

Landscape function in bush thickened and -controlled areas of the semi-arid savanna in the Molopo region, South Africa

JH Fouché
22788174

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Supervisor: Prof K Kellner
Co-supervisor: Dr N Dreber

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Abstract

Bush thickening (bush encroachment) and the effects thereof on the environment has been a very well debated topic over the past few decades which led to the formation of two valid but rather opposite opinions. Pasture scientists believe that bush thickening is due to overgrazing/over browsing of forage that is caused by keeping too many livestock and/or game animals, whereas other scientists believe that bush encroachment is mainly caused by changing climatic factors, including a change in CO₂ levels and rainfall patterns or as other management strategies, such as the use of fire as a management tool. Consensus has been reached that bush encroachment is caused by a combination of factors that influence the ecosystem goods and services, including a loss in biodiversity and ultimately affecting the ecological services of the people using the land.

This project forms part of the management and restoration sub-project (B2) of the IDESSA project (IDESSA-Integrative Decision-support System for Sustainable Rangeland Management in southern African savannas) currently carried out between the NWU and the Universities of Goettingen, Marburg and Kwazulu Natal. The project is funded by the BMBF (Federal Ministry of Education and Research or “Bundesministerium für Bildung und Forschung”) in Germany. The main aim of sub-project B2 is to develop a grid-based, spatially explicit rangeland model which will be able to simulate the complex interplay of management and savanna dynamics under different environmental conditions and land use, restoration and climate change scenarios.

The aim includes to determine the landscape functioning in bush thickened and controlled savannas in the Molopo region of the North-West and Northern Cape Provinces, South Africa. The land users of the Molopo region used various methods to combat the thickening of woody species of their pastures. These methods included: chemical control by aeroplane (AC), chemical control by hand (HC), double chemical control by hand (2HC), stem burning (SB) and sustainable management (SM) by using rotational grazing to prevent the bush encroachment. The sampling approach used for this study included the use of the Landscape Function Analysis (LFA) monitoring procedure to determine

three main parameters (stability, nutrient cycling and infiltration) by using 11 soil surface assessment (SSA) indicators.

Incorporation of the SSA indicators include biotic and abiotic factors and are measured close to the soil surface in a certain landscape. Through the landscape organizational index (LOI), the landscape is divided into patch and inter-patch zones where the SSA indicators are used to determine the three main parameters that will give an indication of the functioning of the landscape.

The aim of this study also included the assessment for differences in soil chemical properties at the patch scale, contrasting bush-thickened and controlled areas. Four dominant patch types (inter patch/bare soil patch (IP), grass patch (GP), grass litter patch (GLP) and shrub litter patch (SLP)) were identified in transects used for the LFA monitoring procedure. The dominant patches types were then analysed to determine their contribution to the functionality and soil chemical properties of the landscape that are characterised by still encroached, controlled or sustainably managed.

Results from the LFA's indicated that no significant differences ($p < 0.05$) could be found between the functioning (stability, infiltration and nutrient cycling) of the bush thickened and bush controlled areas. The HC sites had on average the highest functionality scores as a result of a favourable tree to grass ratio, but these scores were not significantly higher ($p < 0.05$) than any of the other controlled or thickened areas. The bush thickened areas scored within a few points of the bush controlled areas with minimal variation over both survey years.

The soil analysis indicated that the grass litter patches (GLP) from the AC sites had the highest average nutrient levels of all the different patches identified, with the SLP only scoring high in Ca % (C %) and pH (KCl). An expected result with regards to the high C and Calcium (Ca) levels at the SLP in the bush thickened sites, with high nutrient levels recorded for the GLP at the AC sites. A possible reason for the high nutrient levels can be ascribed to the tuft sizes of the dominant grass species identified at the AC sites. These large tufts were mostly characterised by one species, i.e. *Stipagrostis uniplumis*. Another contributing factor were the high concentration of cryptogams in biological soil crusts known for the increasing of soil nutrients and infiltration, found surrounding the

base of the grass tufts, as well as around the base of the stems of *Senegalia mellifera* shrubs found in the bush thickened areas.

The overall results from the study confirms that thickened landscapes are fully functional areas and that they will not change without human intervention. Proper management of arid ecosystems like the Molopo region, is key to prevent future woody thickening. Further research is required to determine the effect good land management can have on the functioning of Molopo rangelands. Such studies should focus on the functioning of bush control rangelands compared to thickened rangelands over a longer time period with more emphasis on the effect these actions have on the soil profile.

Key words: Bush thickening; landscape functional analysis; chemical bush control; soil surface assessments; patch and inter-patch zones; nutrient cycling; infiltration; stability.

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List of Abbreviations

2HC – Double hand controlled

2HCO – Double hand controlled site farm 4

AC – Aeroplane controlled

ACG - Aeroplane controlled site farm 1

ACK – Aeroplane controlled site farm 2

BC – Bush controlled

BTB - Bush thickening site farm 3

BTG – Bush thickening site farm 1

BTK – Bush thickening site farm 2

BTO – Bush thickening site farm 4

C/N – Carbon to Nitrogen ration

GLP – Grass litter patch

GP – Grass patch

Gradsect – Gradient orientated transect

GSP – Grass shrub patch

ha/LSU – Hectares per Large stock unit

HC – Hand controlled

HCK – Hand control site farm 2

HCO – Hand control site farm 4

IDESSA - Integrative decision support system for sustainable rangeland management in Southern African savannas

IP – Inter patch

LFA – Landscape function analysis

LO – Landscape organisation

LOI – Landscape organisation index

LP – Litter patch

MAP - mean annual precipitation

MEA – Millennium ecosystem assessment

MFC – Molopo farm complex

mm/a – Millimetres per annum

NAP – Nutrient accumulating zone

PCA – Principal component analysis

PET – Potential evaporation

SBB – Stem burning farm 3

SLP – Shrub litter patch

SMB – Sustainably managed farm 3

SP – Shrub patch

SSA – Soil surface assessment

TE/ha – Tree equivalents per hectare

TTRP – Trigger transfer reverse pulse

Chapter 1

Introduction

1.1 Bush thickening in savanna ecosystems

1.1.1 How do trees and grasses coexist in savannas?

Savannas cover approximately one third of South Africa's and an eighth of the world's surface, making it one of the most important biomes globally (Scholes and Walker, 2004). Trees and grasses have coexisted in these savanna rangelands for thousands of years (Sankaran *et al.*, 2004). This led scientists to develop various hypotheses to explain how trees and grasses coexist in savanna ecosystems (Walker *et al.*, 1981; Teague and Smit, 1992; Higgins *et al.*, 2000; Sankaran *et al.*, 2004; Scholes and Walker, 2004). One of the first hypotheses developed by Walker *et al.* (1981) states that a difference in root depth could be the overriding factor. This hypothesis is called the "two layer hypothesis" and its argument is that because of the difference in root depths of trees and grasses and because of the spatial distribution of resources in the soil profile, trees and grasses will be able to coexist in the same landscape without affecting each other with regards to competition for resources (Teague and Smit, 1992).

Unfortunately, this hypothesis by Walker *et al.* (1981) is only true for "intact savannas", as this might change when the grass layer is removed by overgrazing, uncontrolled fires and woody thickening (bush encroachment); trees may become more dominant and start to outcompete grasses (Higgins *et al.*, 2000). The growth rate, reproductive capabilities and ability of grasses to compete against woody seedling establishment is decreased by overgrazing, which may lead to poor veld conditions for grazing animals (Smit, 2004). The poor veld condition of a pasture can also change the plant species composition (Owen-Smith, 1999; Snyman, 2004, 2005). The abundance of more palatable, perennial grass species is decreased and replaced by less palatable perennial and annual species (Owen-Smith, 1999; Snyman, 2005). The latter usually have weaker root structures and

are weaker competitors with shallower root systems, causing an increase in the woody species (Snyman and Van Rensburg, 1986; Homewood and Rogers, 1987; Teague and Smit, 1992; Higgins *et al.*, 2000).

Pastures that are in a poor condition are often characterised by open and bare patches with degraded soils. Such patches are more exposed to temperature, wind and water, leading to erosion and a decrease in soil nutrient status and moisture content (Ludwig *et al.*, 2000; Snyman, 2004; Moussa *et al.*, 2008). Open, bare patches are also more readily encroached by ephemerals and annual grass species, changing the composition and type of patches occurring in the habitat (Homewood and Rogers, 1987; Ludwig *et al.*, 2000; Smit, 2004). This phenomenon is easily seen in the sandy Molopo region where this study was conducted. Water infiltrates much faster and with greater ease to deeper soil levels, where it is more accessible by the deeper root systems of the trees (Walker and Noy-Meir, 1982).

Disturbances caused by mismanagement (e.g. overgrazing), fire and climate in the Savanna biome, further led to the formation of a disturbance-based hypothesis (Higgins *et al.*, 2000). This hypothesis states that trees and grasses can only survive in the same landscape if disturbances remove the seedlings of tree species that are in direct competition with grasses, leaving older and more established specimens that are somewhat resistant towards these disturbances (Higgins *et al.*, 2000; February and Higgins, 2010). The disturbance hypothesis thus states that the removal of tree seedlings from the landscape will reduce competition between trees and grasses, enabling them to coexist (Higgins *et al.*, 2000; February and Higgins, 2010). This interspecies competition can lead to the formation of a phytophagic bottleneck, where younger trees are outcompeted, leaving older, more established trees in the area. These older trees also have a more established root system and are able to extract “unused” nutrients deeper in the soil profile (Davis *et al.*, 1998; Higgins *et al.*, 2000). With a lack of intermediately aged trees, a “gap” can form for grass species to dominate the landscape, but only if dominant and well-established trees are removed.

However, the disturbance hypothesis also has limitations with regard to the effect of mean annual precipitation (MAP), especially for the establishment of trees in semi-arid and arid

savannas. The disturbances mentioned in this hypothesis (e.g. overgrazing, fire and climate) only really affect tree density in areas with MAP >650 mm and where grass density is high enough to support “hotter” fires (higher fire frequency and intensity) that are able to kill larger trees (Higgins *et al.*, 2000; Sankaran *et al.*, 2005). Another problem with the above-mentioned hypothesis is that the studies used to support them were conducted on trees in different stages of their lifecycles, i.e. larger trees need more intense disturbances to be killed or damaged compared to seedlings or young trees (Sankaran *et al.*, 2004; February and Higgins, 2010). Some scientists also believe that tree and grass coexistence in nutrient-poor vegetation types are driven by nutrient and moisture availability, rather than through disturbances and/or a lack of competition (Davis *et al.*, 1998; Higgins *et al.*, 2000).

Some savanna tree species found in the Molopo region have the ability to completely dominate a certain habitat that was previously characterised by a high abundance of grasses or where a combination of grasses and shrubs existed. This domination by trees is accomplished by outcompeting other plants for nutrients, soil moisture and even sunlight in certain situations. This complete dominance by trees in previously “healthy” savanna ecosystems is referred to as bush thickening or bush encroachment (Smit *et al.*, 1996; Oppelt *et al.*, 2000, Hagos and Smit, 2005; Eldridge *et al.*, 2012).

1.1.2 Bush thickening and its causes

Bush thickening (also referred to as woody thickening or bush encroachment) is defined as an increase in the density of indigenous or exotic woody species, which leads to a reduction in the abundance of more palatable grass and forb species (Wiegand *et al.*, 2006; Joubert *et al.*, 2008). Bush thickening is a global phenomenon, with national and international organisations conducting studies on how to combat the thickening of trees and shrubs. These studies try to determine methods that can be used to repair the damage characterised by the thickening of different woody species in the ecosystem (Smit *et al.*, 1996; Oppelt *et al.*, 2000, Hagos and Smit, 2005; Eldridge *et al.*, 2012).

Bush thickening mainly occurs in semi-arid and arid savannas, as well as some grassland landscapes, affecting grass production and hence the grazing capacity for livestock and

game (Eldridge *et al.*, 2011; Eldridge *et al.*, 2012). This is well documented by case studies from North America, Africa and Australia, where woody species such as mesquite (*Prosopis glandulosa*), blackthorn (*Senegalia mellifera*, previously known as *Acacia mellifera*) and prickly acacia (*Vachellia nilotica*) are reducing the production potential of the land (Archer *et al.*, 2001; Radford *et al.*, 2001; Knapp *et al.*, 2008, Joubert *et al.*, 2008; D'Odorico *et al.*, 2011; Eldridge *et al.*, 2011; Eldridge *et al.*, 2015). Bush thickening in North America has spread over an area of approximately 330 million ha in the semi-arid western states (Knapp *et al.*, 2008; Eldridge *et al.*, 2011). Problem species in the United States of America include mostly the mesquite and creosote bush (*Larrea tridentata*), which have completely desecrated their local grasslands (Knapp *et al.*, 2008; Eldridge *et al.*, 2011; D'Odorico *et al.*, 2011). Studies conducted in Namibia found that bush thickening has affected more than 50% of the country's commercial rangeland management systems (Joubert *et al.*, 2008). The woody species causing the most problems in the semi-arid southern parts of Africa is the blackthorn.

In the semi-arid savannas of South Africa, bush thickening is mostly caused by species such as *S. mellifera*, *Vachellia luederitzii* and *Dichrostachys cinerea* (Richter *et al.*, 2001; Harmse, 2013). Causes of bush thickening can be ascribed to interrelated effects of grazing pressures, rainfall frequency and distribution, lack of fire, effects of browsing by herbivores and the increase in atmospheric CO₂ levels (Oba *et al.*, 2000; Ward and Young, 2002; Sankaran *et al.*, 2004; Joubert *et al.*, 2008). A study by Joubert *et al.* (2008) determined that three years of above average rainfall are required for seeds from woody species to germinate in mass numbers, which may lead to the bush thickening phenomenon in savannas. These authors further state that a landscape must already be in a slightly degraded state for a thickening episode to occur and define "degradation" as slight overgrazing with a reduction in grass biomass and the absence of fire.

The first case of bush thickening in South Africa was documented in 1917, where Bews (1917) found a drastic increase of *Acacia* species in the Pietermaritzburg area of KwaZulu-Natal (O'Connor *et al.*, 2014). This problem later also occurred in the semi-arid parts of South Africa, where acacia trees (*S. mellifera* and *V. luederitzii*) and *D. cinerea* started to increase in abundance, causing bush thickening and forage production

problems for grazing animals because of mismanagement in the Kalahari region (Donaldson and Kelk, 1970). Alien invasive woody species, mainly *Prosopis* species, also create problems because of encroaching in riverine areas in the more arid and semi-arid regions of southern Africa. The encroachment of *Prosopis* species in the Northern Cape Province of South Africa, increased from 314 580 ha in the 1990s to 1 473 953 ha in 2007 (Van den Berg, 2010). The biggest concern with the encroaching of *Prosopis* trees in the Northern Cape is that one plant uses 300–500 mm of water annually in a province that receives MAP <400 mm (Richardson and Van Wilgen, 2004; Venter *et al.*, 2005; Kotzé *et al.*, 2010; Van den Berg, 2010). The palatability of the pods produced by *Prosopis* trees also poses a major concern. As a result of the poor socioeconomic state of most of the communal areas in the Northern Cape, many households are forced to live off the land and thus also from the pods produced by this encroacher plant. The pods of *Prosopis* trees can be used to bake bread or as fodder for livestock, which makes these trees very popular, leading to an increase in their range from riverine areas to more central parts of the province (Kotzé *et al.*, 2010; Van den Berg, 2010).

The Kalahari basin, which stretches from Angola to Botswana, Namibia and South Africa, has well-documented cases of bush thickening affecting farming communities over the past decades (Adams, 1996; Moleele and Perkins, 1998; Hoffman *et al.*, 1999; Richter *et al.*, 2001; Moleele *et al.*, 2002; Joubert *et al.*, 2008; Kgosikoma *et al.*, 2012). Bush thickening of this kind can lead to a decrease in forage production of up to 75%, having a negative influence on the economic status of farms (Adams, 1996). Similar findings have been made in Botswana, where scientists found that areas surrounding watering points are mostly affected by bush thickening and that the problem is spreading at an alarming rate through the whole country (Moleele and Perkins, 1998; Moleele *et al.*, 2002; Kgosikoma *et al.*, 2012).

The Molopo region of South Africa is no exception, with most farmers in the area having great difficulties with the thickening of indigenous woody species like *S. mellifera*, *V. luederitzii* and *D. cinerea*, which results in a decrease in palatable grass production and abundance in the rangelands (Richter, 1991; Barac, 2003; Harmse, 2013). One of the first scientific papers published on the thickening of woody species in the Molopo region

dates back to the late 1900s, where Donaldson (1966) and Donaldson and Kelk (1970) already showed this phenomenon to be a great problem.

Bush thickening is classified as a type of degradation due to its effect on forage production in semi-arid and arid ecosystems (Hoffman and Ashwell, 2001; MEA, 2005). Archer (2010) also states that an increase in bush thickening leads to a decrease in the manageability of an area, as the management of a denser woody area is more difficult, especially with regards to the moving of animals (livestock and game) out of thickened areas into new camps. As mentioned previously, the amount and density of grass patches decrease with an increase in bush density (Archer, 2010) (Figure 1.1). The latter is observed in other studies by Smit *et al.* (1999), Richter *et al.* (2001), Barac (2003), Smit (2005) and Harmse (2013). These authors state that trees are excellent competitors for water and nutrients. Well-established trees easily outcompete grass tufts for these resources, but this is only true for certain soil types like the very sandy soils of the Molopo basin. *Senegalia mellifera*, the biggest role player in bush thickening in the Molopo region (Smit and Rethman, 2000; Richter *et al.*, 2001; Barac, 2003; Smit, 2005; Harmse, 2013), has very shallow lateral roots that compete directly with the roots of grass tufts (Smit *et al.*, 1999).

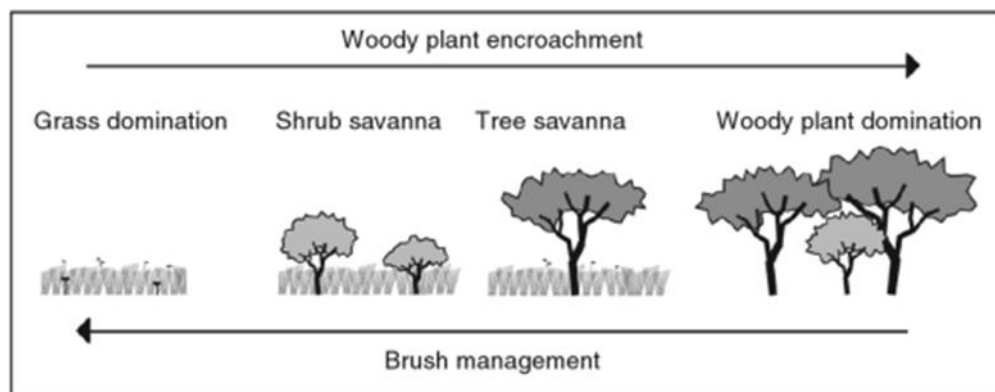


Figure 1.1: Increases in bush thickening leads to a decrease in the manageability (animals or vegetation) of that specific rangeland (taken from Archer, 2010).

1.1.3 The effect of bush thickening on ecosystem goods and services

Ecosystem goods and services can be defined as benefits gained from ecosystems either obtained actively by working in the ecosystem, such as cultivating crops, or passively, where the ecosystems provides benefits of which mankind is often unaware, (Daily *et al.*, 2000; De Groot *et al.*, 2002; Brauman and Daily, 2008; TEEB, 2011).

Ecosystem services can be divided into four categories, namely provisioning services, regulating services, supporting services and cultural services (MEA, 2005). These categories divide up all the different ecosystem services people receive from nature into easier understandable groups.

Provisioning services can be described as ecosystem services that provide material or energy outputs (goods) to local communities (MEA, 2005). These goods include food, raw materials (wood, charcoal), fresh water, clean air and medicinal resources (MEA, 2005). Examples of goods produced by bush-thickened ecosystems include the high volumes of wood made available after the control of bush thickening. This wood can be used as fuel for energy or as construction material for housing and paddocks or biomass in the form of brush (twigs from trees that have been controlled) can be used to rehabilitate degraded areas by improving the soil fertility with the organic material produced by the woody species (TEEB, 2011). The wood made available after the control of bush thickening can also be used by local communities for various other purposes, like fire for fuel and energy, furniture and carvings. These products can therefore be used to generate extra income for poorer communities (Smit, 1999, 2004) contributing to poverty alleviation. Wood biomass used for cooking and heating is often the only source of fuel for rural communities and therefore forms a very important part of their daily lives (Smit, 1999, 2004). Tree species with spines, (e.g. *S. mellifera* and *V. luederitzii*) are used to make fences or kraals to keep animals close to the homesteads and away from nearby roads and predators.

Many of the tree species found in the Molopo region are also known for their “hard” wood, which is ideal for making charcoal often used for heating and cooking. This “hard” wood

refers to the dense heartwood of certain tree species such as *V. erioloba* and *D. cinerea* (Smit, 2004). Some of the tree species causing bush thickening are also quite palatable and their leaves provide fodder for browsing animals, especially during dry periods (Schmidt *et al.*, 2002). Scientists also believe that thickened areas provide habitats for bird and reptile species and can provide shelter for game species (Daryanto and Eldridge, 2012).

Bush thickening may be less beneficial for farmers keeping cattle and grazers (Eldridge and Soliveres, 2015), since the pastoral value of the land is decreased as a result of the reduction of palatable, perennial grasses and the increase in the density of woody species. This decreases the grazing capacity of the land. Harmse (2013) found that the grazing capacity of bush-thickened areas can be as high as 93.6 ha/LSU¹ (at densities of 1 500 tree equivalents² per hectare) compared to the grazing capacity of 10–12 ha/LSU at non-thickened sites in the same area. This is a big concern for cattle farmers because with more trees and less grass, they are forced to decrease their stocking rate, which has negative economic consequences. This leads to a lower income for the farmer and less work for the workers, contributing to unemployment and higher rates of poverty. The farmer may adjust his grazing pressure according to the less rainfall in certain regions. Higher rainfall in bush thickened areas may lead to higher grazing capacities due to the increase in grass densities, providing sufficient grass is available for livestock.

Regulating services is the way in which an ecosystem regulates the environment by improving air and soil quality or by decreasing the risk of floods and the spread of diseases (MEA, 2005). Trees have the ability to lower the temperature of its surrounding area by a few degrees, especially if they have big canopies such those formed by *V. erioloba* (Dean *et al.*, 1999). Another positive effect of an increased density of woody distribution (only to the extent where the woody component does not inhibit grass growth), is the ability of trees to store carbon (C) and release oxygen, also known as carbon sequestration (Hudak *et al.*, 2003; TEEB, 2011). Carbon sequestration is the process

¹ LSU – Large stock Unit an animal (cattle) weighing 450 kg

² Tree equivalents – A term used for a tree or shrub that has grown to a height of >1.5 m (Teague *et al.*, 1981; Friedel, 1991).

where plants, or the encroaching woody species in this case, can transform atmospheric CO₂ into soil C. Soil C can be deposited into the plant's roots or soil, increasing soil nutrients surrounding the plant. Eldridge *et al.* (2015) found that the soil nutrients (mostly soil C and nitrogen (N)) are much higher under the canopy of encroaching shrubs than in open patches where little to no plants remain because of competition.

Other studies also found that trees have the ability to increase the nutrient content of its surrounding soil, a phenomenon referred to as the fertile island effect (Teague and Smit, 1992; Dougill and Thomas, 1999; Ludwig *et al.*, 2004; Hagos and Smit, 2005). The enrichment of the soil surrounding woody species is thus not necessarily from the sequestration of C by the encroaching species (Prowse and Brooke, 2011) but from all the other “by-products” produced by a high density of trees, including leaves, twigs, fruits, droppings from birds and other small mammals and the protection of N-fixing soil organic crusts (Belsky, 1984; Teague and Smit, 1992; Berkley *et al.*, 2005; Thomas and Dougill, 2006; Mager, 2010). Another benefit of dense stands of shrubs or trees is that they help animals during severe weather conditions by creating shelter against fluctuating temperatures, rain and strong winds. It is, however, important that the density of the shrubs and trees is not too high and impenetrable for animals to move through, especially if the woody species have sharp spines (Dean *et al.*, 1999; Nxele, 2010).

