush density for a stratum. Determination of bush density for the high bush density stratum (which was given more attention) is as explained in section 3.3. Bush densities were categorized as; Low (below 3000 bushes/ha), Medium (from 3000 to 6000 bushes/ha) High (above 6000 bushes/ha). Changes in bush densities between 1989 and 2017 and areas covered by bush density classes were used to determine how BE has changed over this period.

3.3 Sampling for bush characterization and biomass quantification

3.3.1 Sampling frame and laying of sample plots

This part of the research aimed at characterisation of bushes occurring in areas of Block G, classified as having high bush density areas (Section 3.2) as these are the areas targeted for bush harvesting. The total area having high bush density was about 955 ha out of 1710 ha, the total area for Block G.

Assessment of all ecological factors that may have an effect on bush density was not done as it was not the main focus, the focus being quantification and characterization of the bushes as they currently occur without much investigation on how and why those bushes developed where they are found. However, on the basis of literature

(Section 2.10) and the topographic nature of the study site (predominantly low, undulating hills), topographic position and soil characteristics were considered as important factors in the context of the study and a sampling design was adopted to allow assessment of whether bush densities and characteristics were related to these two factors.

Selection of sampling sites was achieved through subjectively identifying 5 sites having comparable topography (each having a Hill top, Hill side and Hill base) and same aspect in the high bush density stratum of Block G (as classified in Objective 1 – Section 3.2) and then randomly choosing 3 sites out of these five for sampling. 27 plots each measuring 2 m wide and 50 m long were laid out at each of these three sites. A total of 9 plots were assessed at each site (Table 4). For each sampling site, and at each topographic position (Hill top, Hill side and Hill base), a transect 190 m long was established running across the slope. At the mid-point of a transect, the first sample plot was laid with its mid-point being at the same point as the midpoint of the transect. On either side of this first plot, a plot was laid 20 meters away (Figure 4). The coordinates and elevation of each sample plot were recorded using a GPS (Garmin GPS II plus) as well as the distance between the hill top plot and the hill base plot in each set of plots for calculation of slope.

Table 4: Number of sample plots taken in each topographic position of the 3 selected sites of Block G

Sampled sites	Number of sample plots (2 m x 50 m) located at each Topographic position		
	Hill top	Hill side	Hill base
Site 1	3	3	3
Site 2	3	3	3
Site 2	3	3	3

Topographical positions were considered in the study because it affects species composition, density and size of shrubs and trees, soil properties example water retention, drainage, availability of moisture and architecture of the roots system in a specific area/community. According to Brown & Frederisksen (2008), tree density increases with ascending slope position, while DBH decreases. However, the study found out that species richness did not differ significantly by topographical positions.

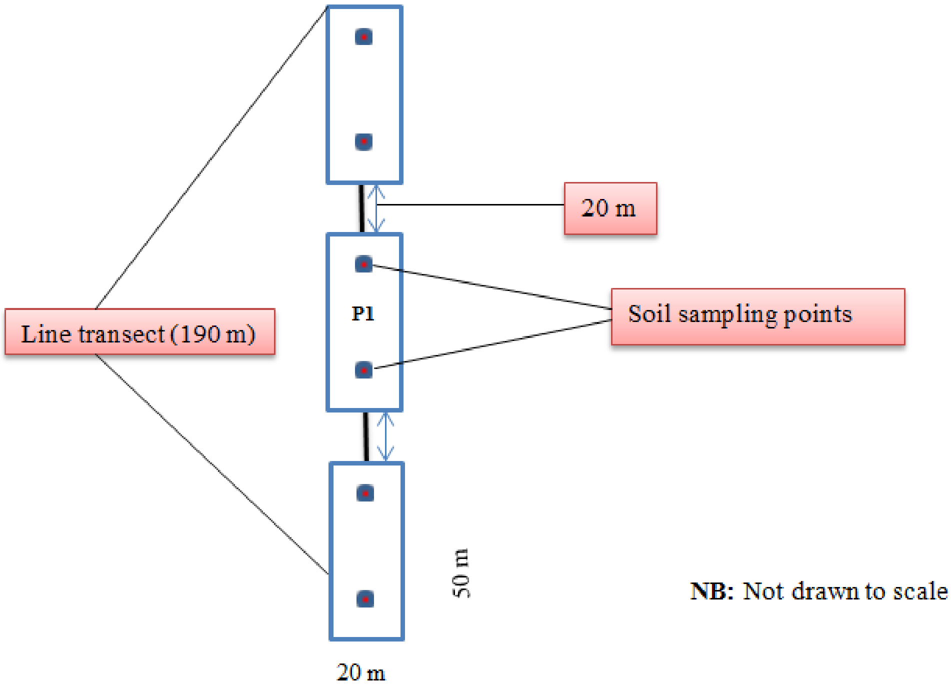

Figure 4: Layout of sample plots at a topographic position in a transect.

The sample plots were demarcated using a measuring tape, ropes, metal rods and a graduated rod (Figure 5). The graduated rod was used to measure the distance between the ropes (width of each plot) and measuring tape to ensure that the plot size does not increase or decrease in size. The metal rods were used to demarcate plot corners and to keep the ropes and the measuring tape straight and from the ground.

Figure 5: Demarcation of sample plots

3.3.2 Vegetation assessment

The sampling was done in June 2018. All woody plant species found rooted within the sample plots were identified and recorded by species and classified as short plants (<0.5 m) and tall plants (>0.5 m). Herbaceous species that were found in the sample plots were not recorded. Heights of plants >0.5 were estimated using a six-meter graduated rod. However, for trees taller than the graduated rod (Figure 6), the heights were estimated to the nearest half meter (the estimates were in relation to the initial 6m covered by the graduated rod). For example of the height above 6m seem to be half of the rod) (Kaholongo and Mapaure, 2012).

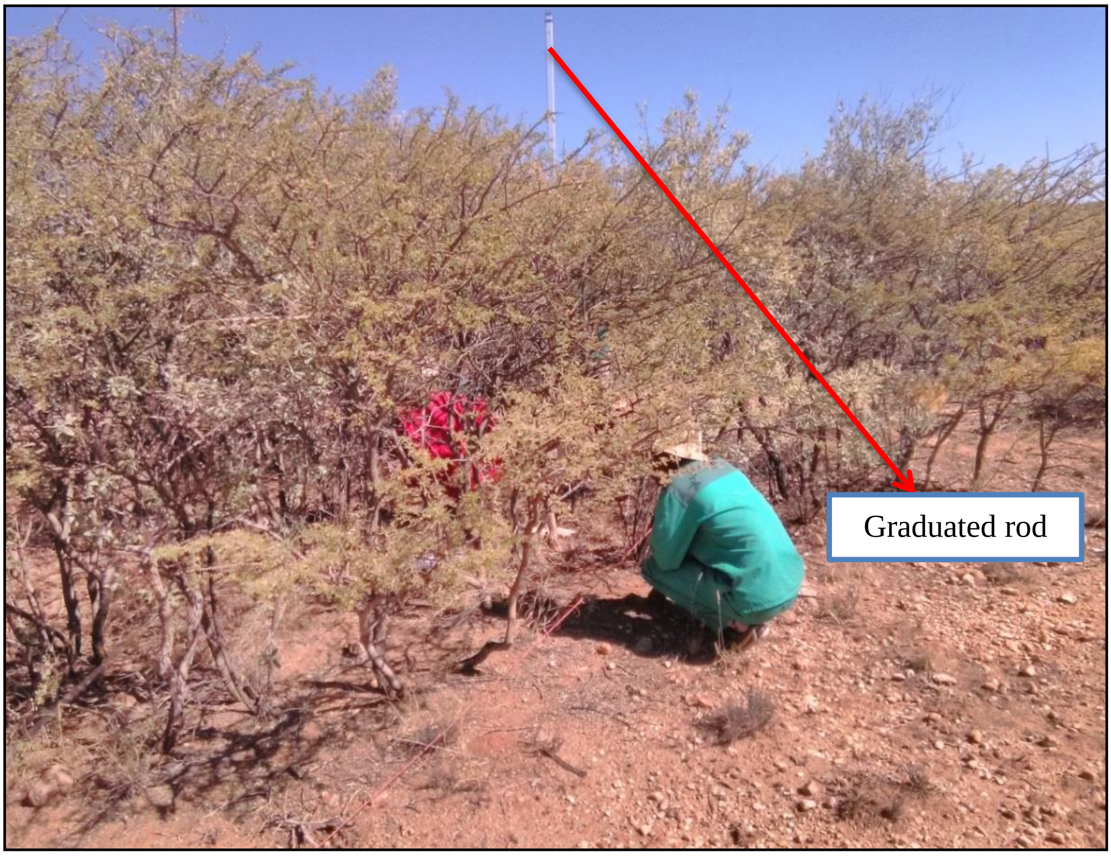

Figure 6: Measuring heights and diameters of trees and shrubs.

Heights and diameters for the short plants were not recorded as they were too many, only their species and numbers were recorded. Height of these short plants was not required since their biomass was not to be estimated as they are not normally harvested for feeds. The diameters for single stemmed (trees) and multi-stemmed (shrubs) were measured using a caliper, at the base of each stem (ground level) as per requirements of the BECVOL 3-model that was later used for biomass estimation. For the multi-stemmed shrubs, the diameter of the bush was estimated by measuring the diameter of each stem and adding them.

3.3.3 Estimation of Above Ground Biomass (AGB)

According to the BECVOL 3-model requirements, eight measurements (Figure 7) were taken from each tree or shrub > 0.5 m.

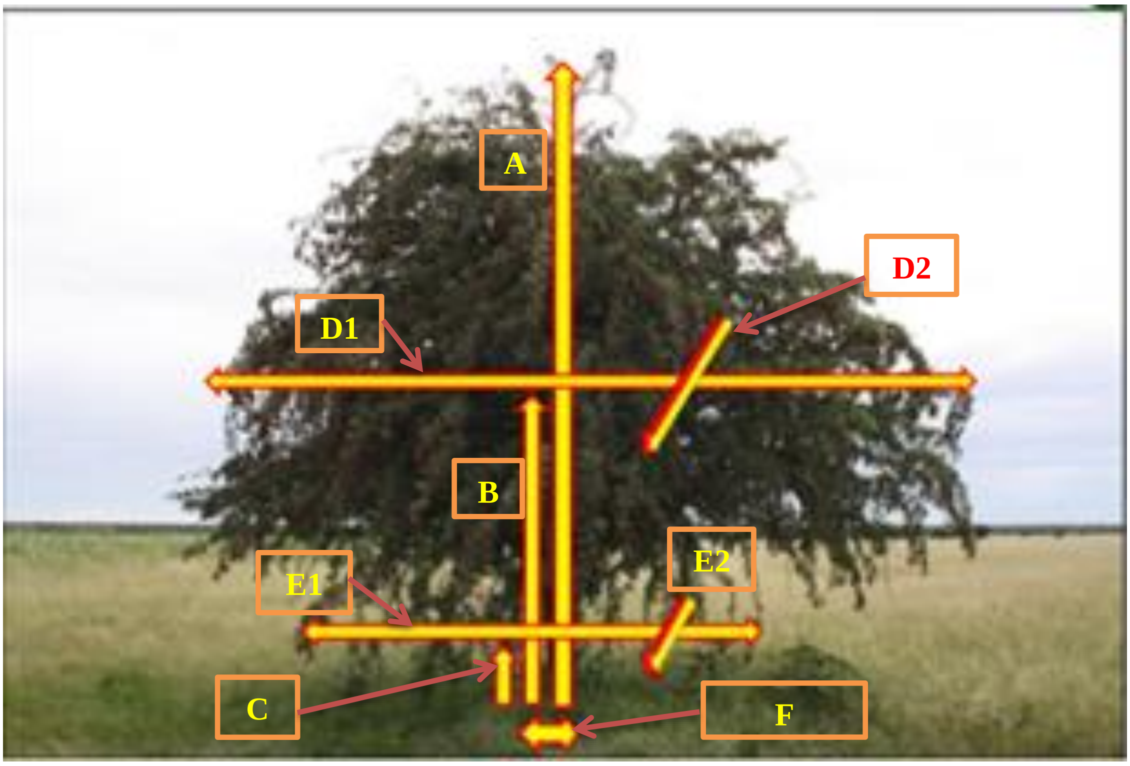

Figure 7: The eight measurements required from a single tree/shrub for biomass estimation by BECVOL 3-model (Source: Rothauge, 2014).

The dimensions included the following;

A) Total tree height (m)

B) Height where the maximum canopy diameter occurs (m)

C) Height of the canopy at the point where first leaves occur (m)

D) Since theoretical tree canopy is considered to be circular, the following dimensions were averaged:

i) D1 - maximum canopy diameter and a diameter perpendicular (D2) to the maximum diameter is measured to get the average canopy diameter measured in metres.

ii) E1 - maximum base diameter of the foliage at the height of the first leaves and a diameter perpendicular (E2) to the maximum base diameter is measured to get average base diameter of the foliage at the height of first leaves measured in metres.

F) Stem diameter was got by averaging the maximum stem diameter (F) and a diameter perpendicular to the maximum stem diameter measured in centimetres.

3.3.4 Soil sampling

Two pooled soil samples were collected from each sample plot. A total of 6 soil samples per topographical position per site and in total 18 soil samples were collected per sampled site. The points where soil samples were taken were cleared of plant debris (leaves or grasses). The soil samples (approximately 150 to 300 g) were collected at two depths 10 cm and 20 cm using a soil auger (Figure 8). However, the collection depth depended on the substrate's hardness. In a plot the points at which soil samples were collected was towards the edge of each plot (5m from or to the end of the plot - Figure 4), and as far away from any nearby trees as was possible. The two soil samples collected at 10 cm from the same plot were mixed to make a composite sample for that depth. The same was done for samples collected at 20 cm depth. After collection, the soil samples were stored under room temperature before analysis.

Figure 8: Collection of soil samples using a soil auger.