Supporting services form the basis of habitat services, providing support to humans and various plant and animal species (MEA, 2005). Habitat or supporting services provide the base on which plants and animals can establish themselves, thereby creating small sub-climates and microhabitats that can accommodate a variety of smaller organisms (TEEB, 2011). Plants and animals help to conserve and protect biological, genetic and evolutionary processes that may have been lost if the ecosystem is not functioning correctly (De Groot *et al.*, 2002). Studies have found that the herbaceous layer (mainly grasses) benefits from the presence of woody species in the landscape (Smit, 2005). This is because woody species (trees) have the ability to extract nutrients from deep in the soil profile (creating a fertile island) and deposit them in shallower soil levels where other plant species like grasses can access them (Smit and Swart, 1994; Hagos and Smit, 2004; Smit, 2005). This fertile island effect around the stem of a tree assists in the establishment

of certain grass species like *Panicum maximum* (Teague and Smit, 1992; Smit and Swart, 1994; Hagos and Smit, 2004; Smit, 2005). The soil surrounding the trees or in the thickened area will thus be more productive than areas with lower tree densities in the same landscape (Smit and Rethman, 2000).

These fertile islands surrounding trees also create sub-climates for the establishment of biological soil crusts (Belnap *et al.*, 2001; Dougill *et al.*, 2004). Biological crusts have the ability to fix N, improve the soil nutrient content and help to stabilise the topsoil of the area, thereby decreasing erosion (Belnap *et al.*, 2001; Dougill *et al.*, 2004). Mager (2010) found that biological soil crusts in the southwest Kalahari produces approximately 75% of the total soil organic C found in the Kalahari soils and that these nutrients are concentrated in the topsoil, decreasing exponentially with depth. The high density of shrubs in bush-thickened areas also protects biological soil crusts from being trampled and destroyed by the hooves of animals (Belnap *et al.*, 2001; Dougill *et al.*, 2004). Denser tree stands, however, have negative effects on the soil water availability required for herbaceous (grass) production (Smit and Rethman, 2000). The removal of trees will thus lead to increases in the abundance of the herbaceous layer and soil water availability, with a decrease in soil organic C (Smit and Rethman, 2000; Breshears, 2006; Maestre *et al.*, 2006; Eldridge *et al.*, 2009; Daryanto *et al.*, 2013; Eldridge and Soliveres 2014; Eldridge *et al.*, 2015).

The last category of ecosystem services is called cultural services. It is the only service that does not deliver physical goods to people (MEA, 2005). Cultural services provided by an ecosystem are about the aesthetical, spiritual, educational and psychological benefits people can receive from the ecosystem.

The aesthetic appeal of an area is reduced by the increase of woody species, as it leads to an imbalance in the grass-to-trees ratio, e.g. making it more difficult for hunters and tourists to spot game at game farms and parks and for farmers to herd livestock (Bezuidenhout *et al.*, 2015). Game parks are also heavily affected by bush thickening, which may restrict the movement of game (Gray and Bond, 2013; Bezuidenhout *et al.*, 2015). Gray and Bond (2013) found that the number of animal sightings decreased dramatically in thickened areas. Some areas showed a 50% reduction in animal sightings

as a result of bush thickening. Surveys used in their study concluded that tourists will avoid game parks or game farms that are heavily thickened because of poor animal sightings and the abnormal thickening of trees causing bush encroachment in these areas (Boshoff *et al.*, 2007; Gray and Bond, 2013).

Eldridge and Soliveres (2014) recently concluded that bush thickening can be very beneficial to various other ecosystem services, including soil fertility, hydrology, biodiversity and carbon sequestration, if the critical threshold density is not surpassed (Figure 1.2). Bush thickening therefore does not only have negative effects on the ecosystem, as perceived by many scientists working in savanna rangelands used for game and cattle farming (Ludwig and Tongway, 1997; Richter *et al.*, 2001; Barac, 2003; Smit, 2005; Archer, 2010; Kgosikoma *et al.*, 2012; Harmse, 2013; Gray and Bond, 2013; Bezuidenhout *et al.*, 2015). Studies by Breshears (2006), Maestre *et al.* (2009), Daryanto *et al.* (2013), Eldridge and Soliveres (2014) and Eldridge *et al.* (2015), proved that if the bush density does not surpass a certain threshold, biodiversity, carbon sequestration, soil fertility and hydrology may increase in the thickened areas (Figure 1.2).

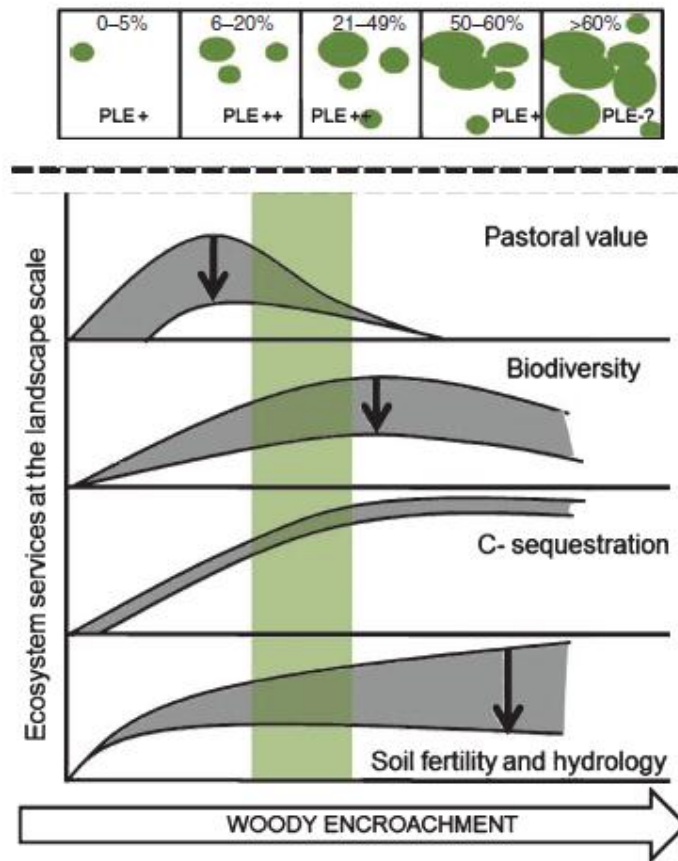


Figure 1.2: The green band indicates the threshold or density at which bush thickening will be most beneficial to certain ecosystem services (taken from Eldridge and Soliveres, 2014).

Therefore, depending on the land use and what aspects are considered during bush thickening, it may have a positive or negative affect on the entire landscape and can improve the functioning and services of a landscape. If bush encroachment is seen from a wildlife or agriculture perspective concentrating on pasture management, it may have a negative effect on the ecological processes of the land (Breshears, 2006; Maestre *et al.*, 2006; Eldridge *et al.*, 2009; Daryanto *et al.*, 2013; Eldridge and Soliveres 2014; Eldridge *et al.*, 2015).

1.1.4 Controlling bush thickening in the Molopo region

1.1.4.1 Different control methods

There are various ways to control and combat bush thickening in bush-encroached savanna ecosystems. These include chemical, mechanical, manual and biological control, as well as stem burning (Barac, 2003). Chemical control includes non-selective control, e.g. by airplane and selective control, e.g. by controlling certain target species by hand with arboricides (Harmse, 2013). Various studies have shown that if considered from an agricultural and pasture perspective, the control of thickening species by means of various methods have positive and negative effects on the functioning of a landscape (Smit, 2004).

Some scientists have found that by selective controlling and keeping larger tree individuals in the landscape, interspecies coexistence and competition (e.g. woody vs. woody and woody vs. herbaceous species) still exists but will minimise the re-establishment of woody seedlings (Smit *et al.*, 1996; Smit, 2004). However, woody species that are left untreated should not be too dense in order to also facilitate the re-establishment of herbaceous species. Woody species that are controlled and left to decompose in the veld may contribute to the increase of soil nutrients for herbaceous species. Woody species with spines that are controlled may also prohibit further grazing by animals, giving herbaceous species a competitive advantage to establish. These controlled areas also tend to be more stable and less susceptible to disturbances (Smit, 2004).

The combating of bush thickening in the Molopo region started in the mid-1900s, where farmers used mechanical and chemical methods to control the increasing density of *S. mellifera* (Donaldson, 1966). Donaldson and Kelk (1970) also state that earlier attempts to control increasing *S. mellifera* density started in the 1950s, where farmers used petrol to burn *S. mellifera* shrubs, thickening in approximately 856 000 ha in the Molopo rangelands (Ebersohn *et al.*, 1960). More recent studies by Richter *et al.*, (2001), Barac (2003) and Harmse (2013) found that farmers from the area preferred the use of chemicals or arboricides to fires, especially in areas affected by severe cases of thickening. No veld fires has occurred in the Molopo area for the last 10 years (personal

communication Pierre Bruwer). Farmers who do not want to kill favourable trees or shrubs, like *V. erioloba* and *Grewia flava*, found close to the thickening species prefer selective control methods over non-selective control methods. In the selective approach, the arboricide is selectively applied to the unwanted trees or shrubs and is thus labour intensive (Richter *et al.*, 2001; Barac, 2003; Harmse, 2013). In this approach the applicator walks with a bag of herbicide and applies 2 – 6 g of the herbicide by hand as close as possible to stem of the tree or shrub. The non-selective approach is more expensive but much faster. With the non-selective approach, the arboricide is broadly applied by aeroplane to a designated area. The aeroplanes have a specially designed bucket attached to the bottom of the aeroplane that can be calibrated to apply a certain amount of herbicide per hectare. This bucket was specially designed for the aerial application of herbicides in granular form. This approach controls all woody species, favourable and unfavourable, found in the designated area (Richter *et al.*, 2001; Harmse, 2013). *Boscia albitrunca* (Shepherd's tree) is the only tree species in the Molopo area that shows resistance against non-selective chemical application used to control the encroachment of *S. mellifera* (Harmse, 2013). Many farmers do not like this approach as *V. erioloba* trees get killed in the process. *Vachellia erioloba* is a highly sought-after tree in the Molopo region and is synonymous with the Molopo bushveld vegetation type (Rutherford *et al.*, 2006).

Open patches created in the landscape by clearing the thickening species can lead to more opportunistic and possibly less favourable species establishing in these patches (Teague and Smit, 1992). This is why the method used in clearing thickening/woody species from a landscape should be determined through thorough research to prevent the re-establishment of woody species that may cause re-thickening (Smit *et al.*, 1996; Barac, 2003; Smit, 2004). The suggested method for managing a thickened area is to selectively thin the woody species and to keep larger individuals in the landscape (Smit *et al.*, 1996; Smit, 2004). When using arboricides it is important not to under- or overdose the thickened area. Experts must be consulted on the correct dosage for the specific area and the prescribed dosage should be followed strictly to assure the correct results (Du Toit, 2012).

The different succession rates of grass species play an important role when thinning problematic woody species; these succession rates vary from landscape to landscape (Smit and Rethman, 1999). Farmers or land owners should also not expect a dense stand of perennial grass species during the first season after the woody species where thinned. The first species to colonise cleared areas will be more undesirable/unpalatable annual species, for example *Aristida* species in the Molopo region, followed by more palatable, poor perennial species and then the favoured, very palatable and strong perennial species, if the area is managed properly (Smit and Rethman, 1999; Rothauge, 2011).

1.1.4.2 Stable and unstable landscapes

Savanna landscapes with various species of large trees and a good distribution of perennial grass species are seen as more stable, productive systems in an agricultural sense where forage production is the main focus (Figure 1.3) (Smit, 2004, 2005; Archer, 2010). Stable, productive landscapes have larger tolerance ranges than unstructured, less stable landscapes. This means that stable landscapes will be able to tolerate more severe disturbances before any changes will be observed and are thus less prone to change (Smit, 2004; Sankaran *et al.*, 2004).

Stable landscapes or landscapes at equilibrium are seen as areas with a well-established heterogeneous vegetation structure and a healthy tree-to-grass ratio that has not changed in recent years (Sankaran *et al.*, 2004; Sankaran *et al.*, 2008; Archer, 2010). These systems will therefore not undergo a change in composition after a disturbance by climatic (e.g. drought) or management (e.g. fire) factors (Sankaran *et al.*, 2004). In stable and productive landscapes, the species composition and structure remains more stable (Smit, 2004; Sankaran, *et al.*, 2004).

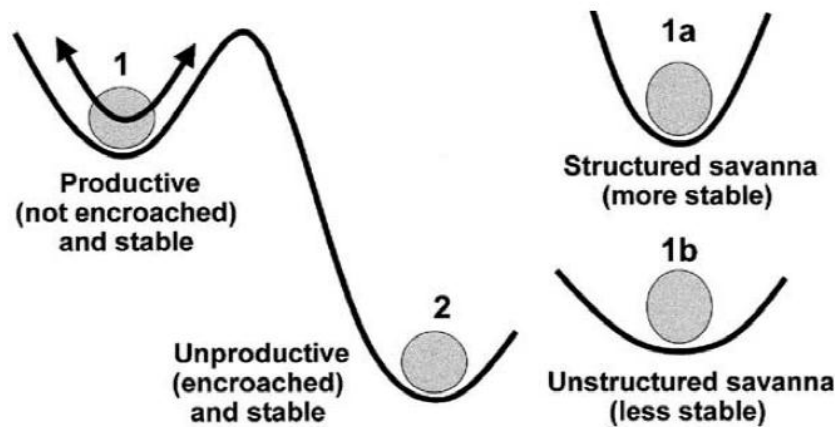


Figure 1.3: Productive (non-thickened) and unproductive (thickened) savanna can be stable, but productive systems are more resilient. The arrows seen in the graph represents the resilience of the productive savanna to a disturbance like bush thickening. Structure savannas are able to endure much larger disturbances over longer time periods (taken from Smit, 2004).

According to Smit (2004) (Figure 1.3), less stable and unstructured savanna systems in a state of non-equilibrium, on the other hand, will undergo more changes in their vegetation composition if disturbances are experienced. These systems will recover more slowly after disturbances. Change to a more stable and structured landscape also decreases and is often unachievable when a certain threshold is passed, especially when working in savanna landscapes used for livestock and game keeping focussed on forage production (Smit, 2004; Sankaran *et al.*, 2004) (Figure 1.3). In agricultural terms, bush-thickened landscapes are classified as stable unproductive systems (Figure 1.3) as a result of their vigour and the type of intervention (chemical control) that will be needed to transform them into more stable productive systems (Figure 1.3) (Smit, 2004). The types of impacts that are able to change the state of a landscape can be either natural, such as droughts, or through the application of management practices, which include aspects of fire and grazing/browsing. The latter also includes human-induced interventions, such as the application of arboricides in bush-thickened areas.

The density of shrubs and trees in bush-thickened areas are normally >2 500 tree equivalents/ha (Teague *et al.*, 1981; Friedel, 1991; Richter *et al.*, 2001). Areas with such high tree/shrub densities are usually unable to change from an unproductive to a productive landscape through natural events. Human intervention, including the

application of different control methods such as chemical control or mechanical removal, are needed.

1.2 The landscape function analysis (LFA)

1.2.1 The origin of the LFA

The landscape function analysis (LFA) was developed by Tongway and Hindley (2004a) to aid the monitoring of rehabilitated areas. The LFA's main focus is to determine how the landscape functions and, by doing so, also to determine the current state of the landscape which is an expression of the inter-play of dynamic physical, chemical and biological factors over time and in response to climatic conditions and managerial inputs. The method is mostly used to monitor rehabilitation practices applied in mining areas but can also be used on degraded rangelands. An LFA is a simple and inexpensive technique that can be taught to almost anybody because it requires no laboratory analysis to reach a result (Tongway and Hindley, 2004a).

Monitoring techniques that were used in the past focussed on the composition of the vegetation in the landscape. Most of the techniques used monitoring to determine the biomass production of the area to estimate the grazing capacity and to prevent overgrazing (Friedel, 1991; Hobbs and Norton, 1996; Tongway and Hindley, 2004a). The lack of monitoring techniques focussing on ecosystem functioning as well as increasing interest in the rehabilitation of degraded areas, sustainability and conservation of ecosystem biodiversity, scientists have shifted their attention to developing a technique that can be used in the rehabilitation of degraded areas (Cairns, 1988; Jordan *et al.*, 1988; Hobbs, 1993; Saunders *et al.*, 1993; Tongway and Hindley, 2004a).

Walker (1996) realised that there was a gap in the literature about the functioning of rangelands and suggested that a model be created to attend to this gap. Ludwig and Tongway (1997) responded to Walker (1996) and designed a framework called the trigger-transfer-reserve-pulse (TTRP) method (Figure 1.4). This framework helps to explain how a rangeland functions by looking at how rangelands are conserving, utilizing and recycling limiting resources (Ludwig and Tongway, 1997; Herrick and Wander, 1998; Ata Rezaei *et al.*, 2005).

The TTRP method is used to describe how the biogeochemical processes of landscapes function and also indicates certain events that can affect the outcome of these processes by identifying a sequence (Ludwig and Tongway, 1997; Herrick and Wander, 1998; Ata Rezaei *et al.*, 2005) (Figure 1.4). The TTRP can be explained as follows (Figure 1.4): The trigger (1) is an external source of nutrition that may result in runoff or displacement i.e. water (transferred) (Tongway and Hindley, 2004a). These triggers may be lost as result of runoff (3) or absorbed into the soil (1). A pulse (2) is an action or reaction to the trigger (1), e.g. plant growth that makes use of the nutrients that have been gathered from the reserve. The growth experienced by the plant may be lost to herbivory or fire (4) and the nutrients that are not lost to these actions are cycled back to the reserve (the nutrient cycling loop also includes seed or propagule production and safe placement in the soil.) (5), where the nutrients can be stored for future use or to transfer (6) to change the transfer methods of the plant (Tongway and Ludwig, 2001; Tongway and Hindley, 2004a).

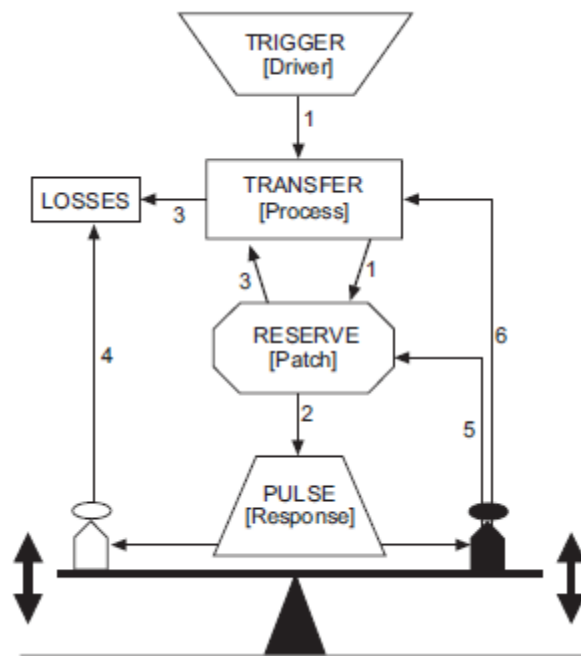


Figure 1.4: This figure, taken from Ludwig and Tongway (1997), illustrates that a trigger is needed before products can be transferred to a patch (reserve), after which a response (pulse) will lead to the product being absorbed or discarded (losses). This framework is known as the trigger-transfer-reserve-pulse method.

The TTRP framework accepts (Ludwig and Tongway, 1997; Tongway and Hindley, 2004a):

- the functional connectivity between ecosystem components in a landscape as a result of the redistribution of resources,
- the importance of spatial sequences of processes,
- that using feedback processes are important when regulating an ecosystem,
- the concept of the economics of vital resources,
- that this framework can be the basis of other simulation models, and
- that it is a generic framework that focusses on the processes that are used to retain and utilize important resources in the landscape.

This framework developed by Ludwig and Tongway was later on used as the basis of various more detailed models like the LFA (Tongway and Hindley, 2004a).

1.2.2 LFA Description

LFA is used as a monitoring procedure that describes or assesses the level at which a landscape is functioning as a biophysical system. Tongway and Hindley (2004a) define a biophysical system as the reactions that occur between abiotic and biotic variables in the environment. These reactions can vary from catastrophic, fast-acting reactions, e.g. erosion caused by flash floods, to smaller, more subtle reactions, e.g. the effect of leguminous trees on soil nutrients. LFAs incorporate rapidly assessed indicators to determine the processes that occur close to the soil surface. These rapidly assessed indicators include any biotic and abiotic object in the landscape (Tongway and Hindley, 2004a).

LFAs are used to monitor landscapes in order to better understand the functioning of the landscape, especially areas affected by disturbances like mining or degradation, including bush encroachment. An LFA's main objective is to determine what processes in the landscape play a key role in the functioning of that landscape. Specialists can use these processes to create a rehabilitation plan suited to the specific situation. The LFA can be used for a wide range of landscapes, e.g. mine tailings, arid rangelands and any

other rangeland that receives MAP of 200–4 000 mm. Importantly, the LFA method must be repeated over time to get a more detailed result with regards to the recovery and functioning of the landscape (Tongway and Hindley, 2004a).

The LFA method is made up of three components that aid the identification of different patches and inter-patches found on a selected transect (Tongway and Hindley, 2004a):

1. The conceptual framework focusses on the transport, utilisation and cycling of limiting resources in a landscape at the soil surface.
2. The field data acquisition component divides the landscape into units or patches. These patches can be nutrient-accumulating patches like grass patches or patches that promote the loss of nutrients from the landscape, namely inter-patches. Inter-patches are areas with no perennial vegetation present in the patch; they can also be referred to as bare-soil patches.
3. The interpretational framework is the last component of the LFA method and focusses on the interpretation of the data collected in the field, by placing it in curves representing a large range in functionality and so determine whether the site being studied has the capacity to regulate vital resources or whether the landscape presently has insufficient resource regulation and if physical or mechanical modification is needed. Tongway and Hindley (2004a) designed 11 soil surface assessments to help with the acquisition of data in the field.

1.2.3 Functional and dysfunctional landscapes

Tongway and Hindley (2004b) and Herrick and Wander (1998) see the functioning of a landscape as a continuum that can either be functional or dysfunctional. A functional landscape or a landscape with a high functional status can be described as a landscape where nutrients, soil and water are retained. Conserved nutrients and water can be used to enrich the soil, thus creating an ideal environment for plants to establish. Areas like these are normally densely populated by big perennial grass tufts that further help with the conserving of nutrients and water (Tongway and Hindley, 2004b). Functional systems are mostly stable systems as mentioned previously (Smit, 2004). Stable systems, and thus functional systems, can tolerate more disturbances of greater intensity before

undergoing structural or compositional changes (Smit, 2004). However, not all stable systems are functional, as mentioned in section 1.1.4, where bush-thickened areas are also classified as stable systems. Such areas are seen as dysfunctional landscapes, especially if looked at from an agricultural point of view (Tongway and Hindley, 2004b).

A dysfunctional landscape with a low functional status, on the other hand, is characterised by a low nutrient cycling rate and water in the soil (Tongway and Hindley, 2004b). These landscapes have large open patches between the vegetation, which makes it difficult for the environment to reserve important plant material and nutrients that are deposited on the surface during rain events. The size, number and spacing of the vegetation declines as this process continues without human intervention, such as chemical control; this is how an area becomes severely degraded (Tongway and Hindley, 2004b). These dysfunctional landscapes can also be classified as leaky landscapes due to the fact that all the important nutrients and organic matter leaks out of the system (Herrick and Wander, 1998; Ata Rezaei *et al.*, 2005). Most bush-thickened areas in South Africa fit the description of a leaky system, especially with the high level of degradation caused by encroaching species. The water does not flow out of the area in the Molopo region but due to the nature of the Molopo's sandy soils and topography the water percolates faster into deeper soil profiles due to a lack of herbaceous plants thus favouring woodies with deeper roots.

Landscapes that are classified as fully functional are in effect “conserving” the area. Fully functional landscapes maintain a healthy covering of perennial grass which is often characterised by an extensive fine root structure and can be utilised by animals, as seen in bush-thickened areas that have been chemically controlled. The extensive fine root structure of perennial grass tufts increases the flow-on effect of root symbionts which rapidly cycles carbon compounds into the soil, improving its aggregate structure. This keeps the lifecycle of the entire area in good condition, because there is enough food for all the organisms. Tongway and Hindley (2004b) illustrate how a fully functional state is the best condition a landscape can reside in (Figure 1.5). Figure 1.5 also shows that a totally dysfunctional or leaky state is the worst condition for a landscape to be in, as a

leaky landscape is incapable of conserving organic or plant material (Tongway and Hindley, 2004b).

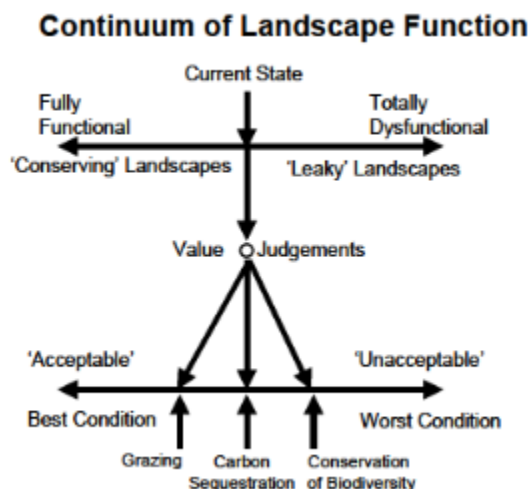


Figure 1.5: Fully functional systems conserve the environment by increasing grazing, carbon sequestration and biodiversity. However, leaky systems are seen as one of the worst states a system can reside in (taken from Tongway and Hindley, 2004b).

Leaky landscapes can only be restored to functional landscapes by human intervention, such as chemical control. Landscapes that have fallen into the leaky category have either been severely overgrazed or encroached by problem species such as alien or undesired spiny species. The only way to restore leaky landscapes is to chemically control the problem species, to remove all animals from the area or to stop any type of utilisation present. These areas will need intensive rehabilitation, which might take several years before reaching full functionality (Tongway and Hindley, 2004b; Smit, 2004).

1.3 Problem statement and study aims

1.3.1 Problem statement

Bush thickening (also referred to as woody thickening and bush encroachment) in the semi-arid savannas of southern Africa is caused by species such as *Senegalia mellifera*, *Vachellia luederitzii* and *Dichrostachys cinerea* (Richter *et al.*, 2001). Causes are to be found in the interrelated effects of overgrazing by livestock in constraint environments caused by fencing, rainfall frequency, lack of fire and browsing by

herbivores (Oba et al. 2000; Sankaran *et al.*, 2004; Joubert *et al.*, 2008). In order to restore stable and productive savannas, farmers often use soil-applied arboricides to control the thickening of woody species (Smit *et al.*, 1999). Although farmers apply different methods to control bush thickening, the application of arboricides by hand and/or aeroplane is preferred (De Beer and Jordaan, 2001; Barac, 2003). The application of arboricides may have negative effects on the soil and vegetation over the short- and long-term, especially an arboricide like Tebuthiuron if applied incorrectly (Du Toit, 2012). The rate at which the arboricides is applied is critical, because if too much arboricide is applied favourable species such as *V. erioloba*, *Grewia flava* and certain grass species start dying at alarming rates. On the other hand, if the application rate is too low the number of unwanted trees killed will also decrease (Moore *et al.*, 1985). Farmers who do not prefer arboricides because of their un-selectiveness, use manual methods (e.g. stem burning, cut stump or bulldozing woody species) to control bush-thickened areas (Strohbach, 1998; De Beer and Jordaan, 2001; Barac, 2003; De Klerk, 2004).

Vegetation surveys or LFAs have been carried out in the semi-arid savanna of the Molopo region in the North-West Province, South Africa, to determine the effect of bush thickening and different control methods on landscape functionality and soil parameters. Ludwig *et al.* (2004) found that Acacia trees (*Senegalia* and *Vachellia* spp.) increase the availability of nutrients by creating fertile islands and limit the herbaceous cover because of competition for soil moisture, decreasing other plants, such as grasses. Eleven soil surface indicators are used in soil surface assessments to determine the infiltration, stability and nutrient cycling of the soils in the landscape.

1.3.2 Study aims

The main aim of the project was to determine whether there is any relationship between the density and structure of the woody layer (height) and landscape functionality, and whether different measures of bush control affect these relationships.

Specific objectives included to:

- qualitatively and quantitatively describe the patch types and related attributes of landscape functioning (infiltration, stability and nutrient cycling) across rangeland conditions and treatments, and
- assess for differences in soil chemical properties at the patch scale, contrasting bush-thickened and controlled areas.

This study formed part of a bigger project that aims to assess the extent of bush thickening in the arid and semi-arid parts of South Africa. The woody vegetation structure and composition is determined by another MSc project carried out for IDESSA (Integrative Decision Support System for Sustainable Rangeland Management in Southern African Savannas) (www.idessa.org).

1.4 Structure of the dissertation

This dissertation consists of seven chapters. The present chapter gives an introduction and literature study on bush thickening and its current extent in the Molopo region of the North-West and Northern Cape Provinces, South Africa. Chapter 2 gives a detailed description of the materials and methods used in the study, as well as a description of the study area, while Chapter 3 (the first results chapter) focusses on the effect of bush density and type of bush control on LFA indices and patch type distribution in the Molopo Bushveld. Chapter 4 looks at the relationship between LFA indices and soil chemical properties at the patch and inter-patch scale in selected bush-thickened and controlled Molopo savanna areas. Chapter 5 is the synthesis chapter, with Chapter 6 containing the reference list. The Appendix follow at the end.

Chapter 2: Material and Methods

2.1 Study area

2.1.1 Location and land use

This study was conducted in the Molopo region located in the North-West and Northern Cape Provinces, South Africa. Exactly the same study sites were used by another student from the North-West University – Potchefstroom campus: “Composition and structure of woody vegetation in thickened and controlled savanna in the Molopo, South Africa. MSc thesis. North-West University: Potchefstroom” (Van Rooyen, 2016) during the same period. Thus the similar description of the study area is given. The Molopo region is found in the southern parts of the Kalahari basin, stretching over two provinces and covering more than 1,25 million ha (Rutherford *et al.*, 2006; Harmse, 2013; www.localgovernment.co.za) (Figure 2.1). The Molopo River forms the northern border between the Molopo region and Botswana (Donaldson, 1969; Harmse, 2013). The study area falls within two local municipalities, namely the Kagisano-Molopo local municipality (Figure 2.1), which in turn falls under the Dr Ruth Segomotsi Mompati District Municipality in the North-West Province³, and partly in the Joe Morolong local municipality⁴, which falls under the John Taolo Gaersewe District Municipality (www.localgovernment.co.za).

The Molopo region was a hunter’s paradise in the early 1900s, with uninhabited, open rangelands dominated by large herds of game (Donaldson, 1969). Farmers only moved into the region with the curing of “gallamsiekte” (Bovine paratuberculosis, paralysis of hindquarters in cattle) in the 1920s and the sinking of boreholes in the 1940s. The settlement of farmers in the Molopo region changed the region from a hunting area to a cattle farming area (Donaldson, 1969; O’Connor *et al.*, 2014). This was due to its large, open plains dominated by perennial grass with sparse stands of tall trees and scattered shrubs (Donaldson, 1969). The dominant trees identified in the early settling years were

³ Formerly known as the Bophirima District Municipality

⁴ Previously known as the Moshaweng local municipality (Northern Cape Province)

Boscia albitrunca, *Acacia giraffe* (*Vachellia erioloba*) and shrubs species, including *Senegalia mellifera* (Donaldson, 1969). The dominant grass species found in this area were *Eragrostis lehmanniana*, a moderately palatable perennial tufted grass species and *Antheophora pubescens*, a very palatable perennial tufted grass species (Donaldson, 1969; Acocks, 1988; Van Oudtshoorn, 2012). These have been almost completely replaced after 1940 by *Stipagrostis uniplumis*, a less palatable, sub-climax perennial tufted grass species (Donaldson, 1969; Low and Rebelo, 1996). However the grass species composition will be affected by the rainfall events and management strategies applied.

The sparse tree cover and scattered shrub stands started to increase in density shortly after the farmers converted the plains into cattle farms (Donaldson, 1969; O'Connor *et al.*, 2014). This increase in tree and especially shrub densities could be attributed to the exclusion of veld fires and selective grazing (including overgrazing) of cattle (Donaldson, 1969). The rainfall events as well as selective and overgrazing may have caused a substantial decrease in the density of larger perennial climax grass species like *Antheophora pubescens* (Donaldson, 1969; Acocks, 1988). Lower grass density led to reduced fire frequency and fires that did occur were also “cooler”, reducing their effectiveness with regards to the controlling of woody species (shrubs and trees) (Donaldson, 1969). Many farmers completely stopped burning their rangelands because of the loss of fodder for their livestock during winter and non-rainy seasons (Donaldson, 1969). These practices led to the Molopo region becoming encroached by shrubs like *Senegalia mellifera*, changing it from an open savanna to a dense shrubland in some areas closer to the Botswana border (Donaldson, 1969; O'Connor *et al.*, 2014).

According to Van den Berg (2007), cattle and commercial game farming is still very popular in the Molopo region, with some of the largest cattle herds in the world found within the Dr Ruth Segomotsi Mompati District (www.drrsmompatidm.gov.za, 2015). The Joe Morolong local municipality is mostly rural with almost half of its households being supported by agricultural products and the services gained from keeping livestock (Van Rooyen, 2000; Coetzee, 2006). This municipality is characterised by sandy soils, with

60% of its land being virgin, leading to the previous name of Moshaweng, meaning “place of sand” in Setswana (www.localmunicipality.co.za, 2015).

Land degradation in the North-West and Northern Cape Provinces is a very serious problem, with the Molopo region being classified as a moderately degraded area according to the combined degradation index (CDI) (Hoffman and Ashwell, 2001; Van den Berg, 2008). The CDI index includes veld and soil degradation. Bush thickening has been included as a type of land degradation since 2005 when the Millennium Ecosystem Assessment (MEA) altered the definition of land degradation to include the “bush encroachment” phenomenon (MEA, 2005). Extensive areas in the Molopo region are affected by bush thickening (Richter *et al.*, 2001; Dougill and Thomas, 2004; Hagos and Smit, 2005; Van den Berg, 2007; Kong *et al.*, 2014) as a result of mismanagement and environmental factors like the exclusion or reduction of fire, increased atmospheric CO₂ levels and variable rainfall events and droughts (Richter *et al.*, 2001; Hagos and Smit, 2005; Archer, 2010; Harmse, 2013; O’Connor *et al.*, 2014). The extent of bush thickening in the Molopo region has escalated so much that farmers were forced to start using arboricides to control the thickening of the woody species and produce more fodder for the grazers. Arboricide application by means of a non-selective method by aeroplanes is one of the most popular methods used to control the encroaching shrubs in the Molopo region (Richter *et al.*, 2001; Harmse, 2013).

The cattle farmers in the study area make use of rotational grazing regimes, where the pasture is divided into various smaller camps (paddocks) (Harmse, 2013). In a controlled and better management system, these smaller camps are generally grazed more intensively for shorter time periods to include a resting period for camps and grasses that are not grazed to recover (Tews *et al.*, 2004). Some areas will not have bush thickening if properly managed over the long-term (Tews *et al.*, 2004).

The approximate long-term grazing capacity for the Molopo Bushveld vegetation type is 10–12 ha per large stock unit (LSU) (Mostert *et al.*, 1971 cited in Richter *et al.*, 2001; Tews *et al.*, 2004; Harmse, 2013). The communal areas of the Molopo region are dominated by goats and donkeys with the occasional herd of cattle, contributing to the overgrazing problem (Jacobs, 2000). Private, commercially managed farmlands in the

Molopo region are mostly used for cattle and game farming. Commercial game farming became popular in the early 21st century, mostly due to the substantial increase in the value of all game species (Tews *et al.*, 2006). The increase in game farms is a good example of how the good management of pastures in the Molopo can lead to promising netto gains, especially if farmers start to attract international or trophy hunters, who are more focussed on the quality than quantity of the product.

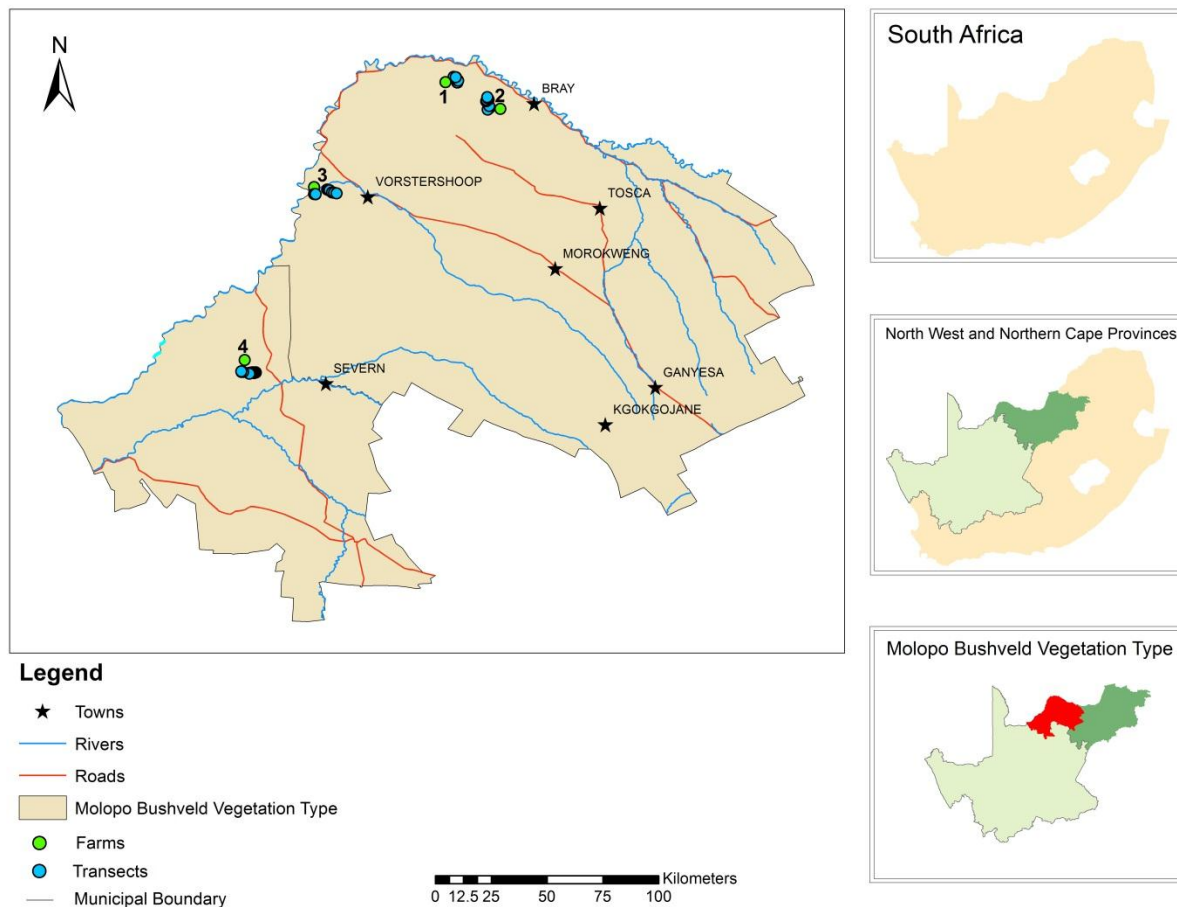


Figure 2.1: Location of the Molopo Bushveld vegetation type and the study area in the North-West and Northern Cape Provinces, South Africa. The location of the four farms and plots where the study was carried out are indicated by the coloured dots.

2.1.2 Climate

The Molopo region is a summer rainfall area that receives MAP of between 250 and 400 mm between October and March (Scholes, 2002; Thomas *et al.*, 2002; Sankaran *et al.*, 2005; Rutherford *et al.*, 2006; Sankaran *et al.*, 2008) (Figure 2.2). Rainfall is very erratic and can vary between extreme dry spells during dry years (<250 mm) and occasional “wet years” (>400 mm) (Thomas and Shaw, 1991; Nash and Endfield, 2002; www.weathersa.co.za). A big concern for most farmers in the Molopo region is the potential evaporation of the region. The PET of the Molopo region is three times higher than the average annual rainfall, meaning that surface water will evaporate before it is supplemented with follow-up rain, which may reduce the recharge to the lower groundwater level needed for the boreholes (Wang *et al.*, 2007).

Rainfall data from the weather stations at Bray (0541297 5) and Severn (0428635 1) were used in the description due to their close proximity to most of the sampling sites (Figure 2.2). On average, Bray receives more rainfall than Severn, with long-term MAP of 320 mm and 273 mm respectively (www.weathersa.co.za) (Figure 2.3).

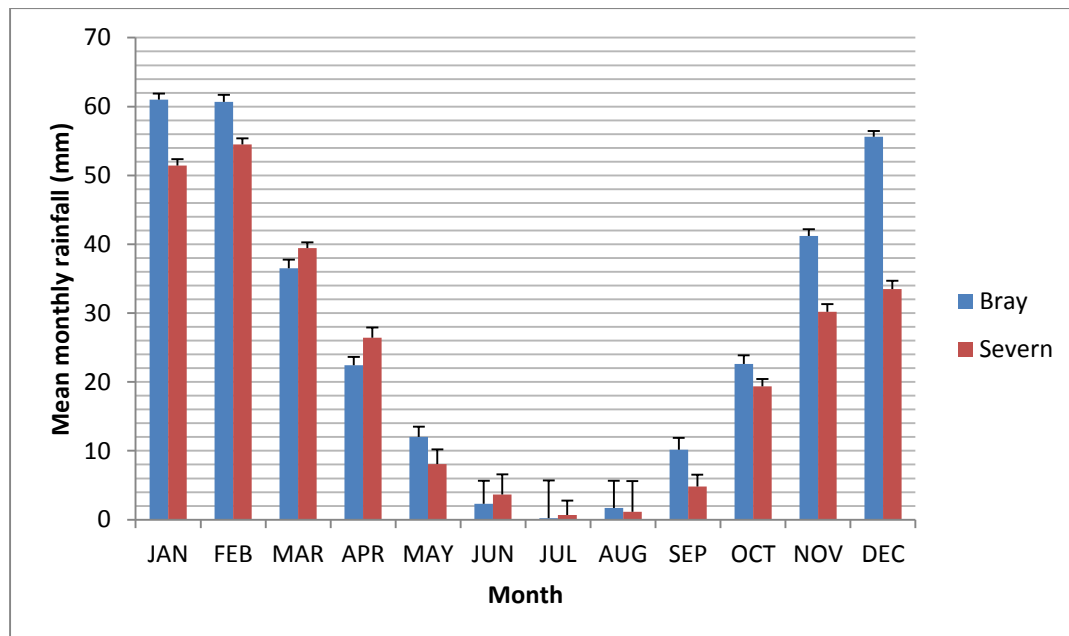


Figure 2.2: The mean monthly rainfall ($\pm$ coefficient of variation) recorded at Bray [0541297 5] and Severn [0428635 1] weather stations in the Molopo study area from 1986 to 2015 (www.weathersa.co.za).

The last thirty years of rain data were summarised and grouped into three groups of ten years each to compare the rain data of the three decades (Figure 2.3). The average annual rainfall for the Bray area shows very high variability (coefficient of variability (CV) = 49%) in the last thirty years. The rainfall increased from an average of 343 mm/a for 1986–1995 to an average of 400 mm/a for 1996–2005, followed by a drier decade with an average of 219 mm/a for 2006–2015 (www.weathersa.co.za) (Figure 2.3). The Severn area had a slightly lower variability (CV = 46%) regarding rainfall events over the last three decades (Figure 2.3). The MAP for the first decade from 1986 to 1995 was 289 mm, followed by a slightly wetter decade (1996–2005), with an average of 308 mm/a, and with a much lower rainfall average over the last decade (2006–2015) of 223 mm/a (www.weathersa.co.za) (Figure 2.3). The first two decades, as in the Bray area, were higher than the overall mean annual rainfall (1986–2015). The rainfall was, however, lower in both areas during the last decade (www.weathersa.co.za) (Figure 2.3).

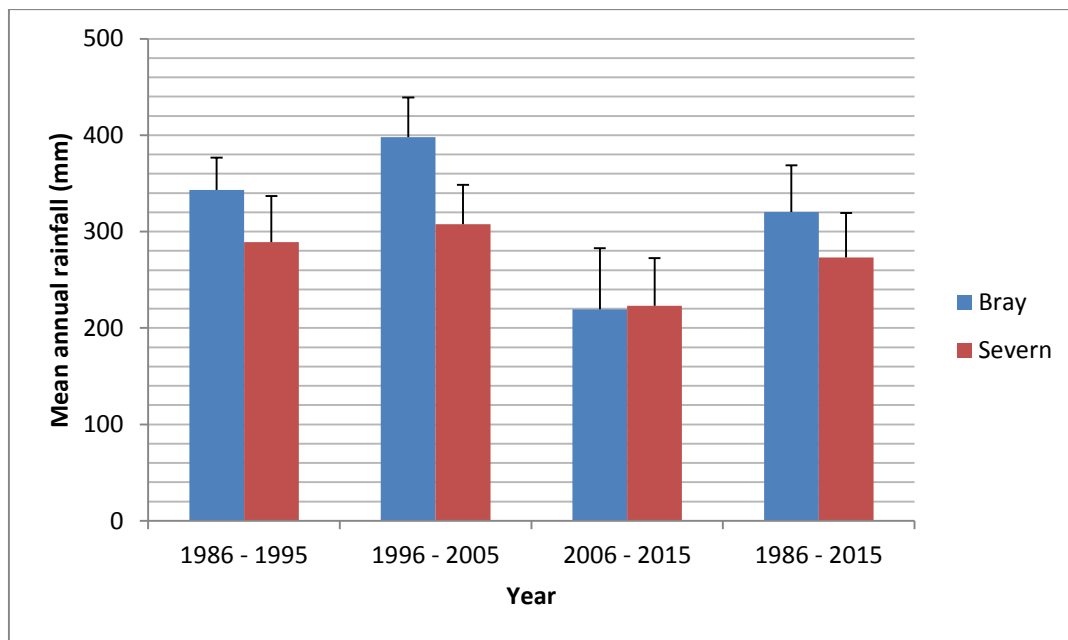


Figure 2.3: The mean annual rainfall ($\pm$ coefficient of variation) recorded for three decades at the Bray [0541297 5] and Severn [0428635 1] weather stations in the Molopo study area and the long-term mean annual rainfall from 1986 to 2015 (www.weathersa.co.za).

These comparisons in rain data for the last three decades for the two weather stations coincides with the results of Thomas and Shaw (1991) and Nash and Endfield (2002), who stated that the precipitation of the Molopo area can vary from very dry spells to occasional wet years (www.weathersa.co.za) (Figure 2.3).

It is generally known that the western parts of South Africa, where the study area was situated, experienced a serious drought from October 2014 to April 2016, prior to the period when the field work was conducted, namely February and March of 2015 and 2016) (www.weathersa.co.za) (Figures 2.4 and 2.5). This led to poor herbaceous vegetation production, making sampling of the herbaceous vegetation difficult. The long-term average rainfall (from 1986 to 2015) for the Bray and Severn areas from October to February are 241 mm and 189 mm respectively, but these values decreased dramatically for the four months preceding the 2015 and 2016 field surveys (Figures 2.4 and 2.5). The Bray area only received 65 mm of rainfall from October 2014 to February 2015 and no rainfall was recorded for October 2015 to the end of February 2016, compared to the long-term average rainfall of 241 mm/a (Figures 2.4 and 2.5). Severn also experienced a decline in rainfall over this period. Only 134 mm was received from October 2014 to February 2015 and 51 mm from October 2015 to the end of February 2016, compared to the long-term average of 189 mm/a. (www.weathersa.co.za) (Figures 2.4 and 2.5).

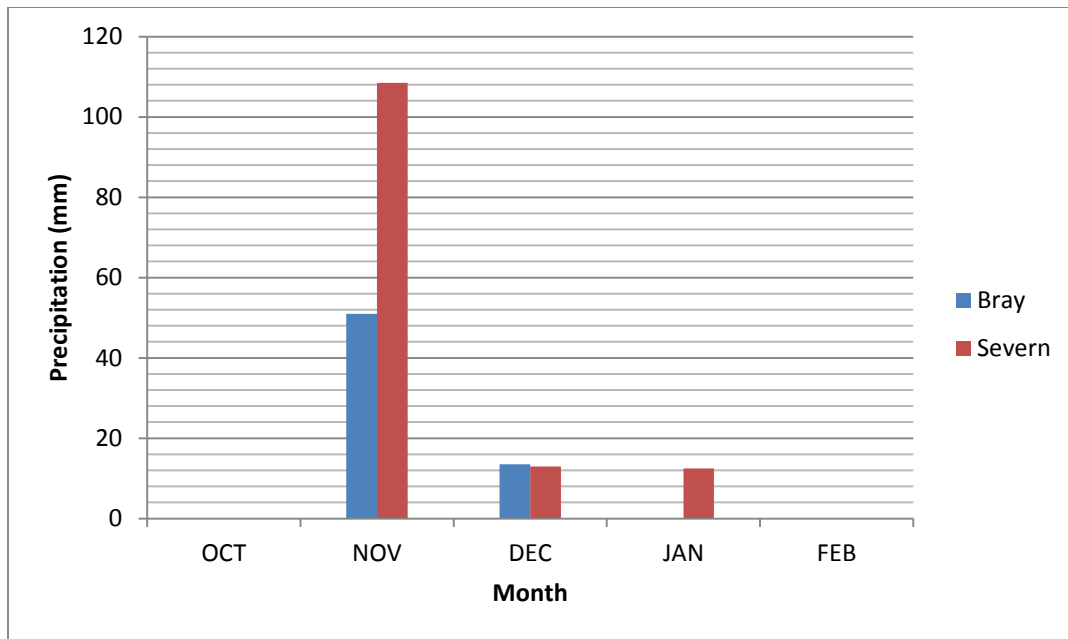


Figure 2.4: Rainfall in the months preceding the 2015 field surveys, from the end of February 2015 to the beginning of March 2015 (www.weathersa.co.za).