3.4 DATA SUMMARIZATION AND ANALYSIS

3.4.1 Classification of satellite images:

After downloading the images, the following steps were followed;

1. Stacking: the bands were combined to have a complete image of the study area. Band combination of 3-2-1 was used for the 1989 and 2000 images and band 4-3-2 for 2017 image.

2. Clipping: the process involved extracting the study area (Block G of approximately 17.7 Km^2) from the whole scene of 170 km X 183 km.
3. Unsupervised classification: since there was no knowledge on land cover for the study area, the land cover classes were determined using the reflectance values. The three bush density classes "high", "medium" and "low" were homogenous for the whole scene. The bush density classes were decided based on the NDVI. The classified image of 2017 was used as reference to classify historical images (1989 and 2000). The classification of all the images was done in ENVI (Environment for Visualizing Images) which is software used in GIS.

4. Projection: the data-sets covered two different time periods (1989-2000 and 2000-2017) with the aim of obtaining the spatial coverage changes. The raw images were projected to the projected geographic system UTM WGS 1984 South (zone 33) datum.
5. Conversion: this was done to calculate the areas that were covered by each bush density class. The areas were in m^2 and were then converted into hectares for ease of interpretation.
6. Land cover change detection: the process involved comparisons of pixel to pixel of the study year, to determine which bush density class changed to which over the years.

3.4.2 Characterisation of the encroacher bushes

The vegetation data were qualitatively and quantitatively analysed. Species recorded during the data collection were tabulated (scientific name(s), common name(s), family and their absence or presence in the three studied sites). Quantitatively, the following were calculated;

(1) Canopy cover: Output from the BECVOL 3-Model data.

(2) Density for individual species: Number of individual bushes found in all sampled plots converted to per hectare basis.

(3) Species Diversity: Shannon's diversity index was used to compare species diversity of sample plots using the formula below (Shannon & Weaver, 1949):

$$\mathrm{Sh} = -\Sigma(\mathrm{pi} \ln \mathrm{pi})$$

Where;

Sh, Shannon index

Pi, the proportional abundance of the ith species (= ni/N)

ln: natural logarithm

(4) Species similarities: Sorenson quantitative index was used to determine species similarities between topographic positions and sites. The formula for calculating the Sorenson quantitative index is as follows;

$$\mathrm{CN} = \frac{2jN}{(aN + bN)}$$

Where;

CN, Sorenson quantitative index

aN is total number of individuals in block A

bN is total number of individuals in block B

jN = the sum of the lower of the two abundances recorded for species found in both stratum

2, Constant number

(5) Species eveness: Pielou's evenness was used to calculate the species evenness for the sites.

$$J = \frac{H'}{In\ (S)}$$

Where;

J= Pielou's evenness

H′=Shannon's diversity index

In(S) = Natural Logarithim of species richness.

(6) Bush biomass: The biomass was determined using the BECVOL 2-Model and BECVOL 3-Model, utilizing all the 7 dimensions of individual bushes taken in the field to estimate the biomass of different components of the bush (See Section 3.4.3).

(6) Importance Value Index (IVI) for every species at each topographical position and sampled site (Greig-Smith, 1957): The IVI was determined as sum of abundance, frequency of occurrence and dominance X 100. Frequency was determined by counting the number of sample plots where the individual species occurred, divided by the total number of sample plots. Abundance was determined by adding the total number of individual bushes for a species that were encountered in all the sampled plots and divide it with the total number of bushes for all the species that occurred in the same sampled plots. The dominance measure used in this study was canopy cover, and not the basal area or the volume. The latter two were not considered in this study to calculate dominance as the main aim is to quantify the biomass suitable for animals feed to be extracted from the tree canopies.

$$IVj = \left(\frac{nj}{N} + \frac{dj}{D} + \frac{xj}{X}\right) \times 100$$

Where;

IV_j = Importance value of jth species

n_j = number of sampling units

N = total number of sampling units

d_j = number of individuals of jth species present in sample populations

D = total number of individuals in sample population ($D = \sum d_j$)

x_j = Sum of crown cover for jth species

X = Total crown cover for all species ($X = \sum x_j$)

The reason why the importance value figures were multiplied by 100 was to remove decimals to ease interpretation.

3.4.3 Estimation of above ground biomass (AGB)

The obtained data from the field were coded, whereby each tree species was given a species number to create a tree list for a sample plot as per BECVOL requirements. The data were entered into BECVOL 2-Model template for primary and secondary data calculations of leaf volume and leave dry mass (Smit, 2004). Primary calculations gave results for individual species, whilst secondary calculations combined the results for all species in a sample plot. The primary and secondary results from the BECVOL 2-Model and the created tree list for the plots were sent to South Africa for woody biomass estimation using BECVOL 3-Model software (Smit, 2014), which is not yet commercialised.

As an output of the BECVOL 3-model programme the following values of all the woody species that were rooted in each sample plot were obtained:

a) Tree density (plants/ha)
b) Evapotranspiration Tree Equivalents (ETTE/ha)
c) Leaf biomass (kg DM/ha)
d) Shoot dry mass - shoots <0.5 cm (kg DM/ha)
e) Stem dry mass - stems >0.5-2.0 cm in diameter (kg DM/ha)
f) Wood dry mass - wood >2.0 cm in diameter
g) Total wood dry mass (kg DM/ha)
h) Total tree biomass - leaves and wood combined (kg DM/ha)

Harvestable ETTE/ha (HETTE) was estimated from the Calculated ETTE/ha (CETTE). ETTE is defined as the leaf volume equivalent of a 1.5 m single-stemmed woody plant (Smit, 2004; Smit, 2014; Smit et al., 2015; Rothauge, 2014). The general rule of thumb for estimation of HETTE is; HETTE = CETTE – mean annual rainfall for the area X 10. Example the mean annual rainfall for Neudamm is 300 mm. 3000 ETTE/ha can be retained per hectare. Therefore, anything above 3000 ETTE/ha is considered a problem (encroached) as there will be competition between woody and non-woody species. This portion can be harvested.

3.4.4 Soil laboratory analysis

3.4.4.1 Soil Samples preparation

Soils samples were prepared in a standard way for laboratory analysis. All the samples were given laboratory codes which ranged from 35631-35684. The air-dried soil samples were passed through a 2 mm mesh sized sieve (Figure 9B) to get the "fine earth" fraction that were used for analysis. Materials that were greater than 2 mm in diameter termed “stones and gravels” were not considered for analysis, therefore they were discarded.

Figure 9: (A) Sorting and labelling (lab codes) (B) Sieving and bottling the soil samples; and (C) soil samples ready for analysis

The following physical and chemical analysis were carried out for all 54 soil samples; pH, electrical conductivity (EC), soil texture (sand, silt, clay), Total Nitrogen (TN), phosphorus (P), potassium (K), soil organic matter (SOM), Organic Carbon (OC), calcium (Ca), magnesium (Mg), and sodium (Na). The analysis was done at the Ministry of Agriculture, Water and Forestry at the Soil Science Laboratory. Total Nitrogen was analysed at the Analytical Laboratory Services, in Windhoek. The pH (water) was determined using a 1:2.5 soil: water ratio suspension on a mass to volume basis. P was determined using the Olsen method: Extraction with sodium bicarbonate. Phosphate measured spectrophotometrically using the phosphomolybdate blue method. Measurement of available K, Mg, Na and Ca was by inductively coulped plasma (ICP), using Extraction with 1M ammonium acetate at pH 7.

EC was determined in the supernatant of the 1:2.5 soil:water suspension prior to measurement of pH. Organic Carbon was determined using Walkley-Black method (sulphuric acid-potassium dichromate oxidation). A factor of 1.74 was included in calculations to take account of incomplete oxidation. Organic matter content was calculated as organic: C x 1.74. Soil texture was determined using the pipette method. The soil was dispersed with sodium hexametaphosphate/sodium carbonate. Sand fraction was determined by sieving to retain >53 micron fraction. The textural classes were determined using the USDA classification system (Soil Survey Division Staff, 1993). The Total Nitrogen was determined using Modified Kjeldhal method. The detailed procedures of each analysis method are given in appendix 24.

3.5 STATISTICAL ANALYSES

The data were statistically analysed using XLSTAT software and R Software. Normality of the data was tested using Shapiro Wilk test ($p>0.05$) and Chi-square test ($p>0.05$). The data that was not normally distributed was transformed using square root transformation in cases where parametric tests were applied. The following tests were carried out:

a) Bush densities for low, medium and high-density strata were subjected to Two-Way ANOVA to check if bush density of the strata differed significantly.
b) Two-Way ANOVA was also used to check if changes in bush density in Block G from 1989 to 2017 were significant or not.
c) Species dominance patterns between sites and between topographic positions were tested whether they were significantly different using Kandell rank correlation coefficient.
d) Two-Way ANOVA was used to test whether in the high bush density stratum, species diversity, bush density, crown cover and biomass (different

components of biomass example leafy and woody biomass) varied significantly between sites, between topographic positions and between the first three dominant species. The bush density data used in this test was transformed using the square root transformation.

e) Pearson correlation test was used to determine which soil properties were significantly correlated to bush density.

f) Kruscal Wallis test was used to test whether soil properties varied across the sites and topographical positions. The same test was used to test whether the biomass of dominant species varied significantly between sites and between topographic positions.

CHAPTER 4: RESULTS

4.1 Spatial coverage of different bush densities areas (Low, Medium & High) at Block G, Neudamm Farm in 1989, 2000 and 2017

Using unsupervised classification of satellite images, Block G was stratified into three bush density areas (classes) (Low, Medium and High). Ground assessment determined the bush densities of each class. The average density for Low density class was 2530, 4340 for Medium class and 10520 for High class (Figure 10). Although bush densities between classes overlapped slightly, bush densities of different classes were significantly different (F=11.9; DF=2; P=0.00019) (Appendix 28).

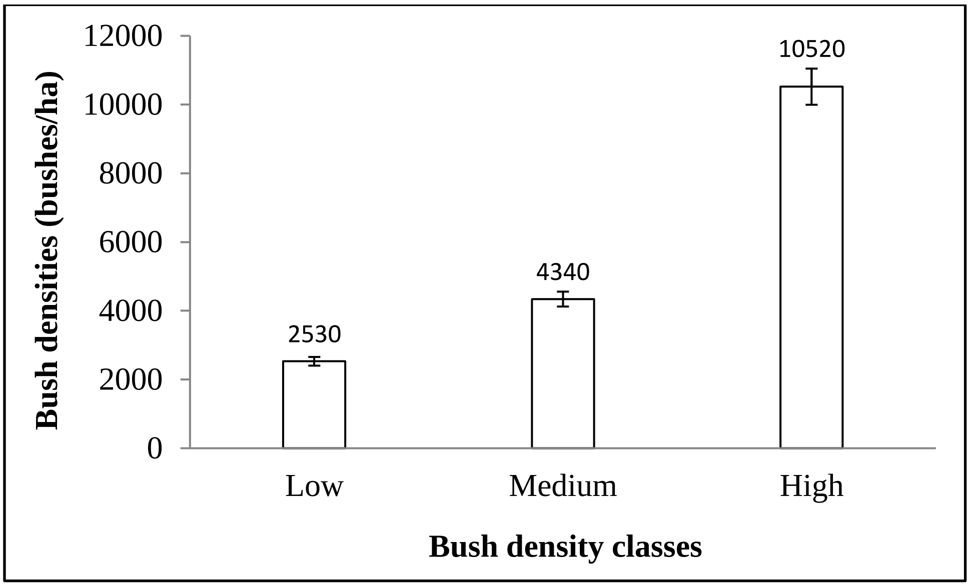

Figure 10: Average bush density and standard errors of the bush density classes.

There was a change in land areas covered by different bush density classes between 1989 and 2017 (Figures 11, 12 and 13). High density class was dominant followed by the low class and then the medium density class in all the years analyzed (1989, 2000 and 2017). In 1989, the high-density class was predominantly in the North-western and South-western parts of the study area (Figure 11) but by 2017 this class had covered most parts of the study area (Figure 13). The change from medium to low during the two epochs (1989 to 2000 and 2000 to 2017) was more on the first epoch and it occurred on the North-western part of the study area. The change in medium class to high class was more during the first epoch and the same was with low to high class (Figures 11-13). The change was all over the area, expect towards the South-Western side.

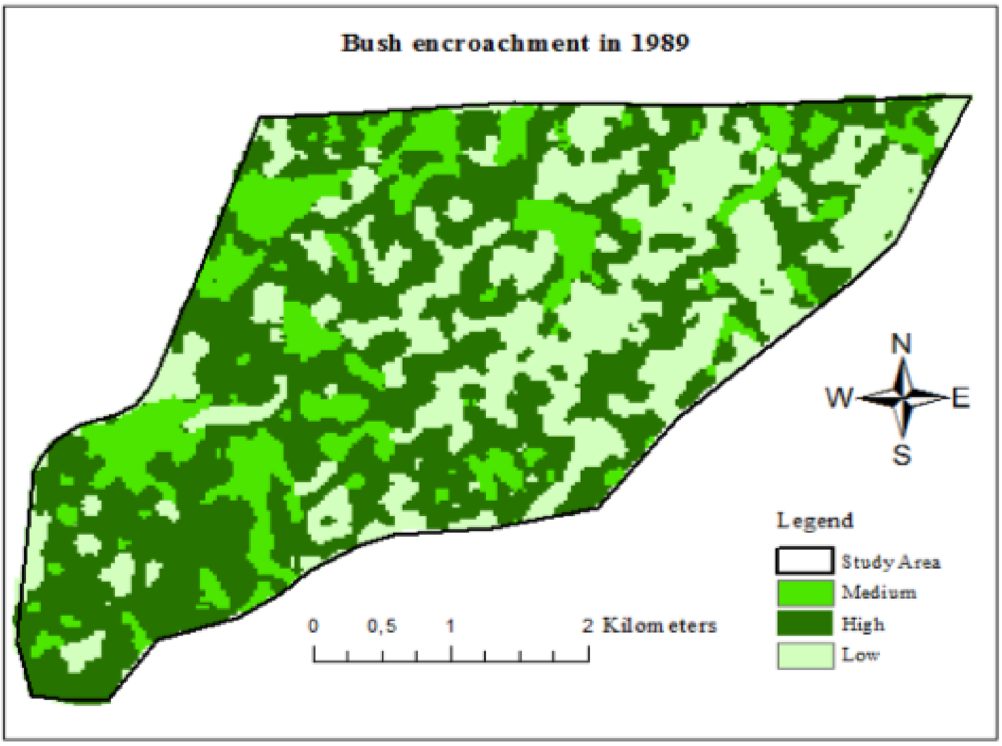

Figure 11: Areas covered by different bush densities in Block G, Neudamm Farm in 1989; High density (838 ha), Medium (335 ha) and Low (622 ha).

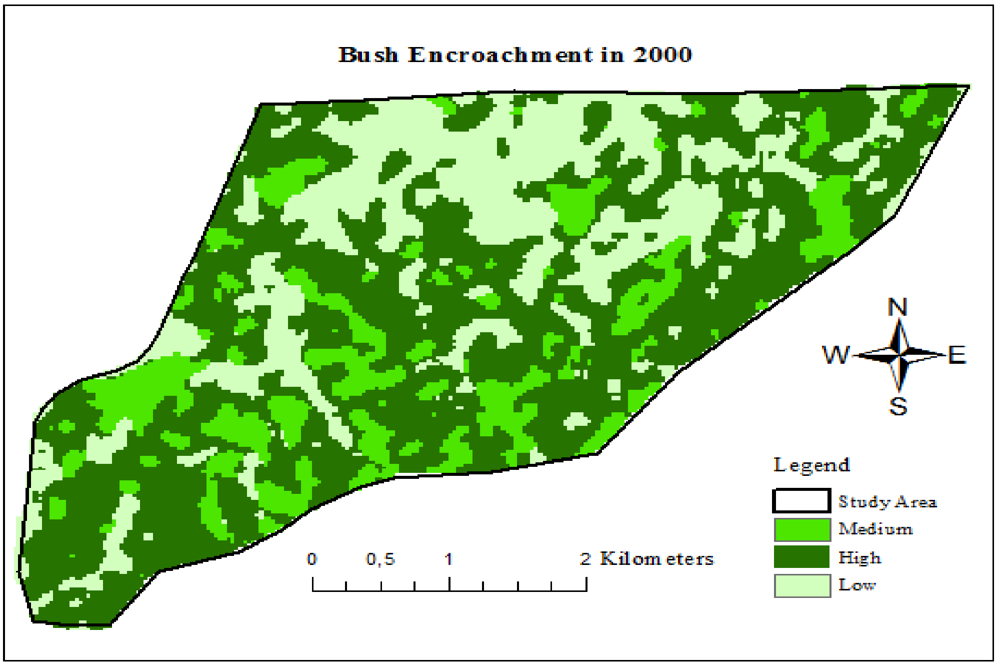

Figure 12: Areas covered by different bush densities in Block G, Neudamm Farm in 2000; High density (893ha), Medium (328 ha) and Low (575 ha).

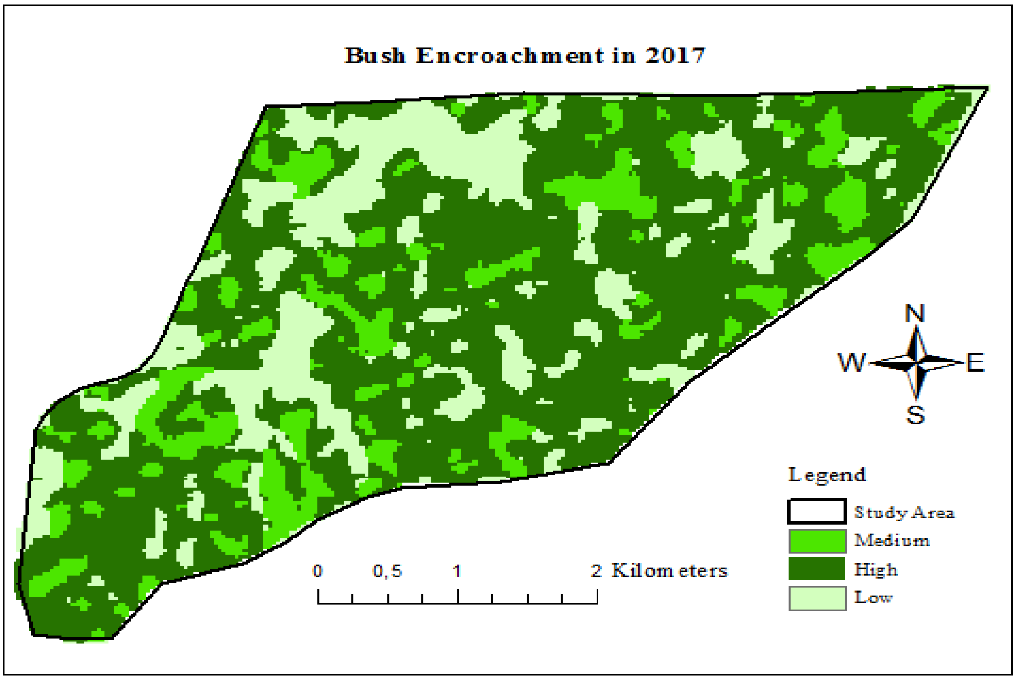

Figure 13: Areas covered by different bush densities in Block G, Neudamm Farm in 2017; High density (955 ha), Medium (335 ha) and Low (504 ha).

The land area covered by each bush density class was calculated and presented in Figure 14 and the degree of change (percentage increase or decrease) from 1989 to 2000 and from 2000 to 2017 is shown in Table 5. Total areas covered by each bush density class have changed between the years. Area under high bush density increased from 838 ha in 1989 to 955 ha in 2017 and there was a decrease, from 622 ha to 504 ha in area under low bush density. Area under medium bush density remained more or less the same, 335 ha (Figures 14).

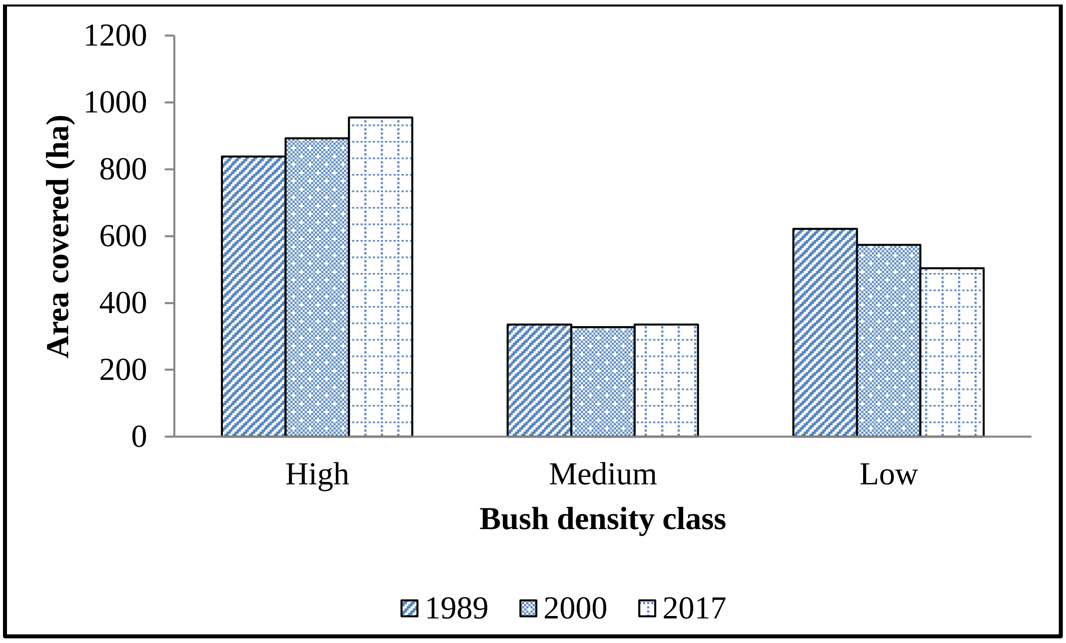

Figure 14: Area covered by the different bush density classes in hectares in 1989, 2000 and 2017.

Percentage changes in areas under different bush density during the two epochs (1989-2000 and 2000-2017) and the overall change (between years 1989-2017) are shown in Table 5. Overall there was a 19% reduction in low class area between 1989 and 2017 and 14% increase in area of high bush density while the area of medium bush density remained the same during this period. This means bush encroachment in Block G has been increasing with low bush density areas slowly changing to medium or high. Medium density area reduced between years 1989-2000 but increased by approximately the same amount between years 2000-2017 (Table 5).

Table 5: Percentage increase and decrease of area covered by different bush density classes over the two epochs, 1989-2000, 2000-2017 and overall change between 1989-2017.

	% Change in area covered by different bush densities between:		
Bush density class	**1989-2000**	**2000-2017**	**1989-2017**
High	7 (+)	7 (+)	14 (+)
Medium	2 (-)	2 (+)	0
Low	8 (-)	12 (-)	19 (-)

The plus signs in brackets mean that there was an increase in area covered by a bush density class and the negative sign indicates a decrease in area.

4.2 Characteristics of bushes in relation to site, topographical positions and soil properties

4.2.1 Features of the sampled sites

The coordinates, altitude, aspect and slope of each sample plot are shown in Appendix 23. Aspect for all the sites was the same (North). The sample plots were generally in relatively flat areas the slope between Top Hill plots and Hill Base plots was 7% for Site 1, 7-8% for Site 2 and in Site 3 the slope was ranging from 3-6% (Appendix 23). The altitude also differed slightly between the three sites. Since the focus of the study was to check whether encroacher bush characteristics were related to geographical position (site), topographical positions and soil properties, the influences of slope and aspect on encroacher bush characteristics was not tested.

4.2.2 Species composition of bushes

A total of 2269 woody plants were recorded in the three sites belonging to 16 different plant species, from 10 families (Table 6). However, the species did not occur uniformly in all the sites owing to the fact that species have different habitat preferences among other factors. *Senegelia mellifera* subsp. *detines*, *Boscia albitrunca*, *Maerua parvifolia*, *Catophractes alexandrii*, *Grewia flava*, *Searsia marlothii*, *Tarchonanthus camphoratus* and *Ziziphus mucronata* occurred in all the sites. *Senegelia hereroensis* and *Searsia lancea* were only found in one of the sites. Other species occurred in two of the sites (Table 6).

Table 6: Species composition of woody plants recorded in Block G, Neudamm Farm.

Scientific name (common name)	**Family name**	**Present (✓)/Absent (×) in:**		
		Site 1	**Site 2**	**Site 3**
Vachellia hebeclada (Candle-pod)	Mimosaceae	✓	×	✓
Senegelia hereroensis (Mountain-thorn)	Mimosaceae	×	✓	×
Vachellia karroo (Sweet-thorn)	Mimosaceae	✓	✓	×
Senegelia mellifera subsp. *detines* (Black-thorn)	Mimosaceae	✓	✓	✓
Boscia albitrunca (Shepherd's tree)	Capparaceae	✓	✓	✓
Maerua parvifolia (Small-leaved maerua)	Capparaceae	✓	✓	✓
Catophractes alexandrii (Trumpet-thorn)	Bignoniaceae	✓	✓	✓
Grewia flava (Velvet raisin bush)	Tiliaceae	✓	✓	✓

Leucosphaera bainesii (Wool bush)	Amaranthaceae	✓	×	✓
Lycium boscifilium (Limpopo honey thorn)	Solanaceae	×	✓	✓
Lycium eenii (Broad-leaved honey thorn)	Solanaceae	✓	×	✓
Phaeoptilum spinosum (Brittle-thorn)	Nyctaginaceae	✓	×	✓
Searsia lancea (Karee)	Anacardiaceae	×	✓	×
Searsia marlothii (Bitter karee)	Anacardiaceae	✓	✓	✓
Tarchonanthus camphoratus (Camphor bush)	Asteraceae	✓	✓	✓
Ziziphus mucronata (Buffalo-thorn)	Rhamnaceae	✓	✓	✓
Number of species		13	12	13

4.2.3 Species dominance across sites and topographical positions (Importance Value Index - IVI)

Senegalia mellifera was the most dominant species in all the sampled sites and at all topographical positions (Hill Top, Hill Side and Hill Base) (Table 7). It was more dominant in Site 2 (with an IVI of 247) followed by Site 3 (238) and Site 1 (231). *Senegalia mellifera* was more dominant at Hill Tops (IVI, 249) as compared to Hill Side (245) and Hill Base (223).

Table 7: Importance Value Index (IVI) of individual species per site and topographical position

Species	**IVs by site**			**IVs by Topographical position**		
	Site 1	**Site 2**	**Site 3**	**Hill top**	**Hill side**	**Hill base**
Senegalia mellifera subsp. detines	231	247	238	249	245	223
Tarchonanthus camphoratus	126	133	23	74	103	105
Grewia flava	111	83	57	97	67	86
Vachellia hebeclada	25	13	29	13	13	41
Vachellia karoo	23	12	0	11	0	23
Catophractes alexandrii	13	11	12	13	11	13
Ziziphus mucronata	12	46	12	13	12	46
Phaeoptilum spinosum	12	12	27	12	13	27
Lycium boscifilium	12	0	0	12	0	0
Searsia marlothii	25	81	58	81	35	48
Searsia lancea	0	23	0	23	0	0
Senegalia hereroensis	0	17	0	12	24	14
Maerua parvifolia	0	23	0	0	23	0
Boscia albitrunca	0	0	14	14	0	0

Species dominance patterns between sites and between topographic positions were tested (Kendall rank correlation coefficient) to check whether they were significantly the same or not. Species dominance patterns were positively correlated between sites and between topographical positions. Correlation coefficients were low to moderate (0.38-0.58) for sites and (0.33-0.67) for topographical positions (Table 8).

Table 8: Correlation matrix (Kendall rank correlation coefficient) and p-values of species dominance (IVI) patterns between sites and between topographical positions.