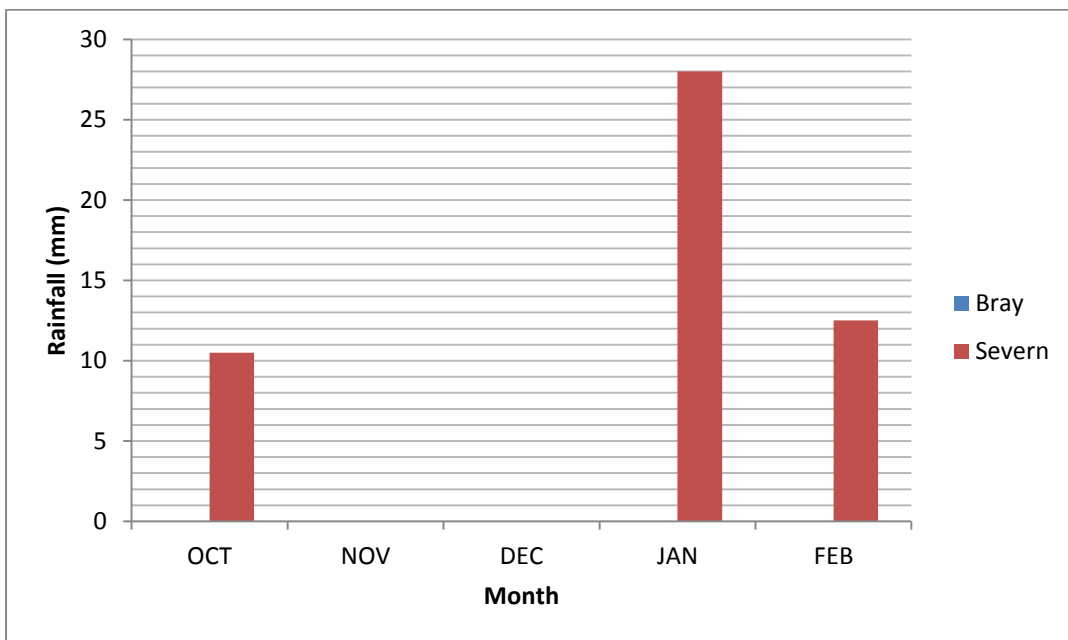


Figure 2.5: Rainfall in the months preceding the 2016 field surveys, from the beginning of March 2016 until the end of March 2016. Bray received no rainfall during these months (www.weathersa.co.za).

From the oldest data received by the South African Weather Services, the drought in 2015 was the most severe drought since 1950 for both the Bray and Severn areas, with the areas recording 29 mm/a and 34 mm/a for the 2015 season respectively (www.weathersa.co.za). The previous driest years for the Bray and Severn areas were recorded in 2012 and 1992, where 82 mm and 79 mm rainfall was received respectively (www.weathersa.co.za).

2.1.3 Geology and soils

In southern Africa, one of the largest sand-covered areas is known as the Kalahari, occupying an area of 2.5 million km² located between 29° south and 14°–28° east of the equator (Scholes *et al.*, 2002). Within this area, Walker *et al.* (2010) describes the Molopo Farm Complex (MFC), which was previously known as the Bushveld Complex. Large parts of the study area is situated within the MFC, which is approximately 13 000 km², layered with ultramafic-mafic intrusions known as the Kaapvaal Craton (Walker *et al.*, 2010). The Kalahari sands (Cenozoic Kalahari Group sediments) and Karoo strata occurring in the northern parts of the North-West Province and south-western parts of Botswana are presently covering this complex (Reichhardt, 1994; Scholes *et al.*, 2002; Anhaeusser, 2006). The thickness of these layers varies between 100 m in the west and south of the MFC, to approximately 200 m in the proto-Molopo palaeo-valleys of the MFC (Walker *et al.*, 2010).

Flat to sinuate sandy plains occur in the Molopo region, with the topography varying between 1 000 m and 1 300 m above sea level (Donaldson and Kelk, 1970; Rutherford *et al.*, 2006). Closer to the drainage valley areas, such as the Molopo River that forms the border between South Africa and Botswana (Figure 2.1), sand dunes occur more frequently (Van Niekerk, 2011). These flat sinuate sandy plains are known as the Cordonian Formation and are red, deep aeolian sand with a surface containing silcrete, calcrete and ferricrete (Low and Rebelo, 1996; Rutherford *et al.*, 2006). The study area has red and yellow sandy soils that are well-drained with a high base status (Rutherford *et al.*, 2006). Kalahari soil is characterised by its high infiltration rate, low organic matter, low nutrient levels and relative level topography, with very little to no water runoff (Donaldson and Kelk, 1970; Thomas *et al.*, 2002). The deep sandy soils (>1.2 m)

(Rutherford *et al.*, 2006) are characterised by a coarse soil texture and low clay content, allowing water, air and roots to easily penetrate, which results in a decreased retention capacity of water and nutrients (Sims, 1981; Gebremeskel and Pieterse, 2006).

The presence of trees in the Molopo region increases the surrounding soil nutrients through nutrient upliftment or the fertile island effect, mostly occurring under tree canopies (Hagos and Smit, 2005; Nxele, 2010). Trees and shrubs have the ability to extract nutrients from deeper in the soil profile and depositing them closer to the surface, making them more accessible to herbaceous species (Dougill *et al.*, 2004; Hagos and Smit, 2005; Nxele, 2010). Hagos and Smit (2005) found that the soil surrounding the stem of *S. mellifera* shrubs (the most problematic encroaching plant in the Molopo region) was significantly higher in N, soil organic matter and calcium (Ca) compared to areas outside of the shrub canopy area or those under grass tufts. Levels of other elements like magnesium (Mg), phosphorus (P) and potassium (K) were also high but not significantly higher than that of the soil surrounding the grass tufts (Smit and Swart, 1994). These findings support the theory that moderate tree densities can increase soil nutrients and herbaceous production (Daryanto *et al.*, 2013; Eldridge and Soliveres 2014; Eldridge *et al.*, 2015), but only to a certain extent, after which a linear decline can be expected in the dry matter production of the herbaceous species (Smit and Swart, 1994). The enrichment of the soil surrounding tree stems can also be ascribed to N-fixation that occurs in the roots of leguminous trees (Smit and Swart, 1994) and the biological soil crusts that form close to the stems of most of the former *Acacia* species (*Senegalia* and *Vachellia* species) found in the Molopo region (Dougill *et al.*, 2004; Mager, 2010). Stem flow from the trees and higher concentrations of animal and insect droppings underneath the canopies of trees and shrubs can also help to increase soil nutrients (Smit and Swart, 1994).

Biological soil crusts are major contributors to the nutrient content of Kalahari soils (Thomas *et al.*, 2008; Mager, 2010; Thomas and Hoon, 2010; Elliot *et al.*, 2014). Thomas *et al.* (2008) concluded that most biological soil crusts found in the Kalahari are made up of cyanobacteria capable of fixing N and C. The Kalahari cyanobacteria soil crust also produces extracellular polysaccharides, which help to stabilise the loose sandy soils of the area and thus also help to prevent soil erosion (Mager, 2010; Thomas and Hoon,

2010; Elliot *et al.*, 2014). Thomas and Hoon (2010) and Thomas *et al.* (2008) found that the respiration rates of Kalahari cyanobacteria can increase substantially after a rain event and that their respiration rates can increase by up to 500%. This is why Mager (2010) concluded that biological soil crusts are responsible for 75% of the total soil organic carbon found in the topsoil of the Kalahari sandy soils.

2.1.4 Vegetation

The Savanna Biome found in southern Africa stretches from Zambia, close to the equator, to the most southern parts of Africa. This stretch of savanna is mostly made up of fine Kalahari sands (Scholes, 2002) and is characterised by a healthy grass-to-tree ratio (Low and Rebelo, 1996; Rutherford *et al.*, 2006; Sankaran *et al.*, 2008). The grass layer is more dominant in this biome, with trees occurring mostly in scattered clumps (Low and Rebelo, 1996; Rutherford *et al.*, 2006; Sankaran *et al.*, 2008). The dryer parts of the Savanna Biome and thus also the dryer parts of the Kalahari basin are known for their more palatable “sweet” grass species (Leistner, 1996). Due to the grass species being more palatable, grazers tend to overgraze these areas, creating opportunities for increaser plant species, including woody increasers, such as *S. mellifera*, to establish (Smit *et al.*, 1996; Richter *et al.*, 2001; Ward and Esler, 2011; O’Connor *et al.*, 2014). Through overgrazing, the herbaceous layer of an area steadily becomes depleted, ultimately forming bare patches with no or little herbaceous cover (including grasses). These bare and low-vegetation cover areas are more exposed and characterised by land degradation (Dougill *et al.*, 1999; Ludwig *et al.*, 2000; Smit, 2004; Snyman and Du Preez, 2005; Sankaran *et al.*, 2008; Kgosisikoma *et al.*, 2013).

The Molopo Bushveld vegetation type (Rutherford *et al.*, 2006) in the Kalahari basin falls under the fine-leaved savannas as described by Scholes (1997). Fine-leaved savannas usually have nutrient-rich soils (Scholes, 1997), but this is not true for the Molopo region; Molopo bushveld is known for its nutrient poor soils (Thomas *et al.*, 2002; Thomas and Dougill, 2006; Moussa *et al.*, 2009). This bushveld vegetation type was also previously driven by fire events, as with most semi-arid and arid savannas, especially in Africa, but after human settlement in the 1940s, farmers suppressed fires, changing the vegetation structure of the entire Molopo region (Donaldson, 1969; O’Connor *et al.*, 2014). After

1940, the Molopo region changed from vast, open pastures with only scattered tree clumps to an almost closed shrubland in some areas, characterised by severe bush thickening (Donaldson, 1969; Acocks, 1988; Low and Rebelo, 1996; Richter, 1999; Richter *et al.*, 2001; Barac, 2003; Harmse, 2013).

The scattered tree layer within this vegetation type before degradation was mostly characterised by species such as *Boscia albitrunca*, *Terminalia sericea*, *Vachellia erioloba* and *V. luederitzii* var. *luederitzii* (Rutherford *et al.*, 2006). Many degraded areas are, however, characterised by a shrub layer of species such as *Grewia flava*, *Lycium hirsutum*, *V. haematoxylon*, *Senegalia mellifera* subsp. *detinens* and *V. hebeclada* subsp. *hebeclada* (Harmse, 2013). Common perennial grass species include *Aristida stipitata*, *A. meridionalis*, *Eragrostis lehmanniana*, *Schmidtia pappophoroides* and *Stipagrostis uniplumis* (Acocks, 1988; Low and Rebelo, 1996; Harmse, 2013). Annual grasses include species such as *Enneapogon desvauxii* and *Schmidtia kalahariensis* (Acocks, 1988; Low and Rebelo, 1996; Richter *et al.*, 2001; Harmse *et al.*, 2013). This vegetation type is known to be the least threatened for conservation according to Van Rooyen and Van Rooyen (1998) and Rutherford *et al.* (2006). Apart from biospheres and areas that are conserved by game farms, the only formally registered reserves in the Kalahari are the Molopo Nature Reserve in the North-West Province and the Kalahari Gemsbok Park in the Northern Cape Province (Van Rooyen and Van Rooyen, 1998; Rutherford *et al.*, 2006).

To control bush thickening, farmers use arboricides to reduce the high densities of trees and shrubs, mainly to increase the fodder production for grazing animals (Donaldson, 1969; Smit *et al.*, 1996; Richter, 1999; Richter *et al.*, 2001; Barac, 2003; Smit, 2004; Lumkomska *et al.*, 2014; Bezuidenhout *et al.*, 2015). One of the most effective arboricides used in the Molopo region is Molopo CC granules that can either be applied selectively by hand or non-selectively by aeroplane (Harmse, 2013). Shrub control by means of non-selective aeroplane treatment is much faster and larger areas can be controlled in a shorter time span. Although this method requires higher financial input, it is less labour intensive, especially when dense stands of shrubs have to be treated (Richter *et al.*, 2001; Barac, 2003).

2.2 Study sites

2.2.1 Selection and description of study sites

The study design includes four bush control treatments, namely (1) selective chemical control by hand (HC), (2) selective chemical control by hand with re-application (2HC), (3) non-selective chemical control by aeroplane (AC) and (4) selective control by stem burning with re-application (SB) (Table 2.1). The respective sampling sites were located on three commercial cattle farms and one game farm in the study area and locations described above (Figure 2.1 and Table 2.1). At farm scale, site selection occurred with the help of the land owner, who was asked to indicate where each of the abovementioned sites could be found, representing a certain type of control technology. Bush-thickened (BT) benchmarks close to the treated sites were selected as control areas and were characterised by similar environmental conditions. As a criterion, these bush-thickened areas corresponded to the initial level of bush thickening of the treated sites regarding biophysical and management parameters. For each site, qualitative data such as camp size, grazing regime, stocking rate, grass layer condition and soil condition were noted. All study sites in an area were similar with respect to climate, substrate (sandy soil), topography (level) and vegetation type (Molopo Bushveld). The sampling sites (on each of the farms) of each treatment were placed approximately 500 m apart in areas that were representative of the landscape.

Table 2.1: General background information regarding the selected study areas within the Molopo Bushveld vegetation type.

Study areas location	Farm 1: Bray (Figure 2.1) Lat. (South): 25.38378 Long. (East): 23.38014	Farm 2: Bray (Figure 2.1) Lat. (South): 25.36234 Long. (East): 23.37437	Farm 3: Vorstershoop (Figure 2.1) Lat. (South): 25.81379 Long. (East): 22.8565	Farm 4: Severn (Figure 2.1) Lat. (South): 26.54924 Long. (East): 22.56828
Total sampling sites	AC: 4 sites BT: 4 sites	AC: 4 sites BT: 4 sites HC: 4 sites	BT: 3 sites SB: 3 sites SM: 3 sites	BT: 4 sites HC: 4 sites HC2: 4 sites
Land tenure type	Commercial game farming	Commercial cattle farming	Commercial cattle farming	Commercial cattle farming
Stock composition	Game Giraffe (browser) Oryx (grazer) Impala (grazer and browser) Kudu (browser) Blue wildebeest (grazer) Eland (grazer) Blesbok (grazer) Springbok (grazer) Buffalo (grazer) Sable (grazer) Zebra (grazer)	Cattle and horses	Cattle	Cattle
Current stocking rate	10 large stock units (LSU) per ha	10 LSU/ha	12 LSU/ha	10 LSU/ha

Grazing system	Open system – no camps (paddocks)	Four-camp rotational grazing system rotating every two weeks.	Eight-camp rotational grazing for nine days; resting period of 63 days per camp.	Six-camp rotational grazing with two camps resting for a whole growing season.
Chemical treatment with arboricide	Molopo CC granules were applied non-selectively in a grid formation by aeroplane (AC) at a dosage of 2.5–3 kg/ha. The size of the treated camp was 1 000 ha. The camps were treated in 2008/2009. The chemicals are reapplied every 10 years. This period falls outside of the project timeframe. Selected species: <i>Senegalia mellifera</i> , <i>Vachellia luederitzii</i> .	Molopo CC granules were applied non-selectively by AC and selectively by hand (HC) at a dosage of 3 kg/ha. The sizes of the treated camps were 245 ha. The camps were treated in 2008/2009. Selected species: <i>S. mellifera</i> , <i>V. luederitzii</i> , <i>Dichrostachys cinerea</i> , <i>Terminalia sericea</i> .	Stem burning (SB*) was first conducted in 1982. The second SB treatment was given in 1999/2000. Selected species: <i>S. mellifera</i> , <i>V. luederitzii</i> .	The double hand control sites (HC2) were treated in 2000 and followed up in 2012, at the start of the growing season (Oct./Sep.). Single hand control sites (HC) were treated in 2006. Molopo CC granules were used. The sizes of the treated camps were 240 ha and 260 ha for HC2 and 119 ha and 115 ha for HC. Species selected: <i>Rhigozum trichotomum</i> , <i>V. luederitzii</i> , <i>S. mellifera</i> .

***SB:** the act where the soil around the stem of a tree is removed and a fire is made next to the stem in order to burn the growth point of the tree.

***AC:** A non-selective approach of bush control where the arboricide is applied by means of aerial application.

***HC:** A selective approach of bush control where the arboricide is applied only to the unwanted species.

***BT:** Bush thickened sites. Areas with approximately 1500 TE/ha

***SM:** Areas where no chemical or biological bush control methods were applied. The bush densities were only controlled by grazing regimes.

2.3 General sampling approach

Before vegetation surveys were carried out at the sample sites, general information was collected at each site and documented on the data sheet. This included aspects such as:

- GPS coordinates of each transect at the sample sites, site number and date of survey,
- dominant plant species and vegetation type,
- land use,
- possible disturbances,
- general soil type and topography, and
- any other information that might help in the description of the area and the analysis of the data.

2.3.1 The landscape function analysis (LFA) methodology

The vegetation and soil sampling involved the LFA monitoring approach (Tongway and Hindley, 2004b). Two LFAs were conducted on 50 m transects at each site mentioned in Table 2.1. The starting points of the two transects were selected at random, approximately 30–40m apart, representing the identified methodology (bush-control treatments) in each study area (Table 2.1 and Figure 2.6).

The first step of the LFA included the landscape organisation (LO), where the “landscape” on the transect was divided into patch zones representing different obstacles that can trap resources (resource accumulating zones) and inter-patch zones (non-accumulating zones) (Tongway and Hindley, 2004a) (Figure 2.7). The transect was laid out in the direction of the water flow, i.e. from a higher to lower point on which resources can be trapped, and the patches identified on the gradient of the transect are commonly known as a gradsect (a *gradient* orientated transect) (Tongway and Hindley, 2004a). The size (width and length), nature and location of all the patches were then identified and documented on a prescribed data sheet (Tongway and Hindley, 2004a) (Figure 2.7).



Figure 2.6: Transects (50 m) were placed parallel to each other, approximately 30–40m apart, representing a certain methodology(Bush control treatment) in each study area.

The different patch types were identified and the soil surface assessment (SSA) was carried out in 3-5 query zones⁵ of the gradsets at each patch type. During the SSA, eleven indicators (Table 2.2) were assessed to determine the functioning of the patch types as a biogeochemical systems (Tongway and Hindley, 2004a). The 11 SSA indicators and a short description of the type of assessment carried out to determine the three parameters (stability, infiltration and nutrient cycling) – which are used to explain the functionality of the landscape – are given in Table 2.2 and Figure 2.8.

⁵ *Query zone: a representative part of the patch placed in the middle of the patch, not close to the boundary of the two patches.

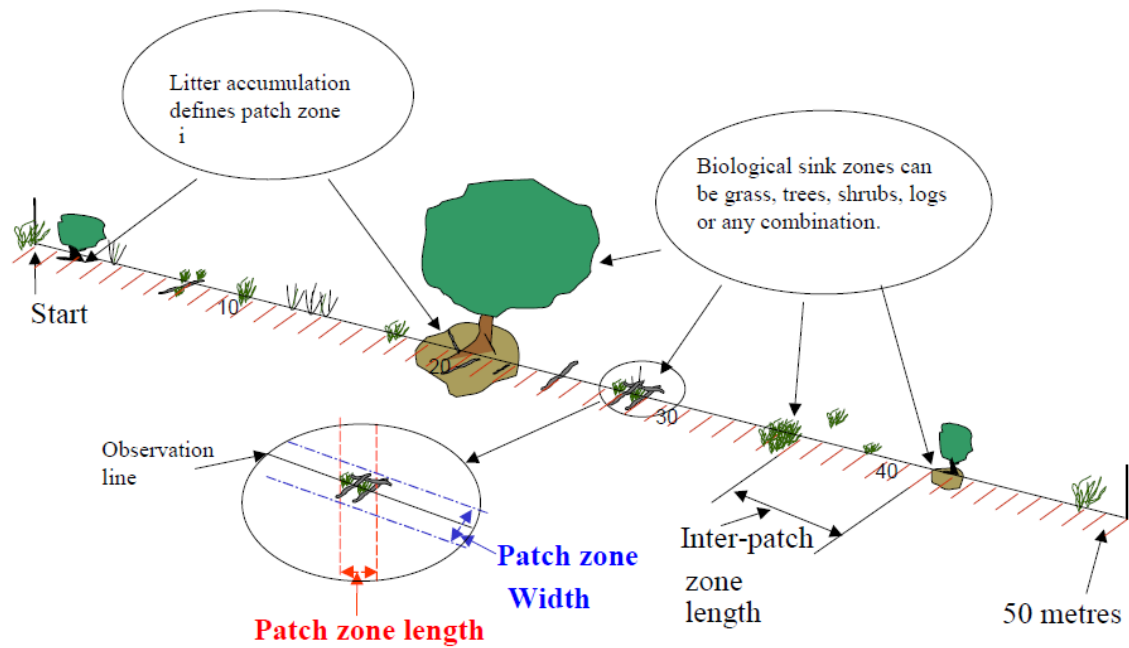


Figure 2.7: Landscape organisation by dividing the landscape on a transect into resource accumulating (patch zone) and non-accumulating (inter-patch zone) patches (taken from Tongway and Hindley, 2004a).

Some of the 11 indicators can contribute to more than one of the three main indices, i.e. stability, infiltration and nutrient cycling (Figure 2.8). The three main indices were identified for each patch type and compared for each applied methodology as mentioned in Table 2.1 over the two seasons sampled for this project (2015 and 2016).

Table 2.2: The eleven soil surface indicators used in the soil surface assessment (SSA) as part of the landscape function analysis to determine the infiltration, stability and nutrient cycling parameters of the soils (Tongway and Hindley, 2004b).

Soil surface indicators	Description
1. Rainsplash protection	Assesses the percentage perennial vegetation cover found in the query zone*, up to a height of 0.5 m; it also includes rocks >2 cm and woody material >1 cm.
2. Perennial vegetation cover	Estimates the basal cover of perennial grass species in the query zone and/or the density of the canopy cover of trees and shrubs found overhanging the query zone
3. Litter cover	Verifies the amount, origin and degree of decomposition of the organic litter found in the query zone. Litter is very important because it strongly relates to the amount of carbon, nitrogen and other elements found in the soil.
4. Cryptogam cover	Determines the amount of cryptogams (this includes fungi, moss, lichens, algae and liverworts) visible on the soils surface. Cryptogams are seen as indicators of stable soils with higher surface nutrient levels.
5. Crust brokenness	Evaluates the extent to which the surface crust is broken as well as the amount of loose soil material that can be transported out of the area and lead to erosion. "Crust" is defined as the layer of soil that overlies the sub-crust material.
6. Soil erosion type and severity	Assesses recent or current erosion in the query zone. The type of erosion referred

	to in this assessment is accelerated erosion that can be caused by climatic events rather than geologic erosion.
7. Deposited materials	Assesses the amount of alluvium found in the query zone. Deposited materials are seen as a sign of some instability in the landscape. Deposited materials consist of silts, sands and gravel and are mostly transported from upslope areas.
8. Soil surface roughness	Determines the roughness of the surface in the query zone. In so doing, estimations can be made as to the amount of resources that the area can capture.
9. Surface nature	Tests the amount of resistance the soil has to mechanical disturbances that can yield material suitable for erosion (by wind or water).
10. Slake test	Assesses the stability of the natural soil fragments and is conducted by placing a 1-cm cube of soil into a small bucket of water.
11. Texture	Classifies the texture of the surface soil and relates it to the permeability of the soil. This test only requires one measurement and can be done at the beginning of the assessment.

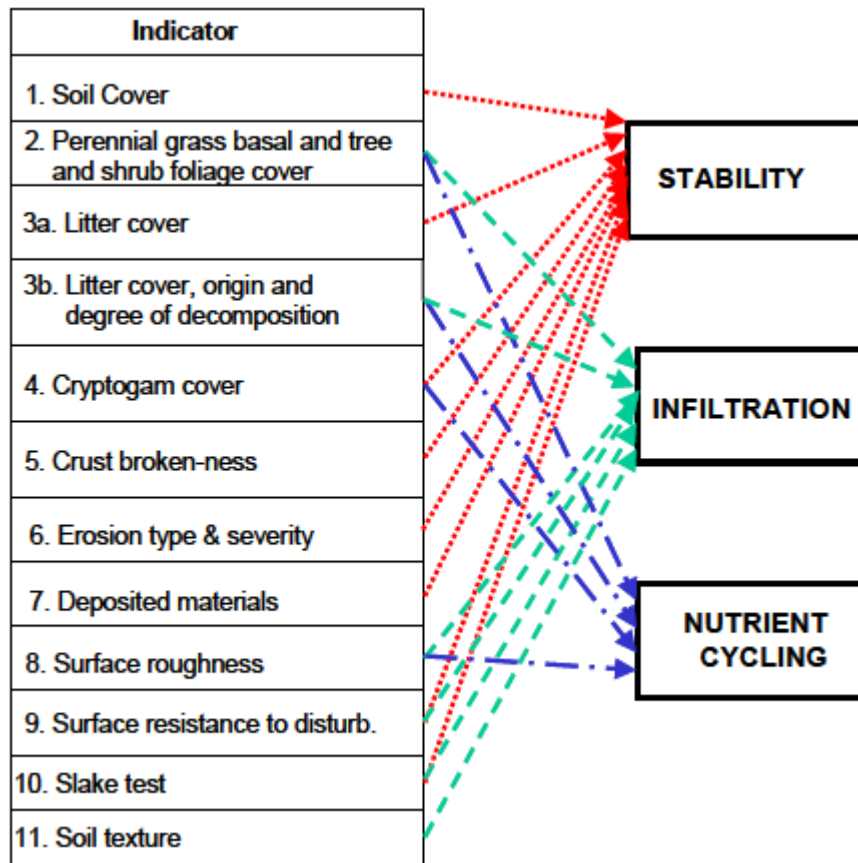


Figure 2.8: The eleven soil surface indicators used in the soil surface assessment and how each indicator contributes to the three main indices, i.e. stability, infiltration and nutrient cycling (taken from Tongway and Hindley, 2004a).

2.3.2 Patch description

The following patch types were identified on the transects in the two seasons (2015 and 2016) for each methodology: inter-patches (IPs), grass patches (GPs), grass litter patches (GLPs), litter patches (LPs), shrub litter patches (SLPs) and grass shrub patches (GSPs), with the addition of shrub patches (SPs) only in 2015. Short descriptions of the patch types and the possible flow of resources over the landscape are given below.

2.3.2.1. Inter-patch (IP)

An IP is classified as any patch under the line of the transect with no perennial plant material present that might obstruct nutrients or water (resources) from flowing out of the system (Tongway and Hindley, 2004b). Inter patches (IPs) can also be further described as zones where water, soil particles and litter are free to move either in the direction the wind is blowing or downslope, if the water's velocity is high enough to pick up and move materials or litter (Tongway and Hindley, 2004b). The IPs were also described to help distinguish between them, as not all IPs were alike. The IP shown in Figure 2.9 was classified as a “bare soil inter-patch” or “IP bare soil” due to the large exposed areas of soil. Other IPs included *Cucumis* IPs (Figure 2.10), referring to the annual creepers *Cucumis africanus* or *Acanthosicyos naudinianus* found under the line of the transect. These creepers did, however, not trap any resources (e.g. water).

The *Cucumis* IPs obstruct more material from exiting the landscape than the bare soil IPs, which will result in higher amounts of nutrients present in the patches. These differences will not be large, but just enough to make a difference. *Cucumis* IPs were mostly found in the controlled areas between the grass tufts (Figure 2.10), whereas the bare soil IPs were more common in the encroached sites.



Figure 2.9: An example of an inter-patch (IP), in this case IP bare soil, with arrows indicating the direction in which water will flow through the patch (Photo: JH Fouche).



Figure 2.10: A *Cucumis* inter-patch found between two grass tufts, with the red line indicating the extent of the patch (Photo: JH Fouche).

2.3.2.2. Grass patch (GP)

The grass patches (GPs) identified in this study all contained perennial grass species, characterised by a deep root system. Annual grass tufts were not included in GPs, as they do not contribute enough to landscape stability, infiltration and nutrient cycling (Tongway and Hindley, 2004b). A GP can either be a single tuft of grass (Figure 2.11) or a combination of perennial grasses dominant in the landscape, forming a unit where resources are trapped (Figure 2.12). Figure 2.11 indicates a typical GP, characterised by the dominant perennial grass species found in the study area, namely *Stipagrostis uniplumis*, a semi-palatable perennial grass tuft found in semi-arid to arid areas of southern Africa (Van Oudtshoorn, 2012).



Figure 2.11: Example of a grass patch mostly found in the controlled areas with red lines indicating the dimensions to distinguish the patch from its surroundings (Photo: JH Fouche).



Figure 2.12: A group of perennial grass patches forming a single large patch, with the red lines indicating the dimensions of the patch (Photo: JH Fouche).

Some of the litter and nutrients transported by rain water will be deposited close to the base of the grass tufts, making GPs very valuable in semi-arid rangelands. The larger and denser grass patches will have nearly no flow of resources (e.g. water) through the patch (Tongway and Hindley, 2004). Most resources are transported around the GP (Figure 2.12). Larger, denser GPs will reduce the amount of nutrients transported out of the area.

2.3.2.3. Grass litter patch (GLP)

GLPs are combinations of dead plant material like branches and dead grass patches (litter) and any perennial grass tufts (actively growing). An example of a GLP can be found in Figure 2.13, showing the living tufts of *Stipagrostis uniplumis* and litter from branches of trees. Both the grass tufts and the tree branches acted as resource retaining zones. The resources trapped by this patch are used to enrich the soil surrounding the patch (Tongway and Hindley, 2004b).



Figure 2.13: Example of a grass litter patch found throughout all the sites. The red lines visible in the figure indicate the dimensions of the GLP patch type (Photo: JH Fouche).

2.3.2.4. Litter patch (LP)

LPs are characterised by dead vegetation, mostly formed by woody biomass in areas where bush thickening has occurred. LPs showed the most variation and included patches containing dead tree branches (Figures 2.14 and 2.15a) and patched with dead grass (Figure 2.15b). LPs trap resources, especially water and nutrients (Tongway and Hindley, 2004b). The possible flow of resources around LPs is shown in Figure 2.16.

Larger LPs (Figure 2.14) trap the most resources, including seed, and act as fertile islands, which aid the establishment of new tree seedlings or grass tufts. Smaller LPs, characterised by loosely arranged litter material (Figure 2.15a and 2.15b), only decrease the speed at which the resources flow through the landscape, without trapping large amounts of nutrients and water, especially before they decompose.



Figure 2.14: Example of a litter patch. The red lines visible in the figure indicate the dimensions of the LP patch type (Photo: JH Fouche).

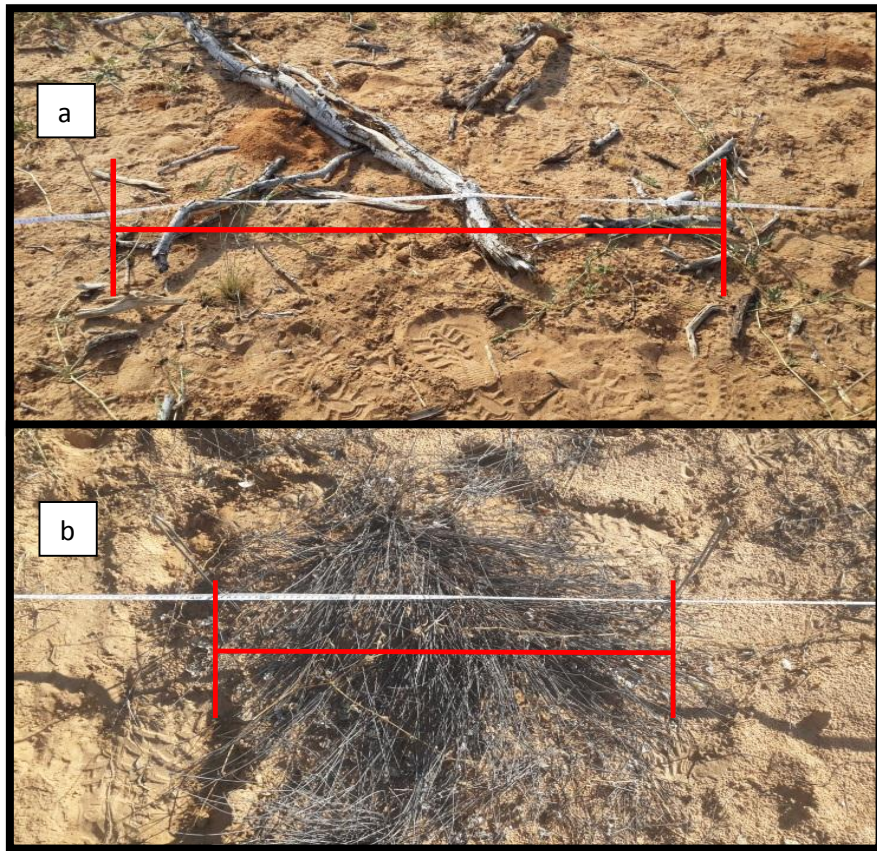


Figure 2.15: Loose-lying branches of woody material (a) and dead grass (b), forming litter patches (LPs). The dimensions of the LPs on the transect are indicated by the red line (Photo: JH Fouche).

2.3.2.5. Shrub patch (SP)

Most of the SPs identified in this study were characterised by woody trees and/or shrubs of *Senegalia mellifera* (e.g. Figure 2.16), *Vachellia luederitzii* and *Dichrostachys cinerea*. SPs included small shrubs from a height of 30 cm to taller trees (>2 m) (Figure 2.17). Shrubs were classified as woody plants with one or more stems, independent of their height class.

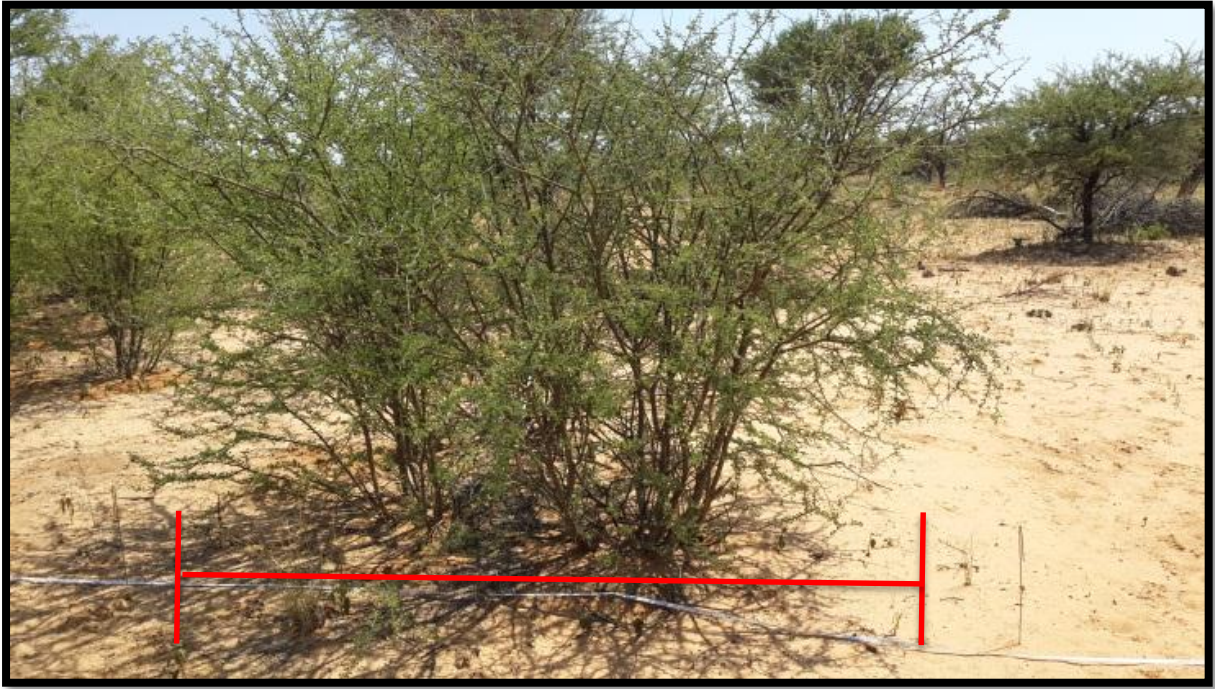


Figure 2.16: Example of a shrub patch (SP) characterised by living trees and/or shrubs. The dimensions of the SP on the transect are indicated by the red lines (Photo: JH Fouche).



Figure 2.17: Taller tree species (>2 m) were also classified as shrub patches with the red lines indicating the extent of the patch on the transect (Photo: JH Fouche).

2.3.2.6. Shrub litter patch (SLP)

Many of the SPs had various types of litter underneath them, ranging from dead grass to small branches. All these patches were classified as SLPs (Figure 2.18). As in the case of SPs, the woody shrub species that characterised SLPs included *S. mellifera*, *V. luederitzii* and *D. cinerea*.



Figure 2.18: An example of a shrub litter patch, including living woody shrub and litter. The dimensions of the SP on the transect are indicated by the red lines (Photo: JH Fouche).

2.3.2.7. Grass shrub patch (GSP)

GSPs were characterised by woody shrubs with grass growing underneath (Figure 2.19). The shrubs occurring in these patches were mostly *Grewia* spp.; the root systems of these shrubs are more deeply rooted, allowing grasses to grow under the shrub. The shrubs also act as defence mechanisms, protecting the grass tufts against herbivory and high temperature.



Figure 2.19: Example of a grass shrub patch, with the red lines indicating the extent of the patch under the transect (Photo: JH Fouche).

2.3.3 Soil analysis

After the completion of the LO, the two most dominant patch types were identified on each transect. Three soil samples were then taken up to a depth of 5 cm at each patch. The three samples were combined to form a composite sample. Litter was not included in the soil sample.

The soil samples were analysed to determine the levels of soil macro-elements, namely C, P, N, Mg and Ca, as well as soil micronutrients such as copper (Cu), zinc (Zn) and manganese (Mn), at the Eco-Analytica laboratory in Potchefstroom, South Africa⁶. Other parameters that were analysed included the soil pH (KCl), the C-to-N ratio (C/N), cation exchange capacity (CEC), organic matter (OM), electrical conductivity (EC).

⁶ Eco-Analytica - North-West University: PO Box 19140, Noordbrug, 2522. Tel: 018 293 3900.

Chapter 3

Effect of bush density and different control methods on landscape functionality

3.1 Introduction

Bush thickening or an increase in woody species densities (also called “bush encroachment”) has been blamed for decreased ecosystem functioning for many years by various scientists (Ludwig and Tongway, 1997; Richter *et al.*, 2001; Barac, 2003; Smit, 2005; Archer, 2010; Kgosikoma *et al.*, 2012; Harmse, 2013; Gray and Bond, 2013; Bezuidenhout *et al.*, 2015). However, this perception has been challenged by Maestre and Cortina (2004), Breshears (2006), Maestre *et al.* (2009), Daryanto *et al.* (2013), Eldridge and Soliveres (2014) and Eldridge *et al.* (2015), who found that increased woody densities can improve overall soil quality and infiltration, if the density is limited.

Studies conducted on the effect of bush thickening on the three main indices measured by landscape function analysis (LFA), namely stability, infiltration and nutrient cycling, found that infiltration and nutrient cycling under the canopy of woody species were significantly higher than in open patches (between shrub patches). Daryanto and Eldridge (2010) also found that infiltration, nutrient cycling and stability were higher under woody species and log mounds characterised by dead woody material (referred to as litter patches in this study). Furthermore, recovery rates of landscapes with limited densities of woody species present were faster than that of grassland areas where no woodies were present. It must be emphasised, however, that the latter two findings will differ according to the climatic, soil and type of species in the study areas.

Literature shows that no LFA studies have been conducted in the Molopo region. Studies that have been conducted in the region concentrated on the effect of increased *Senegalia mellifera* densities on the change in biodiversity (herbaceous and woody

diversity and densities) (Richter *et al.*, 2001; Smit, 2004). These studies found that if *S. mellifera* densities surpassed 350 TE/ha, an exponential decline in herbaceous diversity and production can be expected (Richter *et al.*, 2001; Smit, 2004). Richter *et al.* (2001) and Harmse (2013) also found that *S. mellifera* densities of >2000 TE/ha can suppress herbaceous production for a long time. The aggressive root system of *S. mellifera* shrubs also limit the increase in densities of other woody species in the area (Nxele, 2010).

These negative effects of increased *S. mellifera* densities have forced farmers to find different ways to keep this species from thickening, as herbaceous species, especially palatable, climax grasses, are suppressed if this woody species is not controlled. Control measures include active methods, such as stem burning, which entails the removal of soil surrounding the stem of the targeted tree and making a fire next to the stem with dung and/or woody branches to ringbark the tree, thereby killing it. This is a very labour-intensive method but does not involve any chemical herbicides that may pollute the soil substrate (personal communication, Mr Pierre Bruwer, 2015⁷).

On the other hand, other farmers follow chemical control methods, which can be applied selectively (by hand) or non-selectively (by aeroplane) (Richter *et al.*, 2001; Harmse, 2013; Harmse *et al.*, 2016). The most common arboricide used in the Molopo region is Molopo CC, a granular-based arboricide with the active ingredient Tebuthiuron (Du Toit and Sekwadi, 2012; Harmse, 2013; Bezuidenhout *et al.*, 2015; Harmse *et al.*, 2016). Tebuthiuron is a systemic arboricide that needs to be applied close to the stem of the plant where it can be absorbed by the roots (Chang and Stritzke, 1977; Du Toit and Sekwadi, 2012; Harmse *et al.*, 2016). This arboricide affects the plant's electron transport system at photosystem II between Q and plastoquinone (Du Toit and Sekwadi, 2012). Tebuthiuron also affects the mechanism that helps with water oxidation, which is caused by the inhibition of the photosynthetic electron transport system (Hatzios *et al.*, 1980). In so doing, Tebuthiuron stops the plant from photosynthesising, which ultimately leads to its death (Hatzios *et al.*, 1980; Du Toit and Sekwadi, 2012).

⁷ Pierre Bruwer. Farmer. Farm: Lafras, Molopo region, North West Province.
Tel: 082 784 6386.

In this study, the LFA monitoring methodology was used to assess the effects of arboricide application as a method of woody control on the changes in soil and vegetation parameters.

3.2 Materials and methods

As described in Chapter 2, the LFA methodology was used on all four farms studied in the Molopo region to determine the stability, infiltration and nutrient cycling in patches in bush-controlled and bush-thickened (BT) sites in order to compare the functionality of these sites. LFA indices were determined by the LFA SSA Data Entry Sheet V3.0 developed by Tongway and Hindley (2004). Additional information such as location and transect orientation was recorded by GPS to ensure that the 2015 and 2016 surveys were carried out at the same positions for better comparison of the landscape functionality during the two years of study and long-term follow-up monitoring.

Six to seven patch types were identified on the transects in the two seasons for the LFA SSA analysis (Table 3.1):

Table 3.1: Patch types and abbreviations identified for the landscape function analysis SSA during the 2015 and 2016 surveys.

Year	Patch types identified						
2015	Inter-patch (IP)	Grass patch (GP)	Litter patch (LP)	Grass litter patch (GLP)	Shrub litter patch (SLP)	Shrub patch (SP)	Grass shrub patch (GSP)
2016	IP	GP	LP	GLP	SLP	-	GSP

The drought experienced in the 2015/2016 summer season in the Molopo region (Cho, 2016; Engelbrecht and Engelbrecht, 2016) had an effect on the different patch types identified, the frequency of resources accumulating in the patches and the general length and width of all the identified patches. The drought also influenced the results of the study, which are discussed in more detail in Chapter 5. The data and results of the soil samples collected at each of the transects are discussed in Chapter 4.

The three main indices obtained by the LFA methodology (stability, infiltration, nutrient cycling), as well as the landscape organisational index (LOI) mentioned in Table 3.2, were used to compare and analyse the effect of bush densities and different control methods on the functional and structural components of Molopo savanna landscapes. A Wilcoxon test was conducted to analyse the LOI and three LFA indices to determine whether their distribution is structured (parametrical) or unstructured (non-parametrical). STATISTICA software was then used to perform a mixed model analysis to determine whether there were any significant differences between these indices at the various control treatments. CANOCO software (version 4.5) was further used to conduct multivariate analyses to determine whether associations could be found between the LFA indices, LOI, bush density and structural complexity of the woody species (Ter Braack and Smilauer, 2002).

3.3 Results

3.3.1 LFA indices

The results from the LFAs conducted at the various study sites are summarised in Table 3.2. The table contains the cumulative scores of the three LFA indices (stability, infiltration and nutrient cycling) and the LOI for both survey years. If the three LFA indices that are scored out of a hundred (and can be interpreted as percentages) are regarded as the scores for the surveys conducted in 2015 and 2016, it can be seen that they are low, ranging from 12 to 49 (Table 3.2). The stability index had the highest overall scores of the three indices followed by infiltration and nutrient cycling. Therefore, the stability index had the biggest influence with regards to the overall functioning of the area. This is also illustrated in Figures 3.1 and 3.2, where the overall contribution of the different LFA indices are shown for bush-controlled (BC) and BT sites at the various study areas. The stability of the BC and BT sites varied between 41 and 49, with infiltration and nutrient cycling having scores of 34–38 and 12–18 respectively (Table 3.2). The LOI is an index used to express the structure of the landscape by determining the patch: inter-patch ratios. The LOI is scored from 0 (an area with no patches) to 1 (an area consisting of one large patch). Therefore the closer the LOI of a landscape is to 1, the higher the portion of the landscape that is covered in patches or nutrient-accumulating zones.

Table 3.2: Results of the landscape function analysis (LFA) transects, showing the cumulative scores for the LFA indices and the landscape organisational index (LOI) for the 2015 and 2016 surveys at the different study sites.

Treatment*	LOI 2015	LOI 2016	Stability 2015	Stability 2016	Infiltration 2015	Infiltration 2016	Nutrient cycling 2015	Nutrient cycling 2016
ACG	0.17	0.30	42	43	34	36	12	14
BTG	0.28	0.31	44	44	34	36	13	15
ACK	0.24	0.33	44	42	35	37	14	14
HCK	0.25	0.26	43	41	35	36	13	14
BTK	0.22	0.27	42	42	35	36	12	13
BTB	0.42	0.35	43	44	36	38	14	16
SBB	0.51	0.32	43	41	35	37	14	14
SMB	0.28	0.29	44	44	35	36	14	14
HCO	0.25	0.32	45	43	37	37	15	15
2HCO	0.27	0.38	48	45	36	37	16	16
BTO	0.31	0.29	48	49	38	37	17	18

*See p. xiii for a list of abbreviations for treatments

The statistical analyses showed that the scores for the LFA indices over the two sampling years were parametrical, which made it possible to conduct a mixed model analysis to determine whether there were any statistical differences in the LFA indices between the various treatments. The results from the mixed model analysis showed that differences in stability, infiltration and nutrient cycling indices for the different treatments (AC, HC, 2HC, SB, SM and BT – see list of abbreviations on p. xiii) at the various sites were not significant ($p > 0.05$).

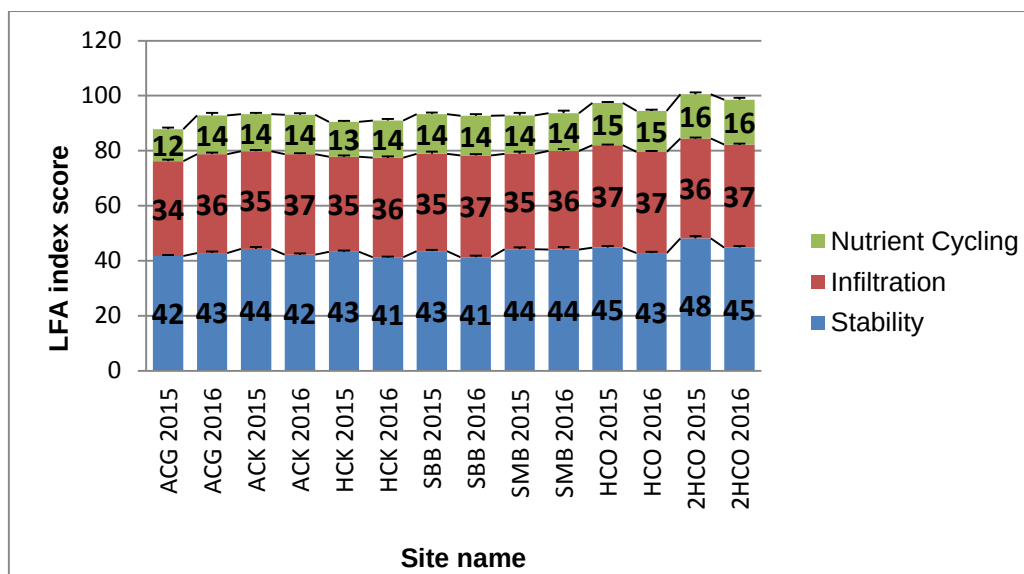


Figure 3.1: The average scores of the three landscape function analysis (LFA) indices for all the bush-controlled sites for both survey years (2015 and 2016). The standard error is indicated by error bars. No significant differences were found between any of the LFA index scores for the various treatments ($p>0.05$). See p. xiii for a list of abbreviations for treatments.