Correlation matrix (Kendall):

Sampled sites	S1	S2	S3
S1	1		
S2	**0.49**	1	
S3	**0.58**	0.38	1

p-values:

Sampled sites	S1	S2	S3
S1	0		
S2	**0.02**	0	
S3	**0.01**	0.08	0

Correlation matrix (Kendall):

Topography	T1	T2	T3
T1	1		
T2	0.33	1	
T3	**0.48**	**0.67**	1

p-values:

Topography	T1	T2	T3
T1	0		
T2	0.12	0	
T3	**0.02**	**0.0016**	0

TI=Hill top, T2=Hill side and T3=Hill base and the values in bold show where the pattern of dominance are significantly correlated (same).

4.2.4 Species composition similarities between sites and between topographical positions.

Species composition similarity (Sorenson quantitative index) of woody plants found in the different sites ranged from 0.468 to 0.762 (Table 9). Site 1 and Site 3 had the highest species similarity (0.762) and Site 1 and Site 2 had the lowest species similarity (0.468). The Hill Top and Hill Side had the highest species similarity (0.961) and between the Hill Top and Hill Base being the lowest (0.860) - (Table 10). Species similarities between topographical positions were higher than similarities between sites.

Table 9: Species composition similarity (Sorenson quantitative index) between the three sites sampled

Sampled sites	Site 1	Site 2	Site 3
Site 1	0		
Site 2	0.468	0	
Site 3	0.762	0.483	0

Table 10: Species composition similarity (Sorenson quantitative index) between the three topographical positions sampled.

Topographical Positions	Hill Top	Hill Side	Hill Base
Hill Top	0		
Hill Side	0.961	0	
Hill Base	0.860	0.910	0

4.2.5 Comparison of species diversity between sites and between topographical positions

The species diversity (Shannon index) data was normally distributed using Shapiro-Wilk test (P=0.6101) and Chi-Square (P=0.3761). The variation in species diversities is illustrated by Figure 15.

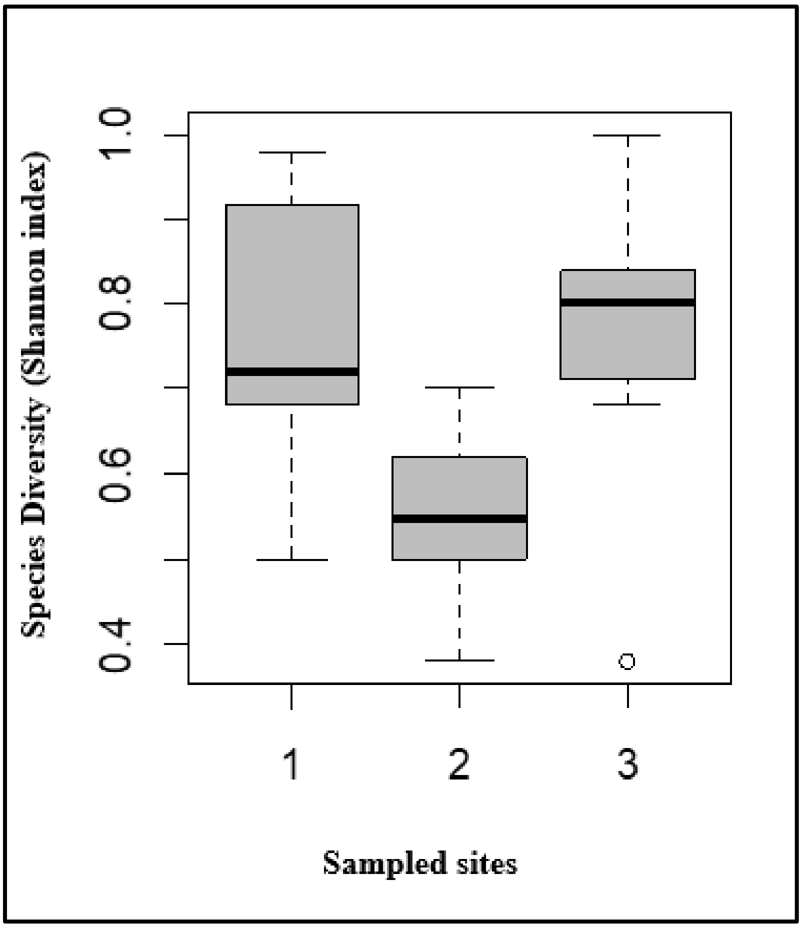

Figure 15: Variation in species diversities sites.

There was a significant difference in species diversity between the sampled sites (F=6.8112; DF=2; P=0.0063, Appendix 6). Site 1 had the highest average species diversity followed by Site 3 and Site 2 had the lowest diversity. Turkeys HSD test, showed that, there was no significant difference in means of species diversity between Site 1 and Site 3. However, Sites 1 and 3 had significantly higher species diversity than site 2. Species diversity was significantly different only between Hill Base and Hill Top (Table 11). The species evenness was low across all the sampled sites (Table 12).

Table 11: Turkey (HSD) pairwise comparison of average species diversity (Shannon index) between sites and between topographical positions.

Factor		LSD means
Site	1	0.766^{a}
	3	0.763^{a}
	2	0.553^{b}
Topographical position	Hill Base	0.7689^{a}
	Hill Side	0.7167^{ab}
	Hill Top	0.5978^{b}

Means denoted by the same letter are not significantly different.

Table 12: Species evenness of the sampled sites

Sites	Evenness index
Site 1	0.299
Site 2	0.22
Site 3	0.296

4.3 Bush densities at different sites and topographical positions

4.3.1 Combined density of both shorter bushes (< 0.5 in height) and taller bushes (≥ 0.5 in height)

The transformed bush density data for all the bushes combined (shorter and taller) were normally distributed tested using Shapiro-Wilk test (P=0.07447) and Chi-Square (P=0.2604). There was a significant difference in average bush density across the sites (F=13.8293; DF=2; P=0.0002) (Appendix 8). Turkey HSD test showed that there was no significant difference in average bush density between Site 3 and Site 1. Site 2 had significantly higher bush density than Sites 1 and 3 and there was no significant difference in bush densities across topographical positions (Table 13 and Figure 16).

Table 13: Turkey (HSD) pairwise comparison of average bush density across sites and between topographical positions

Factor		**LSD means**
Site	2	13488.8[a]
	3	7255.5[b]
	1	4466.6[b]
Topography	Hill side	9188.8[a]
	Hill top	8811.1[a]
	Hill base	7211.1[a]

Means denoted by the same letter are not significantly different.

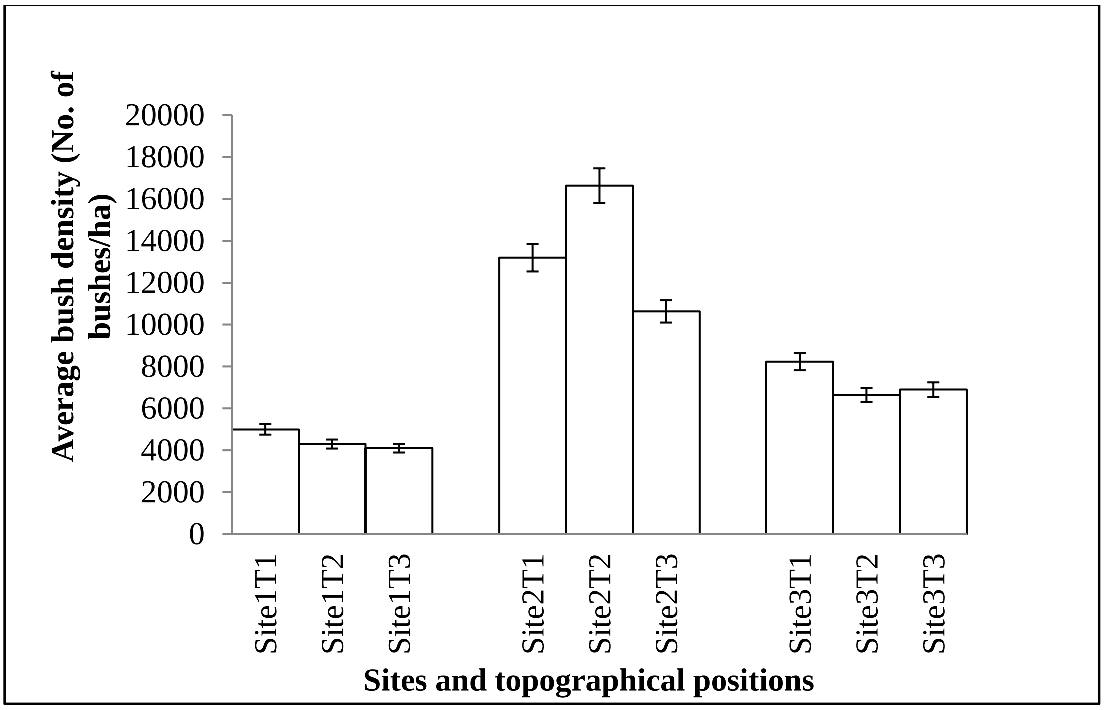

Figure 16: Average bush densities and SE across sites and at different topographical positions.

4.3.2 Average bush densities of shorter (< 0.5 in height) and taller (≥ 0.5 height) bushes analysed separately.

The transformed (Square root transformation) bush density data for taller bushes and shorter bushes were normally distributed using Shapiro Wilk (P=0.3991); Chi-Square (P=0.2169) and Shapiro Wilk (P=0.2603); Chi-Square (P= 0.4682). There were significant differences in average densities of taller bushes (F=8.0742; DF=2; P=0.0031) and shorter bushes (F=6.7866; DF=2; P=0.0063) across the sampled sites (Appendices 9 and 10). For tall bushes, Site 2 had significantly higher average bush density than Site 1 and Site 3. There was no significant difference between the densities of Site 1 and 3. For shorter bushes average density was statistically significantly higher in Site 2 than in Site 1. Average density for Site 3 was not statistically different from that of Site 2 or Site 1. The average densities of taller and that of shorter bushes did not differ significantly between the topographical positions as tested using Turkey pairwise comparison Test (Table 14).

Table 14: Turkey (HSD) pairwise comparison of taller and shorter bushes average densities between sites and between topographical positions**.**

LSD Means for taller bushes density			**LSD Means for shorter bushes**		
Factor		LSD Means	Factor		LSD Means
Topography	Hill top	2300[a]	Topography	Hill side	7088.8[a]
	Hill side	2100[a]		Hill top	6511.1[a]
	Hill base	1877.7[a]		Hill base	5300[a]
Site	2	3066.6[a]	Site	2	10388.8[a]
	1	1733.3[b]		3	5777.7[ab]
	3	1477.7[b]		1	2733.3[b]

Means denoted by the same letter are not significantly different.

4.3.3 Variation of bush densities in relation to soil properties

4.3.3.1Variation of soil characteristics across sites and across topographical positions.

Soil characteristics across sites and across topographical positions are shown in Table 15 and were tested using Kruscal Wallis Test for differences in properties (Appendices 21 and 22). Only P and Na content varied significantly across Sites (Kruscal Wallis Test) ($p=0.011$ and Na; $p=0.000$). Phosphorus was high in Site 3 (12.4±2.3), followed by Site 2 (6.1±1.5) and 5.9±1.0 for Site 1. Sodium was high in Site 1 (99.0±22.0), Site 2 (26.6±18.8) and it was not detected in Site 3 (0.0±0.0). In addition, (ECw; $p=0.040$ and Ca; $p= 0.047$) varied significantly across topographical positions (Kruscal Wallis Test). Electrical conductivity was high in Hill Side (78.9±31.3), Hill Base (46.6±9.7) and 39.9±11.0 in Hill Top. Calcium was high in Hill Side (698.6±181.8), Hill Top (361.2±45.8) and it was lower in Hill Base (635.0±138.9).

Table 15: Soil texture frequencies and other soil properties (Averages and SEs) at different topographical positions and sampled sites.

Soil Characteristic	Site			Topographical position		
	1	2	3	Hill Top	Hill Side	Hill Base
Soil Texture (% of plots having that texture)						
Loamy Sand	78	22	78	78	0	22
Sandy clay loam	0	0	11	44	11	44
Sandy loam	22	78	11	56	0	44
pHw	5.7±0.1	5.9±0.1	6.0±0.1	5.8±0.0	5.9±0.1	5.8±0.1
ECw (uS/cm)	78.7±33.1	49.8±9.5	35.9±2.3	**39.9±11.0**	**78.9±31.3**	**46.6±9.7**
OM (%)	1.0±0.0	1.2±0.1	1.20±0.0	1.12±0.0	1.3±0.1	1.1±0.1
N (mg/kg)	838.6±159.6	957.7±133.7	825.0±58.9	743.0±53.5	1011.5±145.1	866.8±140.4
P (ppm)	**5.9±1.0**	**6.1±1.5**	**12.4±2.3**	6.4±1.8	9.1±2.1	8.9±1.3
K (ppm)	154.9±21.5	213.3±22.2	211.6±27.9	156.8±24.3	200.1±15.7	223.0±29.8
Ca (ppm)	607.8±194.0	584.6±152.9	502.3±26.7	**361.2±45.8**	**698.6±181.8**	**635.0±138.9**
Mg (ppm)	102.9±23.4	106.5±20.5	76.6±4.5	70.6±6.7	107.1±22.1	108.2±20.1
Na (ppm)	**99.0±22.0**	**26.6±18.8**	**0.0±0.0**	54.2±27.1	36.1±19.9	35.2±18.3
OC (%)	0.6±0.0	0.7±0.0	0.7±0.1	0.6±0.0	0.8±0.1	0.6±0.0

Values in bold varied significantly between sites or between topographical positions.