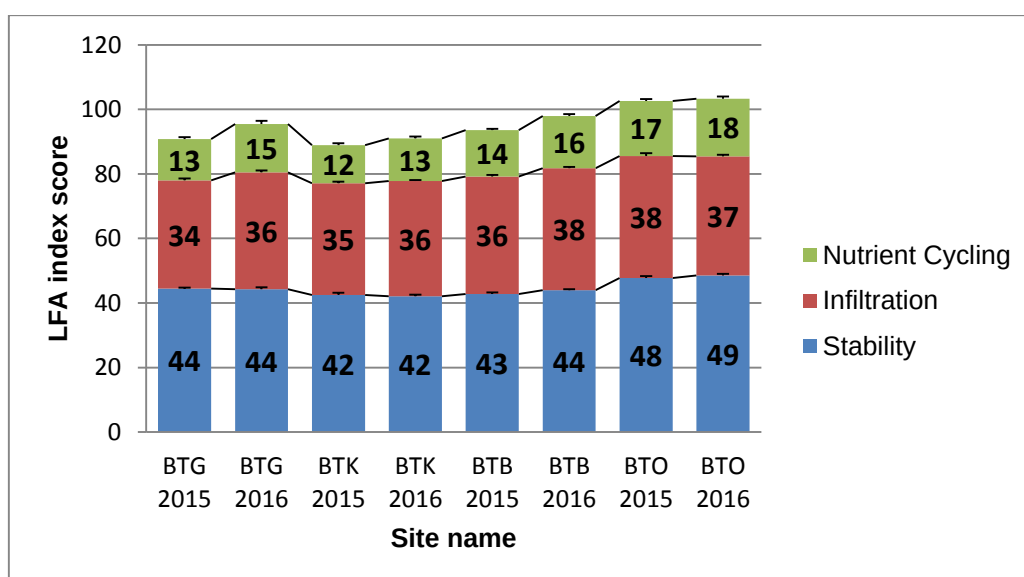


Figure 3.2: The average scores of the three landscape function analysis (LFA) indices for all the bush-thickened sites (BT) for both survey years (2015 and 2016). The standard error is indicated by error bars. No significant differences were found between any of the LFA index scores for the various BT sites ($p>0.05$). See p. xiii for a list of abbreviations for treatments.

The 2HCO sites recorded the highest mean stability scores of the BC sites in 2015 with a mean score of 48, but it decreased to a score of 45 in 2016, lowering its overall mean to 46.5, which was not significantly higher than the mean stability scores of the

other BC sites (Figure 3.1). Stability of the BT sites at the same location (BTO) were also higher than that of the other BT sites, with a mean stability of 48.5 over the two survey years. The stability at the other BT sites (BTG, BTK and BTB) had scores of 44, 42 and 43.5, respectively (Figure 3.2). These differences in the stability of the BT sites were also not significantly higher than that of any of the BC or other BT sites ($p>0.05$). This was an unexpected result, especially with the large inter-patches (IPs) found in most of the BT sites (Figure 3.3).



Figure 3.3: Example of a bush-thickened site at one of the survey areas (BTG) surveyed in 2015 with very large inter-patches and shrub litter patches. Almost no other patches were identified on this transect.

Although the IPs were large (Figure 3.3), the stability index was high (Table 3.2, Figures 3.1 and 3.2). This could mainly be ascribed to the roots of the woody species causing the thickening that helps to maintain the stability of the areas and the formation of a thin crust on the topsoil, reducing the risk of erosion. The canopy of the thickening woodies also reduces wind speeds, limiting the amount of top soil lost through wind erosion.

The infiltration scores of the different BC and BT sites were also similar with no significant differences ($p>0.05$). Although the mean infiltration score for both the ACG and BTG sites was 35, it was only 2.5 units lower than the sites sampled at BTO, which

had a mean score of 37.5 (Figures 3.1 and 3.2). This result was again unexpected and differs from the hypothesis that states that larger IPs, such as those found in the BT sites, would increase the rate of water and nutrient flow out of the system, leading to lower infiltration rates as a result of the lack of patches that can slow down the flow of resources.

The nutrient cycling of the BC and BT sites followed the same trend as that of the stability index, with the 2HCO and BTO sites scoring higher stability values than the other sites (Figures 3.1 and 3.2). The mixed model analysis indicated that the BTO sites had the highest mean nutrient cycling score (17.5) followed by the 2HCO sites (16). The BTK sites (Figures 3.1 and 3.2) had the lowest mean nutrient cycling score (12.5) but it was still not significantly different from the other BC or BT sites ($p > 0.05$). The nutrient cycling scores were similar due to the high amounts of litter found in all the BC and BT sites. The BT sites had a high occurrence of cryptogams, which could have contributed to the overall increase in nutrient cycling of these sites. These nutrient cycling scores coincided with the studies of Donaldson and Kelk (1970), Dougill *et al.* (1998), Thomas *et al.* (2002) and Wang *et al.* (2007) in that the soils of the Molopo region have very low nutrient and organic matter levels.

A principal component analysis (PCA) ordination was carried out to determine the association between BC and BT sites in the two sampling years (Figure 3.4).

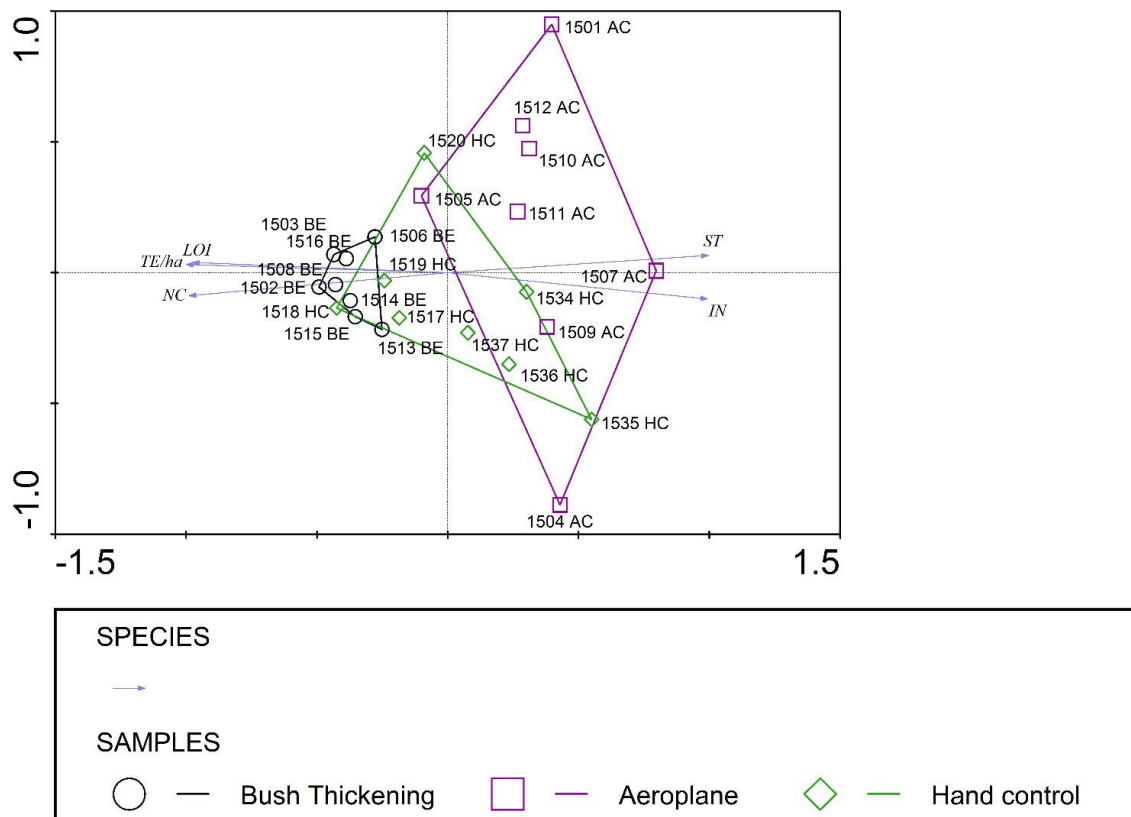


Figure 3.4: Principal component analysis (PCA) biplot indicating how the bush-thickened and bush-controlled sites were associated with regards to the landscape function analysis index scores. The bush density is indicated by tree equivalents per hectare. The Eigen-value of the x-axis is 0.621 and that of the y-axis 0.379. The environmental factors are regarded as “species” in the PCA ordination biplot. See p. xiii for a list of abbreviations for treatments.

The data used for the PCA analysis (Figure 3.4) included the three LFA indices, the LOI and the TE/ha for the ACG (1501, 1504, 1505, 1507), ACK (1509–1512), HCK (1517–1520), HCO (1534–1537), BTG (1502, 1503, 1506, 1508) and BTK (1513–1516) sites surveyed in 2015⁸ (Tables 3.2 and 3.3). The TE/ha data were obtained from another study conducted at the same sites by Van Rooyen (2016). These six sites were chosen for comparison because of their uniform bush densities and structure.

There is a clear gradient on the x-axis from the left (BT sites), indicating high indices for nutrient cycling and LOI as well as higher bush densities (TE/ha) to the right, which characterise sites controlled by aeroplane (AC) and correlated with higher stability and infiltration indices (Figure 3.4). Sites that were controlled by hand (HC) are grouped between the BT and AC sites on the x-axis gradient. This clear grouping of sites

⁸ Only 2015 data were used in the analysis as Mr. Sampie van Rooyen’s sampling was concluded in 2015.

indicates that some differences were detected in the LFA indices regarding BT and BC sites sampled in 2015.

The higher LOI scores of the BT sites can be ascribed to the size difference and frequency of the dominant patches (nutrient-accumulating patches, NAPs) found for the different treatments. The dominant NAPs at the BT sites were shrub litter patches (SLPs), which were much larger than any of the other NAPs identified for the other treatments, namely the grass litter patches (GLPs) and grass shrub patches (GSPs), the dominant NAPs at the AC and HC sites, respectively. The higher nutrient cycling scores at the BT sites may be due to the high amount of litter found beneath the trees, as well as the high cryptogam densities (characterising biological soil crusts) found beneath *S. mellifera* and *Grewia flava* shrubs.

The AC sites were associated with stability and infiltration indices (Figure 3.4). This association can be ascribed to the low LOI and TE/ha scores of the three treatments, explaining why the AC sites are on the opposite side of the x-axis gradient (Figure 3.4, Tables 3.2 and 3.3). This association does not indicate higher scores but rather a strong dissociation to the LOI and TE/ha scores. The HC sites were grouped between the BT and AC sites, which strengthens the notion that BC methods should be more selective, e.g. control by hand (HC), as this will have the least impact on the environment (Harmse *et al.*, 2016). The TE/ha of the HC sites were on average almost double that of the AC sites and almost half of that of the BT sites (Figure 3.4, Table 3.3).

In a second PCA ordination, the height classes for the woody species that were measured at the sites, as mentioned above by the study of Van Rooyen (2016) in 2015, was also included (Figure 3.5). The same information as that used for Figure 3.4 was used here, as were the height class information given in Table 3.3. The PCA biplot (Figure 3.4) shows a clear gradient from AC sites on the left to BT sites on the right on the x-axis (Figure 3.5). The HC sites were also between the AC and BT sites on the x-axis gradient. Except for the stability and nutrient cycling indices, the same environmental factors characterised BT (TE/ha and LOI) and AC (infiltration) sites (compare Figures 3.4 and 3.5). These associations could also be attributed to the larger SLP patches found at most of the BT sites and the high densities of cryptogams found beneath most of the SLP.

Five of the six height classes of the woody species (≤ 0.5 m, >0.5 – 1 m, >1 – 2 m, >2 – 3 m and >3 – 5 m) were strongly associated with BT sites and higher woody density (TE/ha), which could have resulted in the higher stability scores (Figure 3.5). The >5 m height class was the only height class that indicated a strong association with the HC sites (Figure 3.5, Table 3.3). The higher tree densities of the larger trees (>5 m) coincides with the farmers' vision of keeping the large trees in this selective chemical control method, e.g. *Vachellia erioloba* or *Boscia albitrunca* trees, as they are good fodder and shade trees both for livestock and game animals.

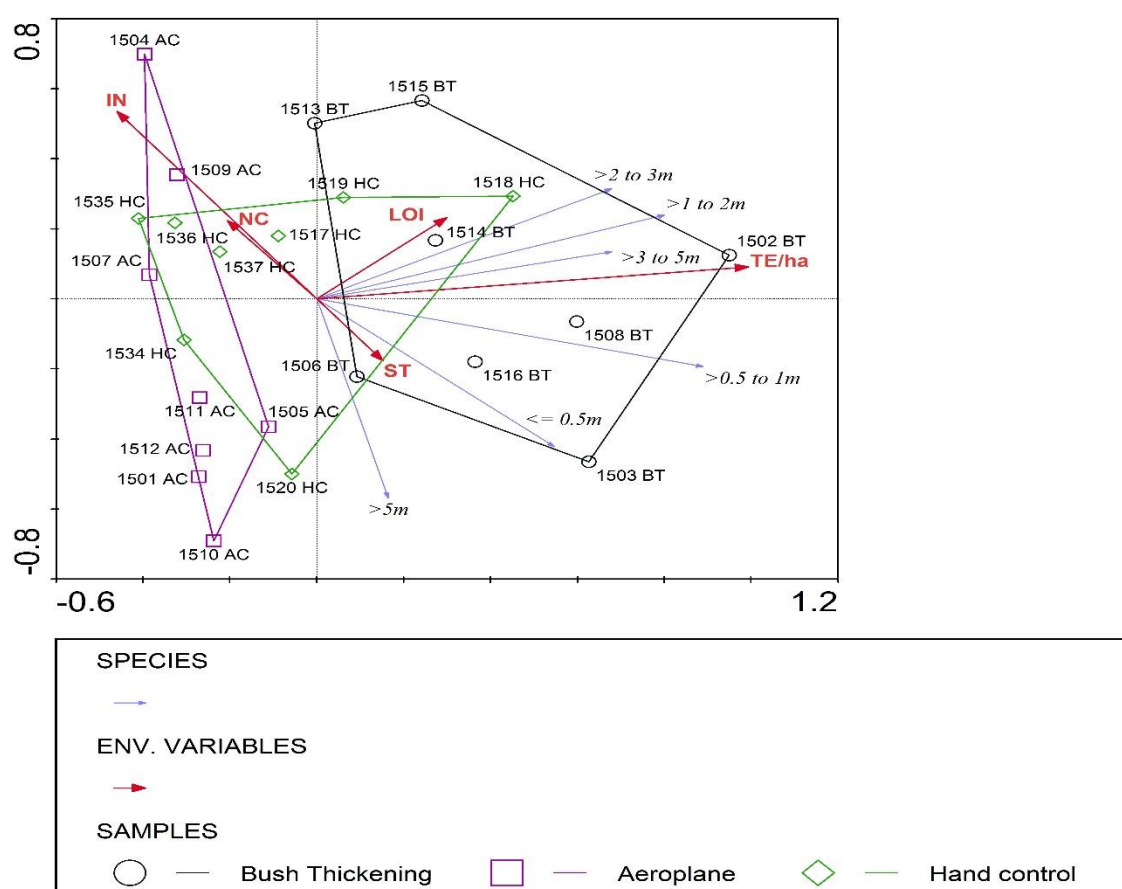


Figure 3.5: Principal component analysis (PCA) biplot containing landscape function analysis indices of two different bush control methods (six sites each) and of six bush-thickened (BT) sites and how they responded to the different height classes of woody species found at these sites. The Eigen-value of the x-axis was 0.447 and that of the y-axis 0.119. The environmental factors are regarded as “environmental variables” and the height classes as “species” in the PCA ordination biplot. See p. xiii for a list of abbreviations for treatments.

An interesting result was that high seedling densities occurred at the BT sites as no BC technologies were applied (Table 3.3). It was expected that the lack of precipitation and inter-species competition would limit the establishment of seedlings in the BT sites, especially during the 2015/2016 drought. This shows that the strong and deep

root system of the small trees species are able to reach the deeper soil moisture levels (Bond and Midgley, 2000; Nxele, 2010). The higher tree densities of the >5 m and ≤0.5 m height classes in the AC sites highlight the fact that a follow-up treatment will be necessary to prevent the re-thickening of the AC sites, as the study sites were treated more than 10 years ago (Table 3.3). It seems that the high densities of larger *B. albitrunca* trees (>5 m) is a result of these trees showing some resistance towards the arboricides used for AC application (Table 3.3). This occurrence could also explain why most of the AC sites are grouped on the left of the a-axis and wide spread on the y-axis (Figure 3.5).

The shrubs within the >1–2 m height class was the most dominant in the HC sites (Table 3.3). This high density was the result of the dominance of *G. flava* shrubs at most of the HC sites especially on one of the farms where the study was carried out. *Grewia flava* has an average height of between 1 and 2 m, rarely growing taller than 4 m (Venter and Venter, 1996).

The infiltration index was strongly associated with the AC and HC sites, especially the former because of the sandy soil types and absence of trees and shrubs (Figure 3.5).

Table 3.3: Landscape function analysis indices, landscape organisational index (LOI), tree equivalents per hectare (TE/ha) and height classes of selected sites sampled in 2015 used for multivariate analyses. TE/ha and height class data were taken from Van Rooyen (2016). The three highest and lowest values per height class are highlighted in dark grey and light grey respectively. See p. xiii for a list of abbreviations for treatments.

Treatment	Stability 2015	Infiltration 2015	Nutrient cycling 2015	LOI 2015	TE/ha	Number of individuals per height Classes (m)					
						≤0.5	>0.5 to 1	>1 to 2	>2 to 3	>3 to 5	>5
1501 AC	41.43	32.16	10.71	0.15	292.28	781.50	78.15	15.63	0.00	31.26	0.00
1504 AC	42.48	37.66	13.73	0.23	300.62	296.97	78.15	46.89	15.63	46.89	0.00
1505 AC	40.59	32.34	9.80	0.08	540.59	1328.55	203.19	31.26	0.00	15.63	15.63
1507 AC	42.43	35.47	12.46	0.20	225.07	187.56	156.30	31.26	0.00	31.26	0.00
1509 AC	43.25	36.32	13.49	0.28	313.64	547.05	109.41	0.00	0.00	31.26	15.63
1510 AC	47.12	36.62	15.10	0.27	353.24	422.01	187.56	0.00	15.63	0.00	31.26
1511 AC	44.19	35.45	13.54	0.22	352.72	265.71	31.26	15.63	0.00	78.15	15.63
1512 AC	42.66	33.61	11.95	0.17	334.45	375.12	46.89	31.26	0.00	31.26	31.26
1502 BT	44.35	32.88	13.34	0.33	1955.78	1391.07	781.50	422.01	125.04	265.71	15.63
1503 BT	44.78	33.13	12.06	0.25	1459.84	1140.99	640.83	312.60	31.26	156.30	31.26
1506 BT	41.61	32.68	10.65	0.16	803.38	328.23	390.75	281.34	78.15	31.26	15.63
1508 BT	46.96	35.78	14.93	0.37	1472.87	547.05	593.94	640.83	171.93	31.26	15.63
1513 BT	42.18	35.51	12.68	0.23	767.95	171.93	62.52	281.34	93.78	109.41	0.00
1514 BT	42.27	34.58	11.51	0.17	1104.52	359.49	312.60	296.97	203.19	93.78	0.00
1515 BT	42.58	35.76	11.60	0.25	1047.73	343.86	156.30	343.86	218.82	93.78	0.00
1516 BT	42.80	32.85	11.51	0.22	1156.62	718.98	484.53	375.12	156.30	62.52	0.00
1517 HC	42.03	35.27	12.26	0.15	661.11	359.49	234.45	312.60	46.89	0.00	0.00
1518 HC	43.05	34.59	12.88	0.23	1363.07	265.71	265.71	375.12	62.52	31.26	0.00
1519 HC	44.22	35.50	13.51	0.35	770.87	125.04	156.30	296.97	93.78	0.00	0.00
1520 HC	43.64	33.12	12.14	0.25	551.26	656.46	250.08	234.45	62.52	0.00	0.00
1534 HC	45.33	36.91	15.24	0.26	347.92	162.50	162.50	175.00	12.50	12.50	0.00
1535 HC	43.32	36.81	14.58	0.21	272.08	87.50	87.50	150.00	12.50	12.50	0.00
1536 HC	44.25	36.87	15.35	0.27	365.83	0.00	50.00	187.50	50.00	25.00	0.00
1537 HC	46.39	38.14	16.13	0.34	459.17	100.00	112.50	287.50	12.50	12.50	12.50

The functionality indicated by the three main LFA indices for the BT, AC, HC, SB and SM sites in this study were all similar and not significantly different ($p>0.05$). This result was unexpected, especially regarding the dominance of SLPs and IPs in the BT sites (Figure 3.3) and the low stability of the BC sites, even if they were dominated by high coverage of grass and forbs. However, it seems that more BT sites in the Molopo region improved or retained stability of the soil by preventing erosion (e.g. by reducing wind speeds and stabilising of the soil with their well-developed root systems). Similar findings were found for the infiltration and nutrient cycling in the BT sites. It was expected that higher tree densities would extract most of the nutrients from the soil, reducing the nutrient content and the infiltration of the area (Hagos and Smit, 2005). This expectation was also proven incorrect especially under some of the smaller *S. mellifera* and *G. flava* shrubs, where high densities of cryptogams were identified, which indicated higher soil nutrients and infiltration rates (see Chapter 4). The high woody densities in the BT sites also increased the LOI in the BT sites, leading to higher functionality scores and the sparse distribution of perennial GPs in most of the AC and HC sites, which led to lower LOI scores. Overall functionality of these sites could also be attributed to the drought.

3.3.2 Patch type distribution

This part of the chapter focusses on the LOI of the various BC and BT sites (Table 3.2). The LOI score in Table 3.2 is the mean for all LFA transects at each site over both survey years (2015 and 2016). The LOI was calculated by the LFA SSA Data Entry Sheet V3.0 developed by Tongway and Hindley (2004). The LOI as mentioned before is an index developed to inform the user of the LFA and indicates what fraction of the transect is made up of patches or nutrient-accumulating zones. The overall LOI of the surveys conducted over 2015 and 2016 were low, with the SBB sites in 2015 achieving the highest mean score of 0.51 (Table 3.2). This means that only 51% of the transects conducted in the SBB sites in 2015 were made up of patches (nutrient-accumulating areas) and that 49% were made up of IPs, with no or little obstructions to accumulate resources (Table 3.2).

The LOI of the transects at the remaining sites scored much lower, indicating that the areas were dominated by IPs mainly characterised by bare soil (Table 3.2, Figure 3.6).

The ACG sites had the lowest LOI scores of all the sites (Figure 3.6), with a mean score of only 0.24 compared to 0.41 of the SBB sites.

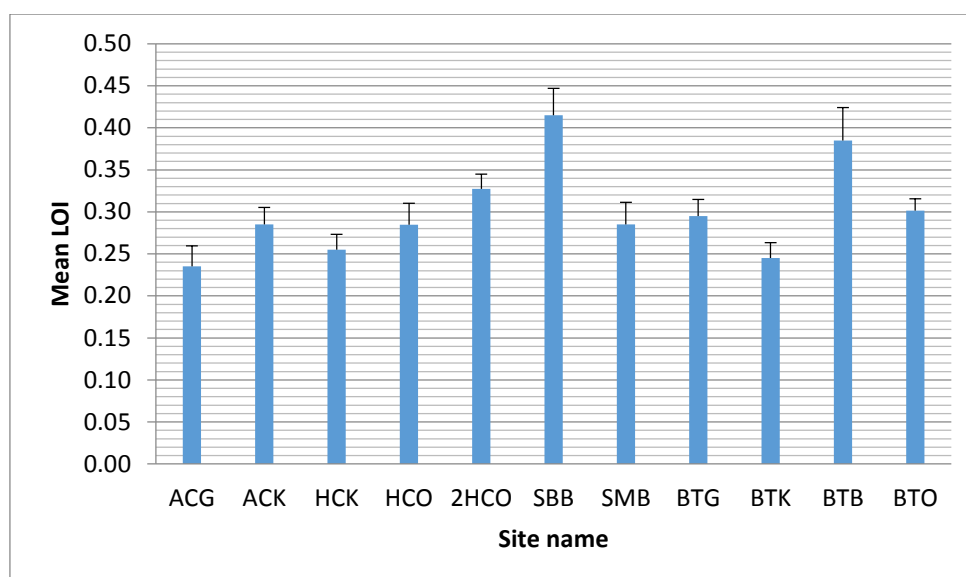


Figure 3.6: The mean landscape organisational index (LOI) of all the bush-controlled and bush-thickened sites determined for both survey years (2015 and 2016). The standard error is indicated by the error bars. See p. xiii for a list of abbreviations for sites.