4.3.3.2 Correlation between soil properties and bush densities at different topographical positions

Out of all the soil properties tested for correlation with variation in bush density, only Sodium (Na) had a significant negative correlation (Table 16). The correlation coefficient (Pearson correlation) between Na content and combined taller and shorter bushes density was 0.3888, and R=0.1512 and for the shorter bushes 0.4371, and R=0.1910. It implies that 15 % and 19 % of the total variation of bush density/ha for taller and shorter bushes combined and shorter bushes respectively, is explained by Na distribution and the other 85 % and 81 % of the total variation is by other factors. The density of taller bushes had no significant correlation with the tested soil properties (Table 16).

Table 16: Pearson Correlation Coefficients and R between soil properties and bush densities

Soil properties	Density of both taller and shorter bushes combined	R	Density of taller bushes	R	Density of shorter bushes	R
pHw	0.0016	0.0000	0.1657	0.0275	-0.0631	0.0040
ECw	-0.1260	0.0159	0.0797	0.0063	-0.1701	0.0289
OM	0.2895	0.0838	0.2757	0.0760	0.2002	0.0401
N	0.0156	0.0002	0.2934	0.0861	-0.0945	0.0089
P	-0.1060	0.0112	-0.1079	0.0116	-0.1337	0.0179
K	0.0218	0.0005	0.1007	0.0101	-0.0224	0.0005

Ca	-0.1757	0.0309	0.2382	0.0567	-0.2743	0.0753
Mg	-0.1119	0.0125	0.2736	0.0749	-0.2069	0.0428
Na	**-0.3888**	0.1512	0.1269	0.0161	**-0.4371**	0.1910
OC	0.1699	0.0289	0.0053	0.0000	0.1369	0.0187

Values in bold show significant correlation.

4.4 Crown cover

The crown cover data were normally distributed as shown by Shapiro-Wilk test (P=0.3835) and Chi-square test (P=0.3607). The average crown cover % for different sites and topographical positions are shown in Figure 17. The average crown covers per site and at different topographical positions were high, ranging from 33.5 % to 75.1 % (Figure 17) implying high bush encroachment. There was a significant difference in average crown cover between the sampled sites (F=4.0219; DF=2; P=0.0360) and the interaction of sampled sites and topography (F=3.9330; DF= 4; P=0.0182) (Appendix 16). There was no significant difference in crown cover across the topographical positions (Table 17). However, there was a significant difference in average crown cover between Site 2 and Site 3. Site 2 had the highest crown cover and Site 3 the lowest as tested through Turkey's Test (Table 17 and Figure 17).

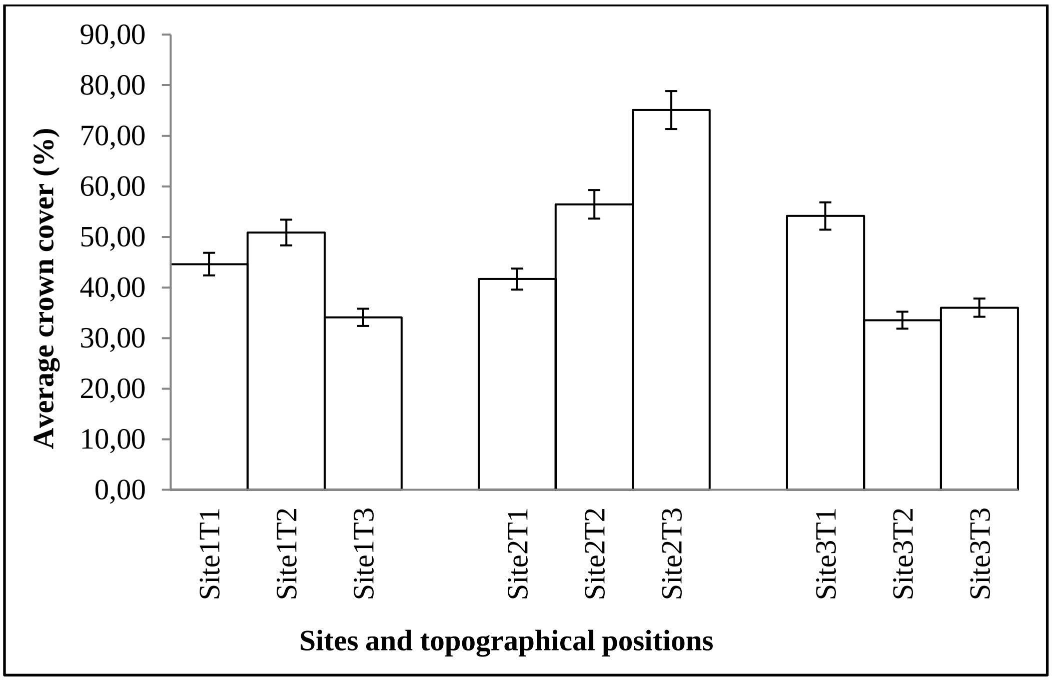

Figure 17: Average crown cover % and their standard errors across sites and at different topographical positions.

Table 17: Turkey (HSD) pairwise comparison of average crown cover percentages between sites and between topographical positions

Factor		**LSD Means**
Topography	Hill top	91.9[a]
	Hill side	89.1[a]
	Hill base	88.9[a]
Site	2	100.6[a]
	1	82.0[ab]
	3	78.3[b]

Means denoted by the same letter are not significantly different.

4.6 Biomass estimates for bushes in Block G of Neudamm Farm.

The total biomass and biomass fit for animal feed (≤ 2 cm) for all species encountered are shown in Appendix 20. The biomass for the three most dominant species and all other species combined (Tables 18 &19) were subjected to further analysis. The total biomass and biomass fit for feed varied significantly across sites (Kruscal Wallis Test, P=0.024 and P=0.027, respectively (Appendix 19). Total biomass was high in Site 2 (17433 Kg/ha), Site 3 (14124 Kg/ha) and it was 13410 Kg/ha in Site 1. Biomass fit for feed was high in Site 2 (9281 Kg/ha), followed by Site 3 (7497 Kg/ha) and it was 6834 Kg/ha in Site 1. The total biomass for the 3 most abundant species *(S. mellifera, T. camphoratus, G. flava*) and all other species combined varied significantly across sites Kruscal Wallis Test p=0,000 (Appendix 19). *Senegalia mellifera* was the highest (11397 Kg/ha), followed by *Tarchonanthus camphoratus* (1826 Kg/ha). Other species combined (1464 Kg/ha) and lowest was *Grewia flava* (303 Kg/ha).

The BECVOL 3-Model output shows that 4.8 tonnes/ha of *S. mellifera* suitable biomass for animals feed (≤ 2cm) is available in Block G stratum classified as having high bush density (Table 18). The three-dominant species (*Senegalia mellifera, Tarchonanthus camphoratus and Grewia flava)* combined would give suitable biomass of 7.25 tonnes/ha.

The Harvestable ETTE (HETTE) is 80 % of the available or Calculated ETTE (CETTE) applying the formula HETTE = CETTE- (Average annual rainfall of Block G in mm (300) x 10 (a constant) – (Appendix 26) and 20 % to be retained, which is other species and big trees of *S. mellifera*.

Table 18: Estimated average biomass fit for the production of animal feed across the sampled sites.

	Biomass fit for animal feed (Kg/ha±SE)			
Species	Site 1	Site 2	Site 3	**Overall Average Biomass**
Senegalia mellifera	5088±972	6540±1253	6664±999	6097 (77.5%)
Tarchonanthus camphoratus	1210±255	1628±340	17±14	952 (12.1%)
Grewia flava	393±119	180±58	31±28	201 (2.6 %)
Other species combined	143±106	933±504	785±718	620 (7.9 %)
Overall Average Biomass	6834	9281	7497	**7870**

Table 19: Estimated average total biomass across the sampled sites.

	Total biomass (Kg/ha±SE)			
Species	Site 1	Site 2	Site 3	**Overall Average Biomass**
Senegalia mellifera	10229±2385	12364±2779	11597±1571	11397 (76.03 %)
Tarchonanthus camphoratus	2442±565	3009±747	27±23	1826 (12.18 %)
Grewia flava	557±147	308±99	43±40	303 (2.02%)

Other species combined	182±140	1752±1057	2457±2363	1464 (9.77%)
Overall Average Biomass	13410	17433	14124	**14990**

CHAPTER 5: DISCUSSION

5.1 Spatial coverage of encroacher bushes in Block G of Neudamm Farm.

The current study applied remote sensing techniques to track bush encroachment in Block G of Neudamm Farm, Khomas Region from 1989 to 2017. Although bush encroachment is directly being observed across the area, there was a need to determine its land cover over the years. With the bush densities and crown cover of the woody species recorded for Block G in this study; 53% of the Block being high bush density areas with 3800 to 22800 bushes/ha and average crown cover of 90.1 %, 28% of the block, medium bush density area with 3000 to 5800 bushes per hectare and 19% of the Block, low with the bush density ranging from 1600 to 3600 bushes per hectare, Block G is considered as highly encroached if criteria of de Klerk (2004) of BE being considered to have occurred if bush densities are > 3000 bushes/ha is used.

According to Yu, Saha & D`Odorico (2017) the increasing of bushes in dry environments is because of the inter-annual rainfall variability. As the drainage increases and the soil moisture will only be available to the woody species. Annual rainfall in Khomas area is recorded to fluctuate widely (Mendelsohn *et al*., 2002). In addition, drought is one of the reasons why bush encroachment has increased because it favors the bushes than grasses. The grass seeds remain dormant in the soil until the condition is favorable for them to germinate. This results in the bushes taking over the space because they can access underground water, unlike the grasses that depend on the surface water. This might be a key reason for the bush encroachment at Neudamm without ruling out other factors like management and presence of an aggressive encroacher species, *Senegalia mellifera*.

Even with this high bush density for Block G, BE is increasing since between 1989 and 2017 (there was a 14% increase in the area classified as High bush density class). The increase of bush density could be owing to grazing pressure (continuous grazing) because the selected block is housing large stocks. Continuous grazing accelerates the rate of herbaceous plants disappearing and this creates favorable conditions for the bushes to take over the area because the competition is reduced between woody and herbaceous plants. To halt or even reverse this trend bush control measures would be appropriate and the intended conversion of bush to feed project for Block G is timely.

5.2 Species composition and density of encroacher bushes in Block G of Neudamm Farm.

Species composition similarity between sites was moderate (0.468-0.762; Table 9). This means species composition may change from one geographical position to another even within short distances. In addition, among all the woody species recorded in Block G (Table 6) only *Senegalia mellifera*, *Vachellia hebeclada* and *Catophractes alexandrii* are reported as encroacher species (DECOSA, 2015). These facts justify site specific basic species composition surveys before wide scale bush harvesting projects are initiated, if bush harvesters are to ensure that sustainable bush harvesting is carried out without causing damage to the environment as some rangelands contain some protected species. Species composition analysis would also give an indication of quality and uniformity of feed to be expected.

In Block G, *T. camphoratus* and *G. flava* were among the top three dominant species across the sites with average densities of; Site 1 (4467 bushes/ha), Site 2 (13489 bushes/ha) and Site 3 (7255 bushes/ha). If the criterion for determining a bush encroacher is being dominant in a bush encroached area, as it seems to be applied in drawing the list of encroacher species (DECOSA, 2015), then these two species ought to be included as bush encroachers in the category of encroachers of localized distribution. *S. mellifera* is overwhelmingly dominant (1550 out of 2269 total density) across all sites giving the Farm Management the option of only harvesting this species. Alternatively, the two other relatively common species, *T. camphoratus* and *G. flava* can be harvested together with *S. mellifera*. The feed value of *G. flava* is known as bad for the animals feed because of high amount of fibre content and low crude protein (Katrina Shiningayamwe, personal communications, 2019[5]) and *T. camphoratus* feed value is not known; therefore, determination of the nutritional value of feed before use of this species is important.

Among the species recorded in Block G only *Boscia albitrunca*, *Searsia lancea* and *Ziziphus mucronata* are protected species (Pallett & Tarr, 2017). This means harvesting bushes from this Block may not offer many conservation challenges. The only other condition to be taken care of is the retention of the bigger sized trees (Pallett & Tarr, 2017) a factor discussed in the section below.

Species similarity between sites was low to moderate (0.468-0.762, Sorenson quantitative index) and high between topographical positions (0.860-0.960), (Table

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[5] Agricultural Scientific officer at MAWF-Windhoek

10 & 11). These similarities can be explained by the high dominance of *Senegalia mellifera* across sites and topographical positions, other species only having a small influence on the index. However, it is worth noting that these results suggest that topographical positions had little or no influence on species composition.

Species diversity (Shannon index) was significantly higher in Sites 1 and 3 than in Site 2 and not significantly different across topographical positions (Table11). This pattern can be explained by the fact that almost the same species were found across sites and across topographical position (Table 6) and the total number of species per site was almost the same, 13, 12, and 13 for Sites 1, 2 and 3 respectively. The higher diversity in Site 1 and 3 is due to difference in species number (one extra species in both Sites 1 and 3). Species evenness was low in all sites (Site 1=0.299; Site 2=0.22 and Site 3=0.296) because *S. mellifera* was dominating in all sites, contributing more than 77.5 % and 76.03 % of bush biomass in all sites (Tables 18 & 19).

Bush density was significantly higher in Site 2 because more plots in these sites had numerous small sized stems. The same site had high N content which can as well be the cause of high density of bushes. Bush density did not vary significantly between topographical positions. This may have been due to the fact that Block G is relatively flat (slopes ranging from 3 - 8% and differences in elevation of different topographical positions (Appendix 23) was not big enough to cause significant differences in bush density. However, a study by (Boscutti *et al*., 2018) found out that species composition decreases with elevation and species evenness increases at lower elevation because of soil moisture and it decreases with soil moisture at higher elevation (Tsechoe, Stein, Julia & Ørjan, 2014).

Among the soil properties tested only Na had a negative significant correlation with bush density (Table 15). Samples at the bottom of valleys (S2T3) where Na was more had less bush density. Woody plants in general are severely affected by accumulation of salts (Jouyban, 2012). The salt affects the uptake of the nutrients and water by the plants. In the current study, the negative correlation was on the shorter plants. This could be because one of the effects of Na in the soil is that at times it increases osmotic tension, by which water is held in the soil and as a result the plants die-off.

5.3 Quantity of bush encroacher (biomass) available for harvesting.

The biomass distribution across sites corresponds with the tree density data, meaning that biomass could be more influenced by the number of trees in a site rather than by the size of the trees. This pattern of biomass distribution is due to the fact that Site 2 had significantly higher bush density than Sites 1 and 3. The percentage of biomass fit for animals' feed (≤2 cm diameter) of the three-dominant species across the samples sites is 92.2%, of which *S. mellifera* constitutes 77.5% out of the biomass ≤2 cm diameter. The biomass for *Senegalia mellifera* was dominating on biomass for animals' feed and also total biomass. This clearly shows that it is the dominant encroacher species.

The study found out that if *Senegalia mellifera* is to be harvested from Block G it will give 4.8 tonnes/ha of uniform feed (twigs ≤ 2 cm diameter). This figure is comparable with what was determined at Otjiwarongo. Smit *et al*. (2015) reported that approximately 5 tonnes/ha of *S. mellifera* biomass can be harvested per hectare for animals' feed. In addition, according to Anton Dresselhaus, personnel communication, 21/09/2018, 2 tonnes/ha of *S. mellifera* wood chips are being harvested from the area near Dordabis, Khomas Region. However, these studies did not state whether the harvesting is selective or clearing or the sizes of twigs harvested. Since, there is no clear felling about 20% will be retained per hectare and that will be more of the bigger trees of *S. mellifera* and other species. The advantage of harvesting a single species at a time is that one gets uniform feed and it will make it easier for feed producers to determine what feed additives to use and what amounts to improve the quality of the bush feed. It will also be easier to eliminate the anti-nutritional factors when one is dealing with one or a few species in the feed.

Considering total (woody biomass and biomass fit for feed), Site 2 had more biomass than the other sites. This is mainly due to presence of numerous small sized tree in densities above 10,000 stems per hectare.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study was carried at Neudamm Farm (Block G) in the Khomas Region. The main aim was to determine the species composition and estimate the amount of feed-suitable biomass of the dominant species constituting encroacher bushes in the selected block. Below are the conclusions based on the objectives of the study;

a) This study addressed the issue of BE coverage and land cover change in Neudamm Farm using GIS and remote sensing techniques. The study reveals that there was an increase (14%) in area classified as high bush density class between the years (1989-2017), an indication that BE is increasing. The increase of bush density could be because of grazing pressure (continuous grazing) because the selected block is housing large stocks.

b) The bushes in Block G consisted of numerous (13) woody species but only 3 species *(S. mellifera, T. camphoratus and G. Flava)* occurred in large numbers (combined they constituted 79.9% of all the bushes recorded across the sites and topographical positions. It can only be assumed that the ecological conditions at Neudamm are ideal for these three species otherwise an in-depth study beyond what was studied in this survey, would need to be carried to establish why these species were dominant.

c) The IVI showed that *S. mellifera* was the dominant species across all the sites and topographical positions. Since, the species is reported to have good quality feed (Pasiecznik, 2016); this can be a target species for harvesting for animals' feed.

d) Site (geographical location of sample plots) was found to have a significant influence on bush density with Site 2, having significantly higher bush density than the other 2 sites. Site 2 had numerous small sized bushes, much more than was recorded in the other 2 sites. Bush density did not vary significantly across topographical positions because Block G is relatively flat (slopes ranging from 3 - 8% and differences in elevation of different topographical positions was not big enough to cause significant differences in bush density.

e) Species composition of bushes was more influenced by site than topographical position since species similarity between sites was low to moderate (0.468-0.762 - Sorenson quantitative index) and high between topographical positions (0.860-0.960). Meaning that factors related to geographical position of a site may be more important in determining species distribution than topographical position factors.

f) Among the soil properties tested only Na had a negative significant correlation with bush density. This could be because one of the effects of Na in the soil is that at times it increases osmotic tension, by which water is held in the soil and as a result the plants die-off. High Na levels are known to reduce trees and shrubs growth (Jouyban, 2012).

g) The BECVOL 3-Model output showed that 4.8 tonnes/ha *S. mellifera* biomass suitable for animal feed can be harvested from Block G if 80% of the available biomass is harvested. The biomass fit for feed varied significantly across sampled sites. This figure is comparable to Smit *et al*. (2015) and Anton Dresselhaus findings recorded at Otjiwarongo and Dordabis and recorded at approximately 5 tonnes/ha and 2 tonnes/ha of *S. mellifera* biomass.

The findings from this research will help in applying appropriate forest management activities to alter the abundance of the encroacher species and to ensure that harvesting will be done in an ecological sustainable fashion.

6.2 Recommendations:

6.2.1 Management recommendations

a) Farm management should target *Senegalia mellifera* because it would give uniform feed and it has high protein content. This species occurs in high density across all sites.

b) Since the bushes are constituted by a number of species, clearing should be avoided. Harvesting should be done with care to protect species not being removed, especially species protected by Directorate of Forestry regulations like *Boscia albitrunca, Searsia lancea* and *Ziziphus mucronata*.

c) It was noted that there were high densities of shorter bushes, harvesting, should therefore either harvest even these shorter bushes or come up with after care practices to avoid these shorter plants flourishing and together with sprouts from cut trees re-encroaching the sites where bushes are harvested.

d) Manual and semi-mechanized harvesting methods are recommended due to fewer disturbances on the top soil and the method can be very selective if well managed

6.2.2 Recommendations for further research

Future studies could cover two issues that came up in the course of this study but were not given comprehensive treatment:

a) Botanical and ecological studies to determine characteristics of encroachers species to come up with a precise definition of a bush encroacher species.

b) A more comprehensive investigation into climatic, edaphic, rangeland management factors and other factors that influence density and distribution of encroacher species in Namibia.

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APPENDICES

Appendix 1: Detailed description of Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS).

Band	Wavelength	Useful for mapping
Band 1 – Coastal Aerosol	0.435 - 0.451	Coastal and aerosol studies
Band 2 – Blue	0.452 - 0.512	Bathymetric mapping, distinguishing soil from vegetation, and deciduous from coniferous vegetation
Band 3 - Green	0.533 - 0.590	Emphasizes peak vegetation, which is useful for assessing plant vigor
Band 4 - Red	0.636 - 0.673	Discriminates vegetation slopes
Band 5 - Near Infrared (NIR)	0.851 - 0.879	Emphasizes biomass content and shorelines
Band 6 - Short-wave Infrared (SWIR) 1	1.566 - 1.651	Discriminates moisture content of soil and vegetation; penetrates thin clouds
Band 7 - Short-wave Infrared (SWIR) 2	2.107 - 2.294	Improved moisture content of soil and vegetation and thin cloud penetration
Band 8 - Panchromatic	0.503 - 0.676	15 meter resolution, sharper image definition
Band 9 – Cirrus	1.363 - 1.384	Improved detection of cirrus cloud contamination
Band 10 – TIRS 1	10.60 – 11.19	100 meter resolution, thermal mapping and estimated soil moisture
Band 11 – TIRS 2	11.50 - 12.51	100 meter resolution, Improved thermal mapping and estimated soil moisture

Source: (Barsi, Lee, Kvaran, Markham & Pedelty, 2014).

Appendix 2: Detailed description of Landsat 5 Thematic Mapper

LANDSAT 5 (TM) BANDS

Sensor	Band number	Band name	Wavelength (μm)	Resolution (m)	Band Applications
TM	1	Visible Blue	0.45 - 0.52	30	Bathymetric mapping, distinguishing soil from vegetation, and deciduous from coniferous vegetation
TM	2	Visible Green	0.52 - 0.60	30	Emphasizes peak vegetation, which is useful for assessing plant vigor
TM	3	Visible Red	0.63 - 0.69	30	Discriminates vegetation slopes
TM	4	NIR	0.76 - 0.90	30	Emphasizes biomass content and shorelines
TM	5	SWIR 1	1.55 - 1.75	30	Discriminates moisture content of soil and vegetation; penetrates thin clouds
TM	6	Thermal	10.40 - 12.50	120	Thermal mapping and estimated soil moisture
TM	7	SWIR 2	2.08 - 2.35	30	Hydrothermally altered rocks associated with mineral deposits

Source: https://eos.com/landsat-5-tm/, 2018.

Appendix 3: Advantages and disadvantages of bush control methods.

Method	Advantages	Disadvantages
1. Mechanical 1.1 Uprooting by bulldozer	• Relatively fast. • Effective in killing trees as the roots are ripped out, but not as effective for *D.cinerea* which can coppice form bits of root left.	• Disturb the soil. • Exposes the soil to re-invasion especially by *D.cinerea* (likely to be re-infested with high densities than before within 5-6 years) expensive. • Not recommended, except to clear lands for cultivation.
1.2 Manual or semi mechanised cutting	• Labour intensive – generating employment and therefore distributing benefits. • Can be very selective if well managed.	• Coppicing rate is high, often resulting in denser infestation than before, especially for D.cinerea. For other species it is a bit more effective. • Expensive and time consuming.

	• Suitable especially for bush thinning to the required densities and follow up thinning.	
1.3 Cutting for charcoal production	• Labour intensive – generating employment and therefore distributing benefits. • Some profit achieved from the sale of the charcoal.	• Only the thicker stems are required for charcoal production (2.5 – 3cm) • Therefore, from an ecological viewpoint, the wrong material is selected (ecologically it is better to remove the small bushes and trees and leave the larger ones. • If supervision is poor, labourers often cut larger trees and protected species.
2. Biological 2.1 Browsers, especially goats.	• Goats at high stocking rates can help but are best used as an aftercare measure.	• A high level of management is needed. • At high stocking rates, the desired browser shrubs also decline in numbers.

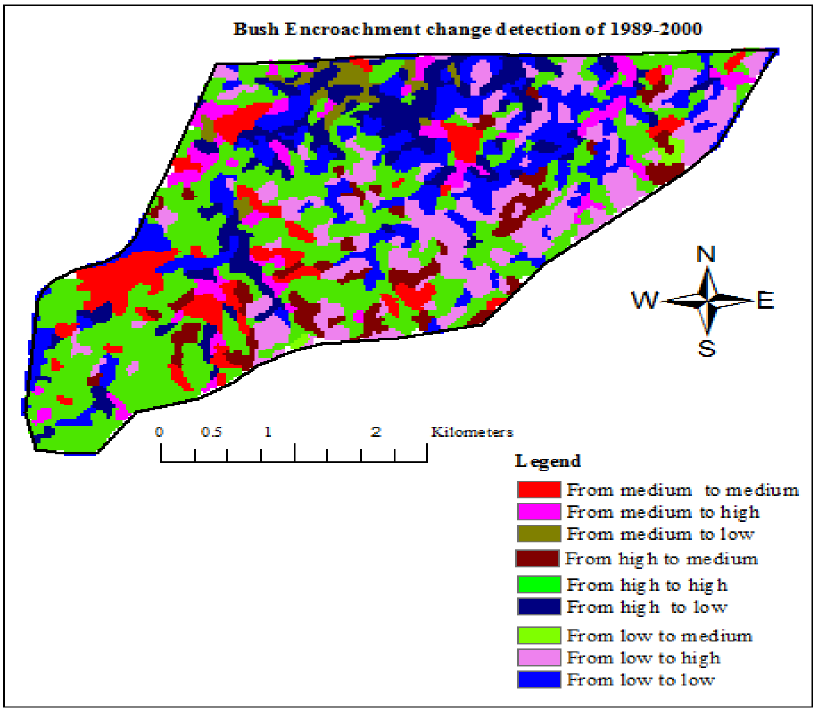
	• When used with cattle, goats help to increase meat production.	• Only effective for aftercare.
2.2 Stem burning – using cow dung packed around stems as fuel	• Effective for some most species. • Provides employment opportunities.	• Not very effective for *D. Cinerea*. • Time consuming.
2.3 Large scale fire application	• Kills small seedlings and saplings. • Useful for aftercare and management. • Returns organic nutrients to the soil.	• Can't be used in dense bush as the grass is too sparse to produce a hot enough fire. • Risks to neighbouring farms. • Not effective for dense bush.
3. Chemical 3.1 Herbicides / arboricides – granules aerially applied to the soil.	• Effective and relatively quick to treat, but slow to act (takes 1 – 2 seasons), but relying on rainfall. • Suitable when bush densities are so high that access is impossible. • Good increases of perennial grasses	• Completely non-selective, so that many ecologically important species and browse species are killed. • Dosage required depends on soil type. • Dead wood does not release nutrients readily. • Although reputed to be safe with fauna and

	reported. • Cheaper for very high bush densities.	birds, any chemical treatment may pose the risk of unpredicted impacts.
3.2 Herbicides / arboricides – granules applied to the soil surface by hand.	• Effective and relatively quick to treat, but slow to act (takes 1 – 2 seasons) • Relying on rainfall. • Good increases of perennial grasses reported. • Can target unwanted species to a large degree. • More targeted and more effective than aerial application. • Residual effect can suppress woody growth for up to 5 years. • Provides employment opportunities,	• May kill non-targeted trees whose lateral roots may spread extensively • Dosage required depends on soil type, e.g. Clay content, pH • Dosage also depends on plant type– *D.cinerea* needs more • Dead wood does not release nutrients readily • Although reputed to be safe with fauna and birds, any chemical treatment can may pose the risk of undetected impacts

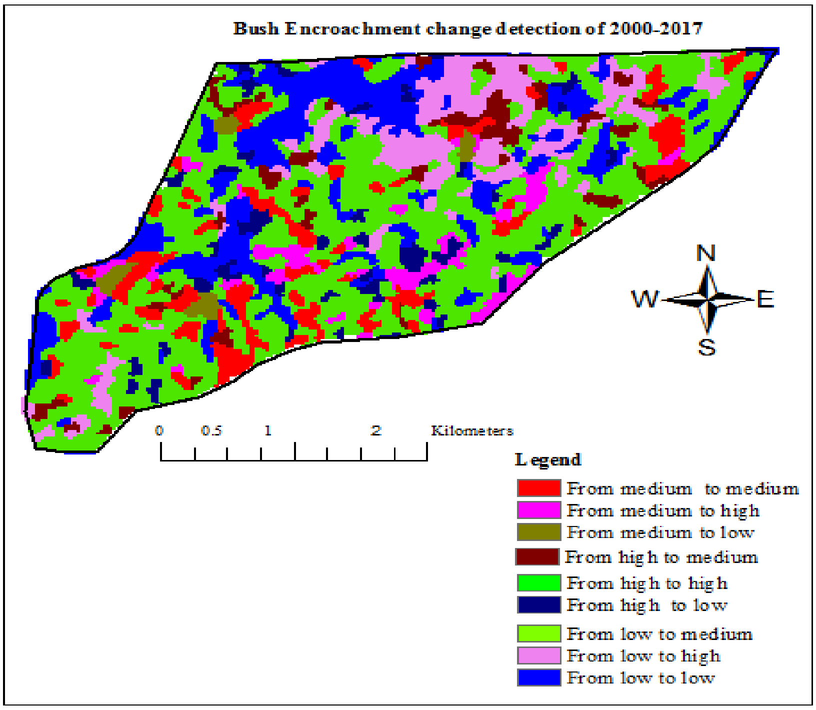
	which is less strenuous than cutting.	
3.3 Foliar and stem applied herbicides, or applied to stems after cutting (especially larger stems)	• Trees that have been chopped down and their stumps treated immediately die immediately. • Provides employment opportunities.	• Little risk of untreated trees being killed. • Very time consuming.