Possible reasons for the significant difference ($p < 0.05$) between the LOI of the two sites (ACG and SBB) could be ascribed to the different management practices applied on the farms (ACG being a game farm and SBB a cattle farm) and the current drought conditions. The SBB sites had high LOI scores in 2015 (Table 3.2) due to the large GPs and GLPs identified at these sites (Figure 2.14, Chapter 2). GPs and GLPs were dominant in the BC areas reducing the mean IP length and increasing the overall LOI of the LFA transects at these sites. The larger GPs and GLPs also accumulated more nutrients, creating favourable growing conditions for other vegetation, making colonisation easier. The farmer at the SBB sites also had a successful rotational grazing regime that enabled him to rest his various camps to ensure optimal herbaceous production. The opposite was found at the ACG sites in 2015. The high grazing intensity/uncontrollable grazing and the lack of rainfall reduced the size and the frequency of the perennial GPs and GLPs present in the ACG sites (Figure 3.7). This led to higher mean IP lengths and smaller nutrient-accumulating zones (characterised by GPs and GLPs), limiting the amount of nutrients kept in the system and thus leading to the mean LOI for the 2015 ACG sites dropping to a low score of 0.17 (Table 3.2).

ACG sites seemed to have a good cover of perennial grass tufts, but with closer inspection, large IPs were found (Figure 3.7). The larger grass tufts were mostly characterised by one species, namely *Stipagrostis uniplumis*, a wiry perennial tufted grass species found throughout the Molopo region (Fouché *et al.*, 2014). *Stipagrostis uniplumis* replaced the more palatable *Antheophora pubescens* after human settlement in the 1940s as the most dominant grass species in the Molopo (Donaldson, 1969). Even though *S. uniplumis* is not very palatable, it plays an important role in the production potential of biomass, especially for livestock farmers in semi-arid and arid regions (Fouché *et al.*, 2014). Studies have found that *S. uniplumis* can be responsible for approximately 80% of cattle's diet during droughts (Fouché *et al.*, 2014), highlighting the importance of this species in the region.

The LOI scores of the ACG sites in 2015 were low, as LFA surveys (Chapter 2) only considered perennial vegetation as nutrient accumulators in the patches, mostly dominated by grasses. The ACG sites in 2015 had very high densities of annual herbaceous plants, such as *Cucumis africanus* and *Acanthosicyos naudinianus*, which occurred at high densities between the GPs, but were seldom rooted in the patches (Figure 2.10, Chapter 2). These two annual creepers produce fleshy fruits utilised by animals during periods of drought and when moisture is limited. The patches where *C. africanus* and *A. naudinianus* were identified were referred to as *Cucumis* IPs to help with the description of the patch (Figure 2.10, Chapter 2).

Although not significant ($p > 0.05$), the BT sites (surveyed in 2015 and 2016) had higher LOI scores than the BC sites on average. This was due to the larger SLPs and LPs found in the BT sites compared to the smaller GLPs and GPs predominantly found in the BC sites (Figure 3.8). The SLPs and LPs were the most dominant nutrient-accumulating zones identified in the BT sites over both survey years. This was due to the high frequency of smaller shrubs (Table 3.3) and the large amounts of dead branches and leaves generated by these shrub species. The SLPs were generally more resistant to the drought conditions and did not reduce in size or densities compared to the GLPs and GPs. The thickening of *Senegalia* and *Vachellia* species found in the Molopo region can also produce secondary compounds (phenols) in their leaves, deterring browsing by animals (Rohner and Ward, 1997; Adler, 2000; Nxele, 2010; Hean and Ward, 2012). This helps these species to retain their leaves and to increase their chances of surviving extreme climatic conditions.



Figure 3.7: Example of an ACG site surveyed in 2015 with low perennial grass densities. The grass tufts were also small compared to the grass tufts found at the 2015 SBB sites. Most of the grasses visible in this transect is *Stipagrostis uniplumis* (moderately palatable, perennial grass species). See p. xiii for a list of abbreviations for sites.

Most of the remaining sites had mean LOI scores of between 0.23 and 0.3, with the exception of the BTB sites, which had the second highest mean LOI score of over 0.39 for both survey years (Figure 3.6). These low LOI scores indicated that the landscapes in the Molopo region where the surveys were conducted were dominated by bare soil (regarded as IPs) and that the nutrient-accumulating zones were limited (Figures 3.3 and 3.7). The lack of nutrient-accumulating zones and the poor water-holding capabilities of the Molopo's sandy soils can also contribute to the low nutrient levels of the soil as well as the low overall functionality when using stability, infiltration and NC as LFA indices.



Figure 3.8: Example of a BTB site surveyed in 2015 with a landscape organisational index (LOI) score of 0.42, meaning that 58% of this transect was made up of inter-patches or bare soil. Dead grass can be seen as a result of the drought conditions at this site. The 2015 BTB sites had the second highest mean LOI score of all the sites. See p. xiii for a list of abbreviations for sites.

3.4 Discussion

The landscape functioning of the BT and BC sites were similar when using LFA methodology. Results showed that the BT areas in the Molopo region were more functional with regards to soil stability and soil nutrients. This can be attributed to the higher densities of woody shrubs and trees found in the BT areas, which have extensive root systems that stabilise the loose sandy soils and prevent soil erosion (Maestre and Cortina, 2004; Breshears, 2006; Maestre *et al.*, 2009; Daryanto *et al.*, 2013; Eldridge and Soliveres, 2014 and Eldridge *et al.*, 2015). These root systems also increase soil nutrients by extracting nutrients from deep in the soil profile and depositing them close to the surface (Daryanto and Eldridge, 2010).

The canopies of both tree and shrub species in the BT areas also facilitate the establishment of cryptogams beneath them, which further increases the occurrence of

soil nutrients and soil stability, as these areas form a biological soil crust that is not grazed (Mager, 2010; Thomas and Hoon, 2010). The cryptogams forming under the canopies in the BT areas can produce extracellular polysaccharides, increasing soil nutrients by fixing nitrogen and carbon, which form part of biological soil crusts (Mager, 2010; Thomas and Hoon, 2010; Elliot *et al.*, 2014). Mager (2010) and Berkley *et al.* (2005) also stated that cryptogams responsible for increased soil nutrients are predominantly found in BT areas beneath *S. mellifera* and *G. flava* shrubs. The higher LOI scores found in some of the BT sites (Figure 3.6) were due to the large SLPs and SPs formed by *S. mellifera* shrubs. This relationship between *S. mellifera* shrubs and cryptogams can be one of the main reasons why BT areas had such high stability and nutrient cycling scores, resulting in higher landscape functionality scores.

The above results emphasise the fact that although areas where higher bush thickening occur appear to be overgrazed and in a “poor condition” for livestock/game production that often depends on perennial grass biomass production, the landscape functionality may be higher.

Figure 3.9 illustrates that smaller IPs, on the other hand, result in lower percentages of landscapes made up of non-nutrient-accumulating zones or bare soil. The number of IPs found in a landscape decrease with an increase in LOI scores and number and size of patches. The patches refer to nutrient-accumulating zones and the IPs to non-nutrient-accumulating zones, which are characterised by bare soil. Higher LOI scores and therefore more and larger patches will cause IPs to decrease in frequency and size. Landscapes with higher LOI scores and lower IP percentages should therefore function better, especially from an agricultural point of view where higher grass production is needed for livestock production.

The different management practices of the study sites on the various farms also influenced the LOI scores. The LOI with the lowest score was found at the ACG sites. These sites were located on a game farm. Game farming is notorious for its almost uncontrollable grazing regimes, which often lead to selective or over-grazing of certain areas, where the tuft size of the perennial grasses were decreased (Van Oudtshoorn and Oosthuizen, 2015), increasing IP size and decreasing LOI score (Figure 3.9). The location of LFA transects is therefore critical, as this could influence the landscape functionality scores.

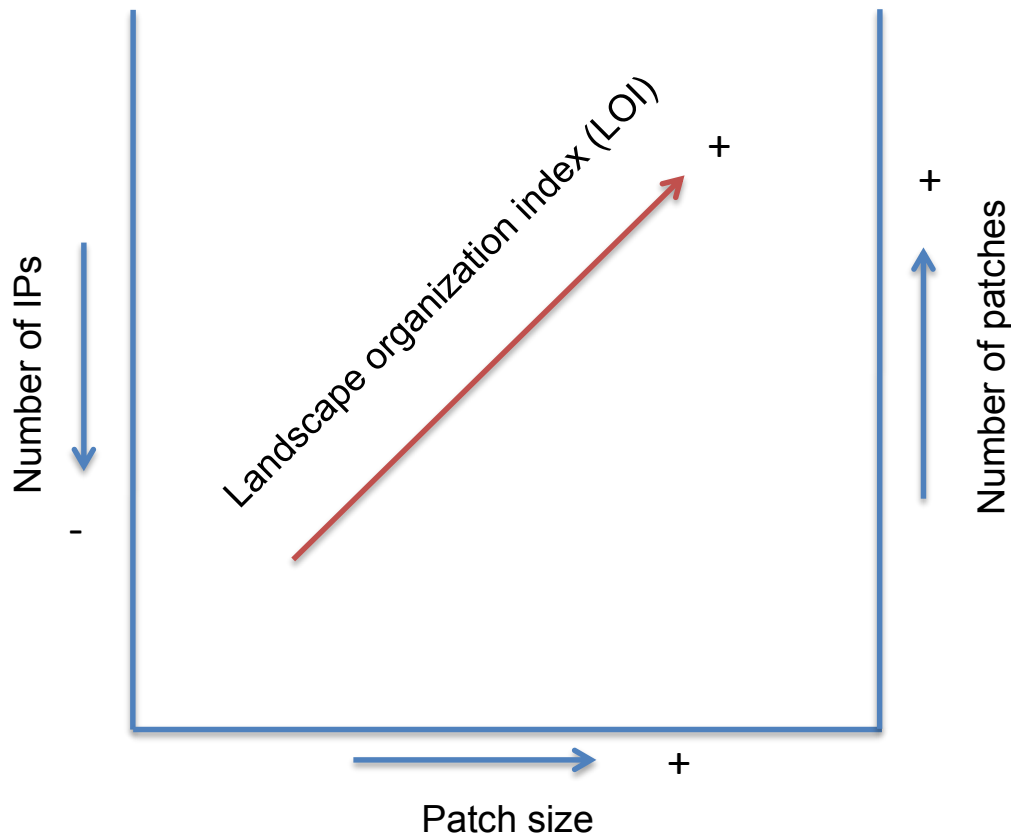


Figure 3.9: Comparison between size, number of patches and landscape organisational index (LOI); a decrease in inter-patches (IPs) is found when these three values increase.

The sites located on cattle farms (ACK, HCK, HCO, SBB and SMB) had higher LOI scores, indicating that controlled grazing could have led to higher grass densities and tuft size and thus higher LOI scores (Figure 3.9). Most of the commercial cattle farmers followed more selective BC approaches (HC, SB and SM), leaving some of the more favourable trees and shrubs untreated, e.g. *V. erioloba*, *B. albitrunca* and *G. flava*. These trees and shrubs still present in the BC areas can increase the recovery time of the rangeland by creating fertile islands with elevated soil nutrients levels (Dean *et al.*, 1999; Daryanto and Eldridge, 2010), promoting herbaceous production in the long-term. Larger trees (*V. erioloba* and *B. albitrunca*) further prevent the re-establishment of *S. mellifera* seedlings through competition (Joubert *et al.*, 2013). The benefits of not controlling larger trees and leaving favourable shrubs in the rangeland can lead to the formation of GSPs (Figure 21, Chapter 2). GSPs were abundant in the selectively controlled areas, which contributed significantly to the landscape functionality. This was also emphasised by the SBB sites, where large GSPs and GLPs led to higher

mean LOI scores (Figure 3.6). As mentioned, no chemical BC technologies were used at the SBB sites. A good grazing management plan was followed at the SBB sites, which could have led to the more abundant “grass type” patches.

The results from the LFAs conducted at the various sites therefore rejected the first hypothesis, namely that the landscape functionality of BC sites was higher than for the BT sites. By rejecting the first hypothesis, the abovementioned results strengthened the argument made by Breshears (2006), Maestre *et al.* (2009), Daryanto *et al.* (2013), Eldrigde and Soliveres (2014), and Eldridge *et al.* (2015), who stated that the effect of bush thickening on an ecosystem depends on the end use. Livestock farmers believe that BT sites are bad for the environment because it reduces grass production and densities, two key factors needed for successful livestock farming. Certain scientists on the other hand see BT as a natural occurrence that increases ecosystem services like biodiversity, carbon sequestration, soil fertility and hydrology, only if the BT does not increase past a certain threshold (Daryanto *et al.*, 2013; Eldrigde and Soliveres, 2014; Eldridge *et al.*, 2015). Woody densities that are too high (> 2500 TE/ha) reduce grass production if the area is used for grazing purposes (Richter *et al.*, 2001; Smit, 2004; Harmse, 2013).

Further research is, however, required over longer time periods and across different areas, where the LFA transects are laid out to validate the abovementioned findings. More LFA surveys are therefore needed to increase the number of data available for statistical analysis. Results from LFAs conducted in good or average rainfall years will further help to describe the difference in the functionality between BT and BC sites.

Chapter 4

The soil chemical properties in bush-thickened and -controlled Molopo savannas at patch- and inter-patch scale

4.1 Introduction

The soil of the Molopo region is characterised as very deep and sandy with high infiltration rates, low nutrient and organic matter levels and almost no water runoff due to flat surfaces (Donaldson & Kelk, 1970; Thomas *et al.*, 2002). Disturbances in arid or semi-arid savannas like the Molopo is mainly caused by high-intensity livestock grazing (over-grazing), which can result in reduced ecosystem functioning if the vegetation cover, carbon (C) cycling, nitrogen (N) fixation, microbial activities and soil physical properties are altered (Neff *et al.*, 2005). The reduced vegetation cover caused by high-intensity livestock grazing can lead to bush thickening due to a lack of competition for nutrients between the low-growing herbaceous species (mainly grasses) and woodies (trees and shrubs). Although bush thickening reduces grass cover, leading to problems for livestock farmers who depend on forage production for animals, it can also increase the nutrient content of the soil, especially under the woody canopy where the movement of livestock is limited (Archer *et al.*, 2001; Hagos & Smit 2005; Nxele, 2010; Daryanto *et al.*, 2011; Daryanto *et al.*, 2013; Eldridge & Soliveres 2015; Eldridge *et al.*, 2015).

In North America, Archer *et al.* (2001) found that BT can lead to increased soil N and C levels due to the increased above- and below-ground primary productivity caused by the roots of woody species. The same was found by Scheslenger *et al.* (1990) in southwestern America, where increased woody densities led to the creation of fertile islands under the canopies of thickening shrubs. In Argentina, Gonzalez-Roglich *et al.*

(2014) found that the soil C level increased significantly along a woody gradient and that soil organic C was the main driver behind these increases. Similar results were documented in Australia by Daryanto *et al.* (2013) and Eldridge and Soliveres (2015), where increased soil N and C levels were found in bush-thickened (BT) areas at landscape scale. Other studies conducted in Australia by Daryanto *et al.* (2012) and Tongway *et al.* (1989) found higher soil N and C levels at patch scale in litter and shrub patches. These differences could be due to the extra litter produced by woody species or by the actions of termites decomposing the litter (Daryanto *et al.*, 2012).

Studies conducted by Hagos and Smit (2005) and Nxele (2010) on the thickening of woody species in the semi-arid savannas of southern African showed that the species generally known for causing most of the thickening, *Senegalia mellifera*, also contributed most to increased soil nutrient levels. The studies further showed that the soil nutrients declined exponentially further away from the stem of the shrub to the middle of a non-vegetated area (inter-patch area). Hudak *et al.* (2003) found that BT leads to an increase in soil C sequestration in the Molopo region of South Africa, but only up until the encroaching species reach a density that suppresses herbaceous cover.

4.2 Material and methods

With the completion of each land function analysis (LFA), the two most prominent patch types were identified on each transect. These patches included: IP, GP, GLP, LP, GSP and SLP (See Chapter 3, Section 3.2 for more details regarding the placements of the LFA transects at the sites). Three soil samples were then taken up to a depth of 5 cm at each identified patch. Only the top 5 cm of the soil profile was sampled due to the concentration of dryland soil nutrients close to the surface of the soil (Tongway & Ludwig, 1994; Dougill *et al.*, 1998; McClaran *et al.*, 2008, Mager, 2010). A pipe coupler and a scraper were used to collect the soil samples (Figure 4.1). The three samples from each patch type were combined to form a composite sample. Litter was not included in the soil samples. The composite samples were approximately 300 g in mass as stipulated by the Eco-Analytica laboratory⁹ used for the soil analyses. The soil samples were placed in plastic zip-lock bags to make

⁹ Eco-Analytica – North-West University, PO Box 19140, Noordbrug, 2522. Tel: 018 293 3900

labelling and transportation easier. The samples were dried and sieved by the laboratory prior to analysis. The concentration of the soil macronutrients, namely C, calcium (Ca), magnesium (Mg), N and phosphorus (P), as well as soil micronutrients, such as sodium (Na), were determined. Other parameters that were analysed included the soil pH (KCl), particle size distribution.



Figure 4.1: Pipe coupler and scraper used for soil sampling. Tape was used around the pipe coupler to ensure that the correct amount of soil was collected at a depth of 5 cm.

Representative soil samples were taken at the identified LFA patches (Table 4.1) in both the BT and bush-controlled (BC¹⁰) sites. The most dominant patches identified in the BT areas were inter-patches (IPs) and shrub litter patches (SLPs). In the BC areas, the dominant patches were IPs and grass litter patches (GLPs). A total of 328 composite soil samples were collected over both survey years (2015 and 2016), of which only 99 composite samples from the 2015 surveys were analysed for financial reasons. The four most dominant patches identified throughout the sites (BT and BC sites) were IP (50), GLP (24), SLP (15) and grass patch, GP (7) (Table 4.1).

The principal component analysis (PCA) biplot ordination technique in CANOCO software (version 4.5) programme was used to conduct multivariate analyses on the results of the soil analyses (Ter Braack & Smilauer, 2002). This ordination technique revealed the best results for comparison (Haager, 2008, van der Walt *et al.*, 2012).

¹⁰ Bush control – Includes all the chemically and mechanically controlled areas i.e. AC, HC, 2HC, SB and SM.

4.3 Results and discussion

4.3.1 Comparison of soil analysis for patch types between treatments

Only 84 of the 99 soil samples analysed were used for comparison¹¹. In this section, only the four most dominant patches (IP, GP, GLP and SLP) with three or more repetitions per treatment were identified across the six treatments (AC, HC, SB, SM, 2HC and BT) (Table 4.1) This decision was made based on the frequency at which the various patch types were found at the BC and BT sites (Table 4.1). See Table A2 (Appendix) for a list of all the soil samples collected over both survey years and p. xiii for a list of abbreviations for the treatments.

Table 4.1: Summary of the dominant patches sampled and analysed in 2015. The samples used in the multivariate analysis ordination are also indicated. (See p. xiii for a list of abbreviations for treatments).

Treatments	Dominant patch types					
	IP	GP	GLP	LP	SLP	GSP
AC	11**	4**	5**	1*	0	1*
HC	6**	0	6**	0	0	0
2HC	3**	0	3**	0	0	0
SB	6**	2*	2*	0	0	2*
SM	5**	1*	4**	0	0	0
BT	19**	0	3**	0	15**	0

*Samples analysed

**Samples analysed and used in multivariate analysis ordination

The results from the soil analyses indicated that the soil from all the sites were made up of 94–98% sand and 1–2% silt and clay (Table A2, Appendix). This type of particle size distribution leads to the assumption that the soils of the Molopo region are mainly

¹¹ Only patches with three or more replicates were considered for the analysis.

sandy, well-drained and nutrient-poor (also see Chapter 2) (Thomas & Shaw, 1991; Dougill *et al.*, 1998).

The values for the nutrients in the BT sites are means calculated from all BT sites across the four farms (Table 4.2) (See Chapter 2, Section 2.2.1 for the four farms). Only one patch type (IP) was selected at the SB sites due to the low frequency of the other patch types found (Tables 4.1 & 4.2). The soil nutrient values for patch types from the AC and HC sites respectively are also means calculated from the different sites where the treatments were surveyed (Table 4.2).

Table 4.2: Summary of the nutrient status from the soil samples collected at the various treatments in the four dominant patch types (IP, GP, SLP and GLP) during the 2015 surveys. The values are mean values calculated from Table A3 (Annexure 2), with the three highest values highlighted. These values were also used for the multivariate analysis ordination. (See p. xiii for a list of abbreviations for treatments.)

Treatments	Patch type	Ca	Mg	K	Na	P	pH (KCl)	C (%)
		(mg/kg)						
AC	IP	209.0	60.0	82.1	3.0	8.7	5.3	0.3
	GLP	256.8	96.6	111.1	5.4	10.3	5.6	0.4
	GP	299.9	40.4	98.3	2.1	7.7	5.3	0.4
HC	IP	124.0	65	48.5	0.5	8	4.8	0.3
	GLP	148.3	81.5	64.7	0.8	7.8	5.2	0.3
2HC	IP	147	82.7	66.8	6.3	7.5	4.8	0.3
	GLP	190.5	91.3	64.2	2.2	8.9	5.1	0.3
SM	IP	119	47.7	52.2	2.8	10.9	4.5	0.3
	GLP	113.4	49.1	57.3	1.8	10.2	4.5	0.3
SB	IP	114	21	40.8	1.2	9.5	4.5	0.3
BT	IP	167.8	47.4	48.4	4.7	9.3	5	0.3
	GLP	108.0	69.2	37.7	1.2	8.4	4.8	0.3
	SLP	350.7	53.0	78.9	2.2	9.6	5.6	0.5

On average, the GLPs at the AC sites had the highest Mg and K levels and pH values of all the patch types at the various treatments (Table 4.2; Figures 4.2 & 4.3), while the remaining elements (Ca, Na, P and C) had the second or third highest values.

These results were unexpected as the AC sites on average had the lowest LFA index scores, especially regarding the nutrient cycling index value (Table 3.2 & Figure 3.1, Chapter 3). The high nutrient levels documented for the GLPs found in the AC sites can possibly be a result of the dominant grass species, *Stipagrostis uniplumis*, found throughout these sites. This species (as mentioned in Chapter 3) is a large perennial tufted grass that can produce large volumes of plant material/litter if exposed to favourable conditions. Biological soil crusts or cryptogams also formed around the base of this grass species in the larger GLPs, especially where more shade occurred. Both these occurrences can lead to elevated nutrient levels in the soil surrounding the GLPs (Dougill *et al.*, 2004; Neff *et al.*, 2005; Mager, 2010). This could also be the reason for the elevated nutrient levels of the GPs sampled at the same sites (Table 4.2). The results to follow will be discussed based on the values from the FSSA (2007) as there is no standards for the nutrient levels of rangelands and pastures.

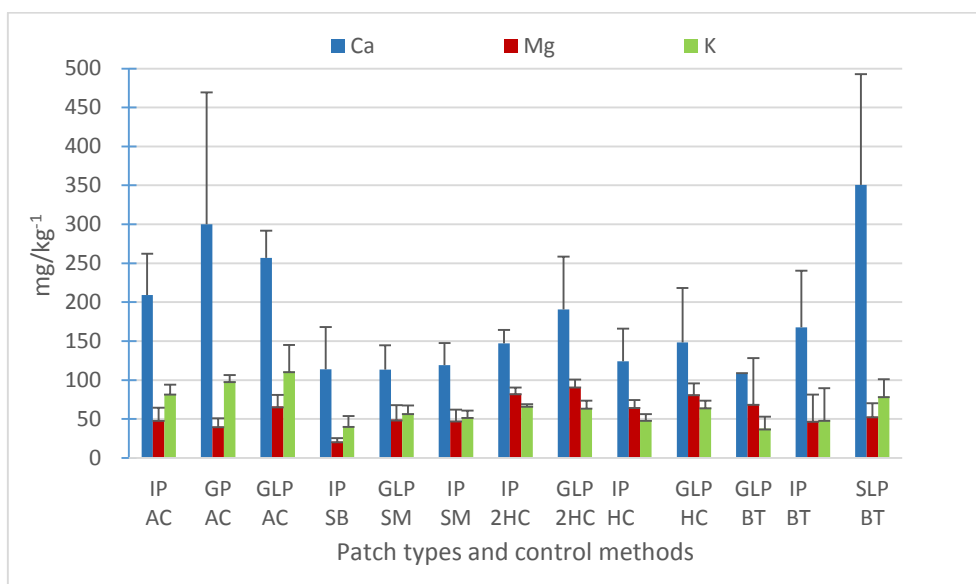


Figure 4.2: The nutrient status of the four most dominant patch types (IP, GP, GLP and SLP) sampled at the six different treatments (AC, SB, SM, 2HC, HC and BT). The values used in the graph are mean values calculated from the 2015 analysed soil samples. Standard deviation is indicated by error bars. (See p. xiii for a list of abbreviations for treatments).