(Source: Christian & CC, 2010).

Appendix 4: Changed and unchanged areas for the first epoch (1989–2000) in the study area.



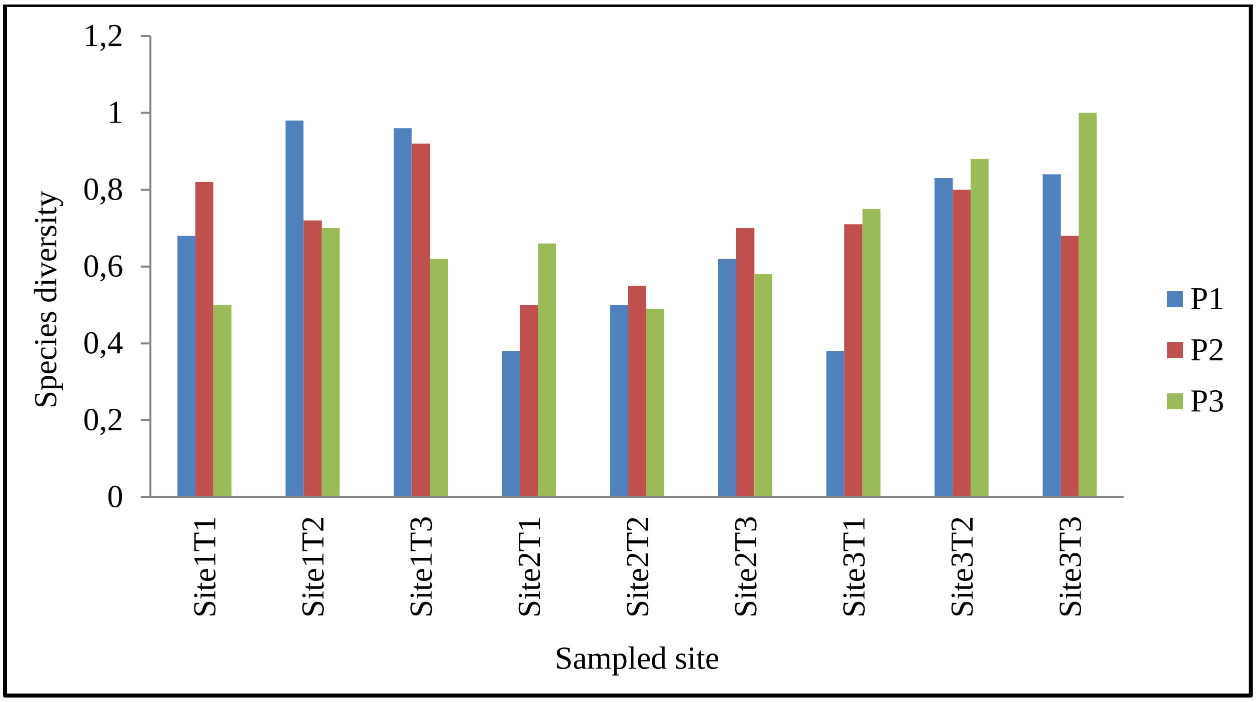
Appendix 5: Changed and unchanged areas for the second epoch (2000-2017) in the study area.



Appendix 6: Two-way ANOVA for Species diversity across the sampled sites and topographical positions.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Sampled Sites	2	0.2689	0.1344	6.8112	0.0063
Topography	2	0.1384	0.0692	3.5067	0.0517
Sampled Sites*Topography	4	0.0383	0.0096	0.4853	0.7464

Appendix 7: Species diversity in each sampled site and at different topographical positions.



Appendix 8: Two-way ANOVA table for combined density in each sampled site and topographical position.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Topography	2	418.7225	209.3612	0.5514	0.5856
Sampled Sites	2	10502.3529	5251.1764	13.8293	0.0002
Topography*Sites	4	795.5327	198.8832	0.5238	0.7196

Appendix 9: Two-way ANOVA table for tall trees density in each sampled site and topographical position.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Topography	2	203.9268	101.9634	1.1424	0.3411
Sampled sites	2	1441.3476	720.6738	8.0742	0.0031
Topography*Sites	4	1141.4662	285.3665	3.1971	0.0378

Appendix 10: Two-way ANOVA table for short plants density in each sampled site and topographical position.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Topography	2	482.7226	241.3613	0.3555	0.7056
Sampled sites	2	9215.2313	4607.6156	6.7866	0.0063
Topography*Sites	4	1170.0704	292.5176	0.4308	0.7845

Appendix 11: Original and transformed data for combined density for all the sampled sites and at different topographical positions.

Topography	Sites	Density/ha	SQR(trans)
T1	1	3800	62
T1	1	8200	91
T1	1	3000	55
T2	1	5200	72
T2	1	3700	61
T2	1	4000	63
T3	1	5100	71
T3	1	4500	67
T3	1	2700	52
T1	2	6100	78
T1	2	17400	132
T1	2	16100	127
T2	2	15600	125
T2	2	22800	151
T2	2	11500	107

T3	2	12300	111
T3	2	14100	119
T3	2	5500	74
T1	3	3900	62
T1	3	9000	95
T1	3	11800	109
T2	3	4100	64
T2	3	7600	87
T2	3	8200	91
T3	3	6700	82
T3	3	4600	68
T3	3	9400	97

Appendix 12: Original and transformed data for tall trees density for all the sampled sites and at different topographical positions.

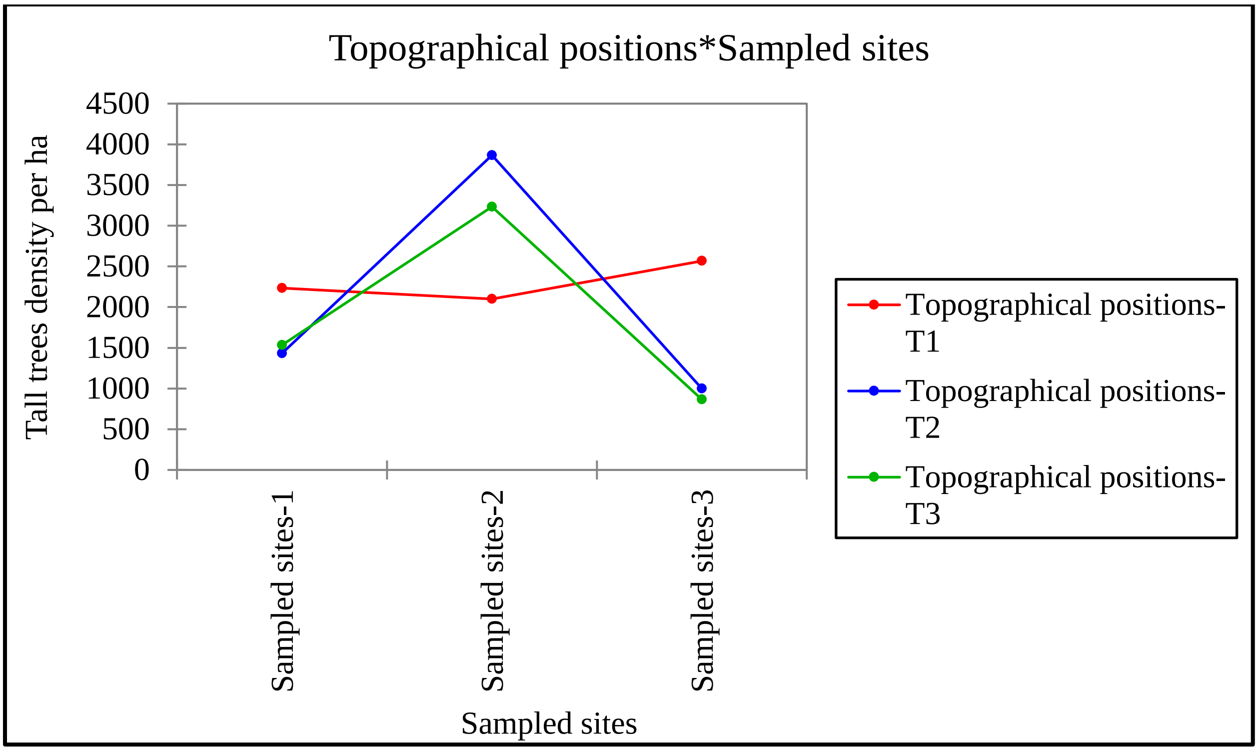
Topography	Sites	Tall trees density/ha	SQR(trans)
T1	1	2000	45
T1	1	3100	56
T1	1	1600	40
T2	1	1900	44
T2	1	1400	37
T2	1	1000	32
T3	1	1600	40
T3	1	2200	47
T3	1	800	28
T1	2	1700	41
T1	2	2200	47
T1	2	2400	49
T2	2	2200	47
T2	2	2900	54
T2	2	6500	81
T3	2	3500	59
T3	2	1700	41
T3	2	4500	67
T1	3	2900	54
T1	3	2600	51
T1	3	2200	47
T2	3	1100	33
T2	3	1500	39
T2	3	400	20
T3	3	900	30
T3	3	800	28

T3	3	900	30

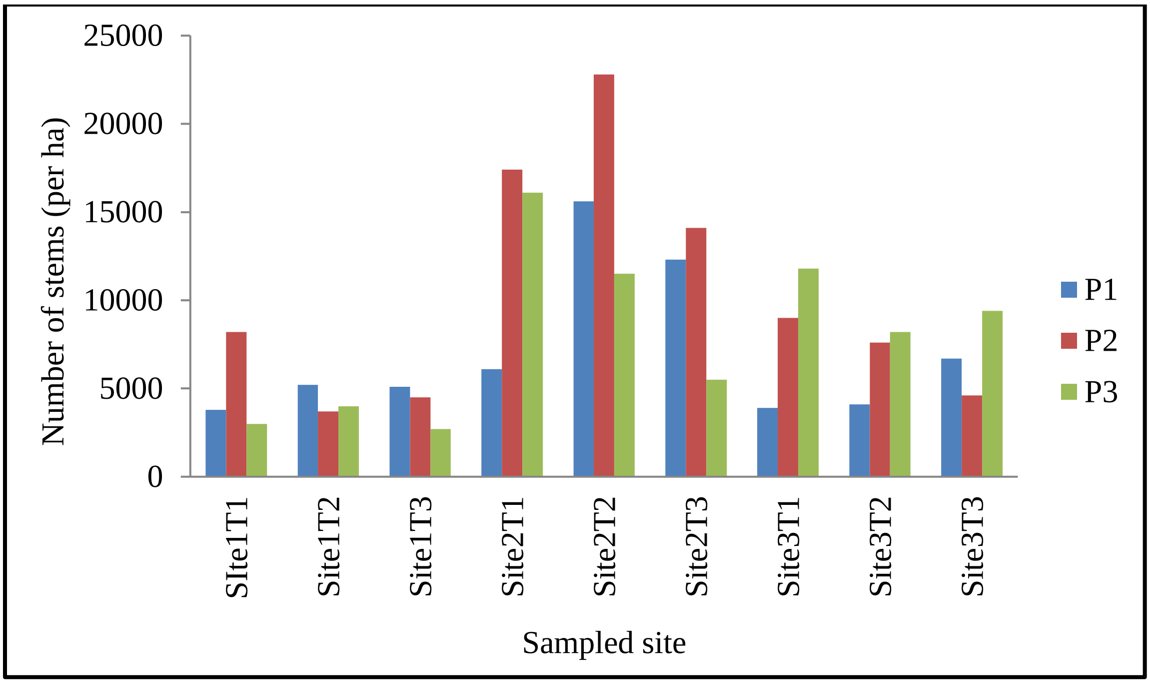
Appendix 13: Original and transformed data for short plants density for all the sampled sites and at different topographical positions

Topography	Sites	Seedling density/ ha	SQR(trans)
T1	1	1800	42
T1	1	5100	71
T1	1	1400	37
T2	1	3300	57
T2	1	2300	48
T2	1	3000	55
T3	1	3500	59
T3	1	2300	48
T3	1	1900	44
T1	2	4400	66
T1	2	15200	123
T1	2	13700	117
T2	2	13400	116
T2	2	19900	141
T2	2	5000	71
T3	2	8500	92
T3	2	12400	111
T3	2	1000	32
T1	3	1000	32
T1	3	6400	80
T1	3	9600	98
T2	3	3000	55
T2	3	6100	78
T2	3	7800	88
T3	3	5800	76
T3	3	3800	62
T3	3	8500	92

Appendix 14: Interactions for tall trees density between sampled site and different topographical positions.



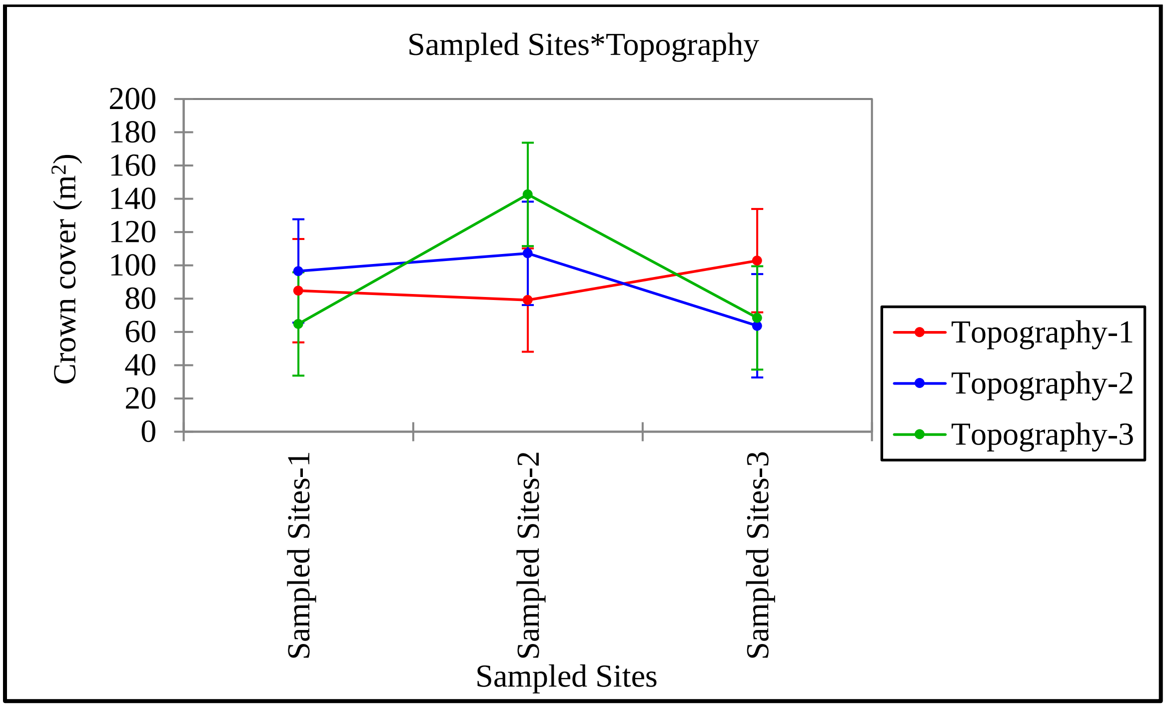
Appendix 15: Combined tree density in each sampled site and at different topographical positions.



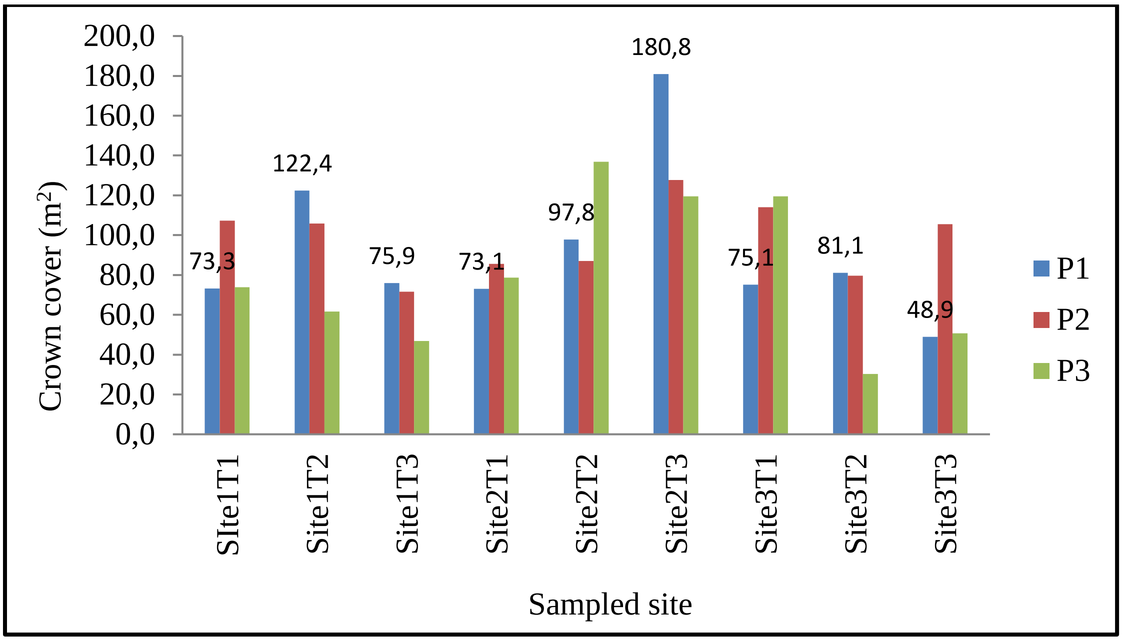
Appendix 16: Two-way ANOVA table for crown cover of trees and shrubs in each sampled site and topographical positions.

Source	**DF**	**Sum of squares**	**Mean squares**	**F**	**Pr > F**
Sampled Sites	2	5278.4055	2639.2028	4.0219	0.0360
Topography	2	50.5199	25.2600	0.0385	0.9623
Sampled sites*Topography	4	10323.3207	2580.8302	3.9330	0.0182

Appendix 17: Interactions for crown cover between sampled site and different topographical positions.



Appendix 18: Crown covers of trees and shrubs in each sampled site and at different topographical positions.



Appendix 19: Test statistics output for biomass fit for feeds and total biomass across sampled sites.

	Biomass fit for feeds	**Total Biomass**	**Total biomass for the 3 most abundant species**
Chi-Square	7.2	7.494	58.9
Df	2	2	3
Asymp. Sig.	0.027	0.024	0

Appendix 20: Test statistics output for biomass fit for feeds and total biomass across topographical positions

	Biomass fit for feeds	**Total Biomass**
Chi-Square	8.222b	10.889b
DF	2	2
Asymp. Sig.	0.016	0.004

Appendix 21: Soil characteristics across sampled sites.

	pHw	ECw	OM	N	P	K	Ca	Mg	Na	OC
Chi-Square	1.891	0.523	2.167	2.201	9.06	2.118	0.567	1.655	16.475	0.222
DF	2	2	2	2	2	2	2	2	2	2
Asymp. Sig.	0.389	0.77	0.338	0.333	0.011	0.347	0.753	0.437	0	0.895

Appendix 22: Soil characteristics across topographical positions.

	pHw	ECw	OM	N	P	K	Ca	Mg	Na	OC
Chi-Square	3.309	6.425	2.167	3.146	3.404	2.997	6.133	5.249	0.987	2.07
DF	2	2	2	2	2	2	2	2	2	2
Asymp. Sig.	0.191	0.04	0.338	0.207	0.182	0.224	0.047	0.072	0.61	0.355

Appendix 23: Characteristics of sample plots.

Site	Transect	Aspect	Altitude			Slope (Between sample plots) (%)	
			P1	P2	P3		
1	T1	N	1830	1830	1829	S1T1P1 -S1T3P1	7%
1	T2	N	1817	1818	1819	S1T1P2 -S1T3P2	7%
1	T3	N	1816	1815	1815	S1T1P3 -S1T3P3	7%
2	T1	N	1851	1852	1853	S2T1P1 -S2T3P1	8%
2	T2	N	1851	1850	1859	S2T1P2 -S2T3P2	7%
2	T3	N	1847	1848	1848	S2T1P3 -S2T3P3	8%
3	T1	N	1835	1837	1837	S3T1P1 -S3T3P1	3%
3	T2	N	1833	1832	1833	S3T1P2 -S3T3P2	5%
3	T3	N	1832	1831	1829	S3T1P3 -S3T3P3	6%

Appendix 24: Steps followed when analysis physicochemical properties of the soil

Phosphorus test

Olsen Method was used to test for the amount of Phosphorus in the soil. The method is recommended for alkaline to neutral soils. The sample was extracted with a 0.5M sodium bicarbonate solution at pH 8.5. Phosphate in the extract was determined colourimetrically by the blue ammonium molybdate method of Murphy and Riley using ascorbic acid as reducing.

The following procedures were followed to analyse the samples:

1. Weighed 5 g of air dry < 2 mm soil (accuracy 0.01 g) into a 125 ml flask. Prepare one blank without any soil.
2. Added 1 scoop (about 0.3 g) of activated charcoal and 50 ml of extracting solution (Sodium Bicarbonate Solution, 0.5 M, pH 8.5) and shake for 30 minutes on the shaker.
3. Filtered the suspension through a Whatman No. 40 filter paper into volumetric flasks.
4. Determine the amount of 4M sulphuric acid needed to change 5 ml of extracting solution from pH 8.5 to pH 5 to 5.5 (colour change of p-nitrophenol from yellow to colourless). This should be about 300 uL.
5. Pipetted 5 ml of the standard series (0, 0.4, 0.8, 1.2, 1.6, 2.0 mg/l), the blanks and the sample extracts into 25 ml volumetric flasks.
6. Added about 5 ml de-ionised water and 3 drops of p-nitrophenol indicator.
7. Added 300 uL of sulphuric acid.
8. Shake the solutions until they turn clear.

9. Added 4 ml of colour reagent and mix well to release any more bubbles of carbon dioxide. Add de-ioinised water to almost fill the bulb of the flask. Shake again and allow the blue colour to develop for about 30 minutes on a shaker.
10. Fill each volumetric flask to the mark with de-ionised water and read absorbance on spectrophotometer at 882 nm. Blank the spectrophotometer with the zero standard.

Soil texture was determined using the pipette method.

The soil samples were sieved using the 2mm sieve. After sieving, the samples were weighed (20.00g) in a volumetric flask (250 ml) using the balance. Dispersing fluid (20 ml) and deionized water (100 ml) was added into the samples. The samples were then shaken using the shaker for 30 minutes at 180 °C and left to stand overnight. Eighty millilitres of distilled water was added to the extract and then shaken for 30 seconds. After that, 5 ml of clay was extracted into an aluminium dish and placed in an oven at 100°C for the whole night. The silt content was weighed. For sand content, the extracts were poured into, and washed through, 5 µm sieve using distilled water, then placed into an aluminium dish. The extracts were placed in an oven at 100°C overnight and were weighed. The textural classes were determined using the USDA soil classification system.

Measurement of available K, Mg, Na and Ca

The above mentioned variables were determined by inductively coulped plasma (ICP), using Extraction with 1M ammonium acetate at pH 7.

pH and EC

pH (water) and EC were determined using in a 1:2.5 soil: water ratio suspension on a mass to volume basis. 20.0 g soil was weighed on a top loading balance into 100 ml beaker and after added 50 ml de-ionised water. Stirred for about 20 seconds three times over a one hour period and then started reading and recording. The readings for pH were taken with an electric pH meter (Multi-lab, model 540) and EC meter was used for reading the EC all the samples.

Organic Carbon and Organic Matter

Organic Carbon was determined using Walkley-Black method (sulphuric acid-potassium dichromate oxidation). A factor was included in calculations to take account of incomplete oxidation. The Organic matter content was calculated as organic: C x 1.74.

Appendix 25: ANOVA for bush density classes

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	351028666.7	2	17551433 3	11.9	0.00019	3.3
Within Groups	395841000	27	14660778			
Total	746869666.7	29				

Appendix 26: Averages and SEs for biomass across the sampled sites (Kg/ha).

	Sites 1					**Site 2**					**Site 3**				
Species	Leaf mass	Wood (0-2 cm)	AFSB	Wood Biomass (>2cm)	Total biomass	Leaf mass	Wood (0-2 cm)	AFSB	Wood Biomass (>2cm)	Total biomass	Leaf mass	Wood (0-2 cm)	AFSB	Wood Biomass (>2cm)	Total biomass
S. mellifera (SE)	952 196	4132 812	5088 972	5141 1523	9610 2588	1368 259	4673 1010	6540 1253	5824 1737	12364 2779	1432 232	5243 768	6664 999	4543 893	11597 1571
T. comphoratus (SE)	391 81	819 175	1210 255	1232 318	2442 565	497 110	1053 254	1628 340	1381 410	3054 759	5 4	11 9	17 14	10 9	27 23
G. flava (SE)	199 32	221 58	343 89	215 58	557 147	66 21	103 32	180 58	128 42	347 98	7 6	24 23	31 28	12 12	43 40
Other species combined (SE)	38 26	105 80	143 106	82 78	182 140	205 101	728 403	933 504	819 560	1752 1057	125 111	658 607	785 718	1672 1646	2457 2363

Appendix 27: Averages and SEs for biomass across the topographical positions (Kg/ha).

	T1					**T2**					**T3**				
Species	Leaf mass	Wood (0-2 cm)	AFSB	Wood Biomass (>2cm)	Total biomass	Leaf mass	Wood (0-2 cm)	AFSB	Wood Biomass (>2cm)	Total biomass	Leaf mass	Wood (0-2 cm)	AFSB	Wood Biomass (>2cm)	Total biomass
S. mellifera	1372	4939	6311	4695	10999	1353	4691	6533	5603	12136	1859	4431	5490	5377	11089

(SE)	246	897	1128	1386	2264	218	970	1028	1591	2415	805	917	1143	1330	2263
T. comphoratus (SE)	240 82	518 184	758 266	652 241	1410 504	296 84	727 227	913 260	874 330	1787 579	358 144	826 311	1185 454	1098 481	2283 931
G. flava (SE)	78 26	155 47	232 73	144 48	376 119	60 29	113 56	173 85	115 60	188 115	56 27	101 47	157 74	96 43	253 117
Other species combined	66 39	173 106	239 145	143 106	382 243	43 32	151 109	194 141	85 65	279 206	260 138	1166 678	1426 814	2302 1666	3728 2448