According to the FSSA (2007), the Mg content of agricultural soil should be 50–300 mg/kg with 50 mg/kg being very low. Five of the thirteen patches sampled (IP of the SB site, IP and GLP of the SM site, and GP and IP of the BT site) scored below 50 mg/kg with the lowest content recorded in the IP of the SB site, namely 21 mg/kg (Table 4.2; Figure 4.2). The patch with the highest Mg content was the GLP of the AC site (96 mg/kg), which is low compared to the FSSA (2007) standards. Mg deficiency

in plants can cause roots and shoots to become smaller and shorter with necrotic spots forming on the leaves. These symptoms are a result of impaired C metabolism and a decrease in the overall chlorophyll and C fixation rates (Hermans *et al.*, 2010; Guo *et al.*, 2016).

Mg deficiencies in soil can be caused by a number of factors, such as high Na, K or Ca levels or leaching, especially in sandy soils (Gransee & Fuhrs, 2012; Guo *et al.*, 2016). Na, K and Ca are strong competitors and can replace Mg, leading to decreased availability of this element (Guo *et al.*, 2016). Mg leaching occurs in the soils of the Molopo where the survey was carried out because of its high infiltration rates (Donaldson & Kelk, 1970; Thomas *et al.*, 2002) and the high mobility of Mg in soil (Gransee & Fuhrs, 2012).

Although the Ca levels were high in all soils for all treatments (Figure 4.2), a trend similar to that of Mg levels was observed for the Ca levels of the sampled patches, with only four patches (IP, GP and GLP of the AC site and SLP of the BT site) having higher levels than the lowest acceptable range of FSSA (2007) standards. The FSSA (2007) states that Ca levels of 200–3000 mg/kg is acceptable and levels below 200 mg/kg are very low. Since the Ca levels of most of the patches (nine out of thirteen) fell below this value, the analysed soils in the Molopo savanna can be regarded as Ca-poor (Table 4.2; Figure 4.2). Calcium plays a crucial role in the strengthening of cell walls and the protection of the plant against diseases and, most importantly, heat stress (especially in the dry Molopo region) (Helper, 2005; Sela, 2016).

Ca deficiency in plants can lead to the die back or scorching of young leaves due to reduced transpiration rates (Sela, 2016) and Ca shortages can be caused by acidic soils or high levels of other positively charged ions, including Mg, Na and K (Helper, 2005; Sela, 2016). However, the high levels of cations in this case cannot be the reason for the Ca levels of the samples being low (Table 4.2; Figures 4.2–4.4). Furthermore, Ca is not very mobile in soil, limiting the effect leaching might have on its availability for the plants (Helper, 2005; Sela, 2016). One of the only remaining factors that could limit Ca availability, therefore, was the pH of the soil and possible antagonistic behaviour between the macro and micro elements.

The K levels of the samples conformed better to the FSSA (2007) standards of 40–250 mg/kg. GLP of the AC site had the highest K levels at 111.1 mg/kg, followed by

the other two patches from the same site, namely GP and IP, at 98.3 and 82.1 mg/kg, respectively (Table 4.2; Figure 4.2). Only one of the patches (GLP of the BT site) had K levels below 40 mg/kg. This is one of the few cases where K levels of most of the patches were within the FSSA (2007) standards for “acceptable” nutrient levels in soils. K is one of the most important plant nutrients after N (Sela, 2016), especially because K cations can be replaced by other cations if the latter are present in large quantities (Helper, 2005). This can have detrimental effects on plants because K helps to regulate CO₂ uptake by playing a role in the opening and closing of stomata. Furthermore, K helps with the osmoregulation of plants to compensate for water loss through the stomata (Liu *et al.*, 2013; Sela, 2016). K deficiency can thus cause chlorosis or scorching of the leaves or stunted growth. The most detrimental effect of K deficiency on plants in the Molopo region is reduced resistance to temperature changes and drought (Liu *et al.*, 2013; Sela, 2016).

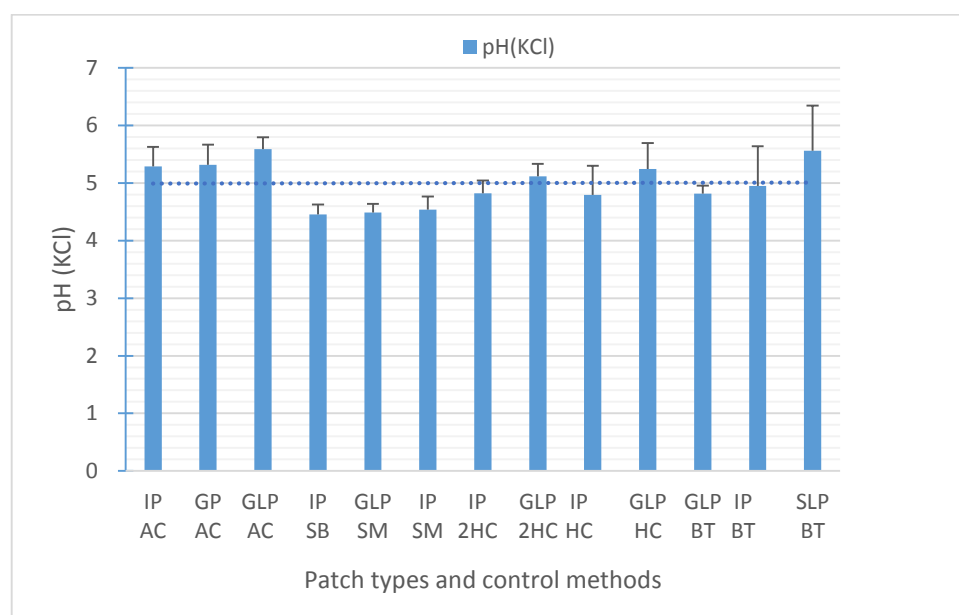


Figure 4.3: The pH (KCl) of the patches (IP, GP, GLP and SLP) sampled in 2015 at the six different treatment sites (AC, SB, SM, 2HC, HC and BT). The values used in the graph are mean values calculated from the 2015 analysed soil samples. The dotted line indicates the mean pH for all the samples analysed. The standard deviation is indicated by error bars. (See p. xiii for a list of abbreviations for treatments.)

An interesting result was found in the patches of the SM and SB sites: The grass densities were high at these sites, leading to the high landscape organisational index (LOI) values (Table 3.2 & Figure 3.6, Chapter 3). Both these sites, however, had the lowest nutrient concentration values, except for P (Figure 4.4). The IPs and GLPs of

the SM sites respectively scored the first and third highest P levels of all the patches at the various sites. Only the GLPs of the AC sites came close to the P levels of the SM sites. The pH levels recorded at these sites were also the lowest of all the patches at the various sites, with all three patches recording a pH of 4.5 (Figure 4.3).

The sites at the BT treatments only scored the highest in three of the seven parameters measured in the soil analysis, namely Ca content, pH and C (%). The Ca concentrations of the soils at the SLPs (350.7 mg/kg) were much higher than that of other patches. GPs and GLPs from the AC sites had Ca concentrations of 299.9 and 256.8 mg/kg, respectively. The Ca concentrations of soils at the IPs and GLPs from the same BT sites were less than half of that of the SLP patches, namely 167.8 and 108 mg/kg, respectively (Table 4.2; Figures 4.2, 4.3 & 4.5). The C (%) of the soils at the SLP samples followed the same trend as that of the Ca concentrations, namely that the second and third highest concentrations were found in the soils of the GPs and GLPs of the AC sites (Table 4.2; Figures 4.3 & 4.5).

The soils from the HC sites had surprisingly low nutrient levels. Mg in the soils of the GLPs was the only soil nutrient with a reasonably high concentration, 81.5 mg/kg (fourth highest). The concentrations of other nutrients in the GLPs and IPs were third or fourth lowest, which was an unexpected result as the HC sites on average scored the second highest (after 2HC) in most of the LFA indices over both survey years (Table 3.2 & Figure 3.1, Chapter 3). The high amounts of litter and the higher shrub densities created the perception that the overall nutrient levels of the HC sites would be reasonably high. The disturbance caused by the high grazing pressure experienced at the HC sites in 2015 probably negatively influenced the nutrient levels in the top 5 cm of the soil profile. Both HC sites were situated on cattle farms and grazed just before or during the 2015 surveys.

The 2HC sites were also located on a cattle farm that was grazed just before sampling. The difference between the 2HC and HC sites was the amount of litter of the woody species that were controlled found at the 2HC sites. The contractors who controlled the woody species in the pasture did not apply selective control, meaning that all the woodies, not only the problem species, were chemically controlled, causing bush encroachment (see Chapter 3 for problem species). Dead tree material or litter of the controlled woodies were left behind by the contractors, which could have led to the

overall higher nutrient levels in the pasture and contributing to the higher LFA indices, especially the C (%) values in the soils of the GP, GLP and SLP (Table 4.2; Figure 4.4).

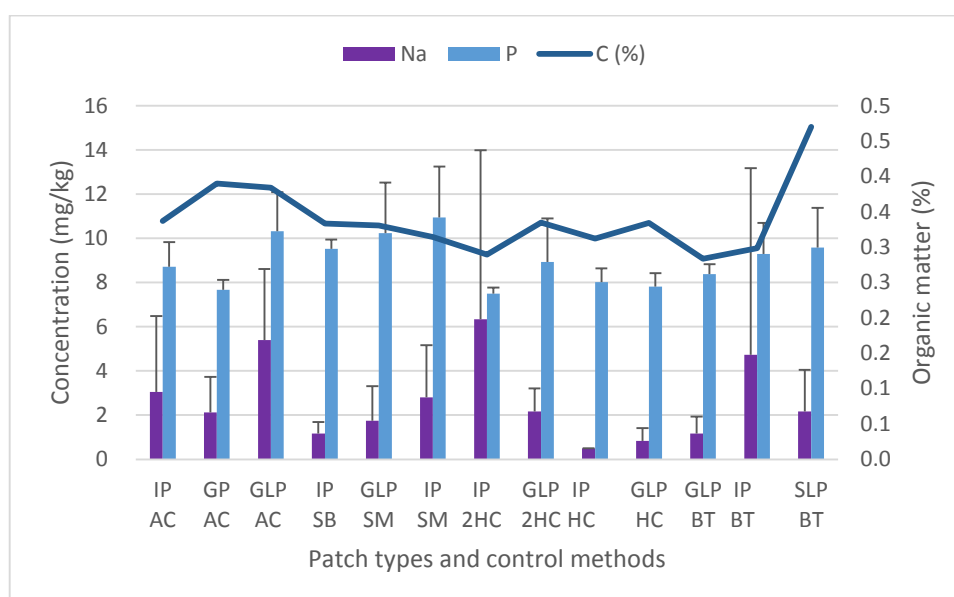


Figure 4.4: The Na and P concentrations (mg/kg) of the patches (IP, GP, GLP and SLP) sampled in 2015 at the six different treatments (AC, SB, SM, 2HC, HC and BT). The values used in the graph are mean values calculated from the 2015 analysed soil samples. The trendline indicates the C (%) of all the samples analysed in 2015, ranging between 0.3 and 0.5%. The standard deviation is indicated by error bars. (See p. xiii for a list of abbreviations for treatments).

Na levels across the soil samples were low, with most levels being around 2 mg/kg. The only patches with moderately high soil nutrient levels were IP of the 2HC sites, GLP of the AC sites and IP of the BT sites with 6.3, 5.4 and 4.7 mg/kg, respectively (Figure 4.4). According to the FSSA (2007) guidelines, Na levels above 15 mg/kg are high for agricultural purposes. The sampled Molopo soils are thus far below this value, possibly explaining the high acidity of the soil.

Na uptake by plants helps to build pressure within cells (to sustain turgor). Similarities between K and Na ions can cause plants' ion transport pathways to struggle with differentiating between the two cations (Pardo & Quintero, 2002; Jones, 2012). This can lead to excess Na cations being absorbed, which can become toxic to the plant and lead to K deficiencies (Pardo & Quintero, 2002). Moreover, high Na concentrations can lead to reduced availability of other nutrients, such as Ca, as observed at the site (Table 4.2) (Jones, 2012).

P is a primary plant macronutrient needed but is not as readily absorbed as N or K is. It plays a key part in fundamental plant processes, including photosynthesis, N fixation and maturation (Brady & Weil, 1999). P deficiencies can be difficult to identify, but more mature plants tend to have darkened leaves, with severe deficiencies leading to yellowing and senescence of leaves (Brady & Weil, 1999). In the soil profile, P is mostly available as inorganic phosphate ions, e.g. HPO_4^{2-} and $\text{H}_2\text{PO}_4^{2-}$, with the former being more readily available in acidic soils (Brady & Weil, 1999) like those found in the Molopo region.

4.3.2 PCA ordination

PCA ordination was used to determine whether there were any correlations regarding the different patch types and their nutrient status in the different treatments. The data from Table 4.2 were used for the PCA. The largest variance in the data was found on the X-axis of the PCA, with an Eigen-value of 0.500 (Figure 4.5).

Three groups of correlations that showed strong associations could be identified. The first group was the association of the IPs and GLPs in the SB and SM sites, which differed distinctly from the patches in other treatments, namely HC and AC (Figure 4.5). Both the patch types (IP and GLP) in the SM and SB treatments were associated with high P levels (Table 4.2; Figure 4.5). A strong disassociation was found between these patches (IP and GLP of the SM site and IP of the SB site) and the other nutrients.

The soils of the IPs and GLPs from the HC and 2HC treatments were strongly associated with one another and had higher Mg and Na levels (Table 4.2; Figure 4.5). The remaining patches found in the grouping, GLP of the BT site and IP of the HC site, were not strongly associated with either of these nutrients, but had a strong disassociation with K as a result of their very low K concentrations (Table 4.2; Figure 4.5).

All the soils of the patch types (IP, GP and GLP) from the AC sites were positively associated with high levels of K and C (%) and with higher pH values (Figure 4.5). High levels of Mg and Na were found in the GLPs of the AC treatment (Table 4.2; Figure 4.5), while GLPs and IPs had the highest K values (Table 4.2; Figure 4.5). The GP in the AC site had a strong association with C (%) (Figure 4.5).

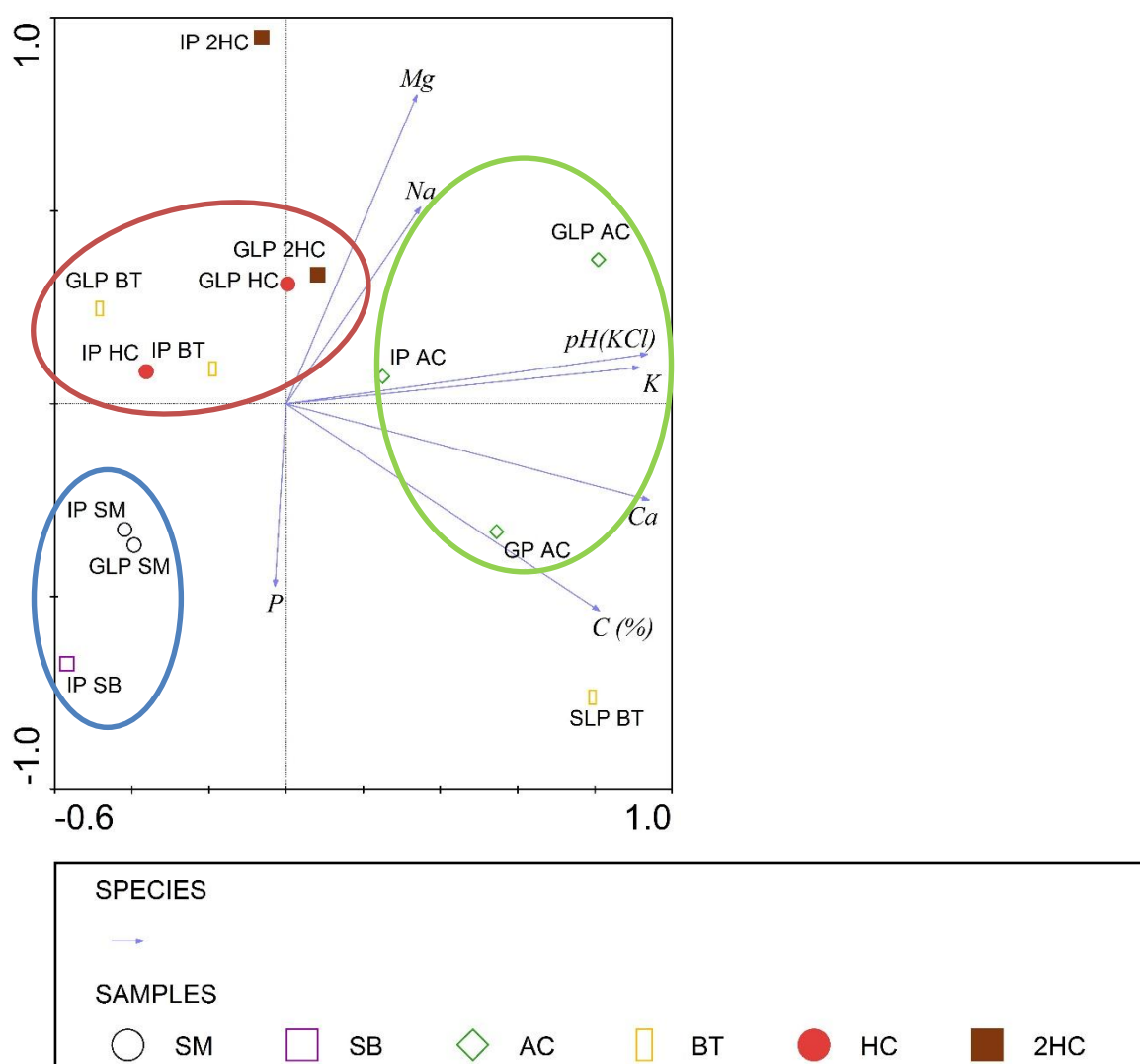


Figure 4.5: Principal component analysis (PCA) biplot indicating how the dominant patches from the BT and BC (AC, HC, 2HC, SB and SM) treatments were associated with the soil nutrients. The Eigen-value of the X-axis is 0.500 and that of the Y-axis is 0.215. The soil nutrients are regarded as “species” in the PCA ordination biplot. (See p. xiii for a list of abbreviations for treatments).

The IP of the 2HC site and the SLP of the BT site can be regarded as “outliers”. The SLP of the BT site was strongly associated with C (%) and to a lesser extent with Ca concentrations (Figure 4.5). The SLP in the BT treatment outscored the next patch by almost 60 mg/kg in terms of Ca concentration and had nearly double the amount of C (%) than most of the other patches. The IP of the 2HC site, on the other hand, had a low P value (Table 4.2) and is therefore not strongly associated with P concentration (Figure 4.5).

4.4 Conclusion

The overall nutrient levels of the surveyed soils in the Molopo region were very low, especially in terms of the FSSA (2007) standards, which are set up for agricultural lands. No soil nutrient standards and guidelines are available for rangelands. The three patches (IP, GLP and GP) of the AC site had surprisingly high nutrient levels, outscoring most of the SLPs of the BT sites. One of the reasons for this phenomenon could be the amount of woody litter and dead plant material present at these sites, as the contractors and farmers left the remains of the AC-controlled trees in the field to promote the recovery of the grass species and increase the overall nutrient levels of the area. Similar phenomena can be seen in the patches of the 2HC treatments, as woody litter is abundantly available at these sites. Another factor that could have contributed to the overall higher nutrient levels in the AC treatment sites were the occurrence of cryptogams that are found around the base of the dominant grass species (*S. uniplumis*). The high values of Ca, pH and C (%) in the SLPs of the BT sites were unexpected, although the Ca and C (%) levels were much higher than in the other patches. Literature states that the overall nutrient levels of encroached areas and especially areas encroached by leguminous trees should be much higher than the surrounding areas.

A statement not completely supported by the findings of this study on the soil analyses of the Molopo regions soil. The thickened sites only had the highest nutrient levels in three of the seven parameters and these three higher scores were not significantly higher than the scores of the closest patch (GLP of the AC). The acidity of the soils also limited the availability of most of the macro- and micro nutrients needed for plant growth. An increase in the pH of the soil can lead to more favourable conditions for plant growth and soil microbes. Further studies will be needed to confirm these findings and especially in a season with average or above average rainfall. Additional soil samples would also be needed from deeper in the soil profile to support the findings made based on the top 5cm of the soil profile.

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

Bush thickening (BT) (increase in density of woody shrubs) is a serious problem in the Molopo region of the North West and Northern Cape Provinces, South Africa. The theory is that the thickening is mainly caused by the mismanagement of the landscape by land-users. Other factors can however also contribute to the thickening of the woody species, such as climate, fire and CO₂ elevation (Oba *et al.*, 2000; Ward and Young, 2002; Sankaran *et al.*, 2004; Joubert *et al.*, 2008). The mismanagement of these Savanna ecosystems include: overgrazing of the herbaceous vegetation in the fenced camps (paddocks) on commercial farms used for livestock production, as well as the control of natural veld fires. The reduction in grass densities and especially the densities of the strong perennial tufted species that occur in these ecosystems, such as *Antheophora pubescens*, led to reduced competition between grasses and shrubs which in turn led to an increase in shrub densities, especially *Senegalia mellifera* densities. *Senegalia mellifera* is seen as one of the most problematic species causing bush thickening in the Molopo region contributing to a reduction of the grazing capacity for livestock.

This study focussed on the effects bush thickening and the control thereof has on the functioning of the landscape. Four commercially managed farms were identified where 164 Landscape Functional Analyses (LFA) monitoring procedures were conducted over a two year period from 2015 to 2016. Soil and vegetation sampling was carried out at each of the LFA transects. The soil samples were only collected at two of the most dominant patches identified at each of the LFA transects (See Chapter 2 section 2.3.2 for description of LFA methodology). Results were analysed to determine whether bush control technologies that were applied at all the study sites influenced the functionality of the landscape in the Molopo region. The bush control (BC) technologies that were applied included aeroplane application (AC), hand application (HC), double chemical control by hand (2HC), sustainable management of the

landscape by implementing good grazing strategies (SM) and stem burning (SB) (See Chapter 2 section 2.2 where the bush control technologies are described).

The results indicate that bush thickened (BT) areas are fully functional landscapes and will persist in their current state for many years if no control technologies are applied. The results further indicate that the bush controlled sites are also fully functional landscapes with similar functionality scores and nutrient levels as the BT sites, but the bush controlled sites do have the potential to “re-thicken” if not managed properly with the correct chemical follow-up treatments (Barac, 2003). It must be mentioned that the LFA’s were carried out in very dry years with below average rainfall. A serious drought occurred in the whole area which could have led to these similar results.

The first objective of the study was to qualitatively and quantitatively describe the LFA patch types and related attributes of landscape functioning (infiltration, stability and nutrient cycling) across rangeland conditions and treatments. As mentioned, 164 LFA transects were conducted over both survey years across the four different farms. Five different bush control and/or management strategies (AC, HC, 2HC, SM and SB) were applied at the study sites on the four farms. The LFA’s were conducted at sites where the different management strategies were applied, as well as at the BT sites on the same farm.

The results found no significant differences between the three main LFA parameters (Nutrient Cycling, Stability and Infiltration) for both the BT and managed/control sites. Although not significant, the BT, HC and 2HC sites had the highest functionality scores over both survey years. These high functionality scores can be acquitted to the high amounts of litter and cryptogams found throughout the three different treatments. The shade created by the larger GLP’s and SLP’s found at these sites manufactured the perfected sub-habitat for the cryptogams. Cryptogams and litter play an important role in the functionality of a landscape with both contributing large amounts to the nutrient cycling and infiltration parameters (Tongway and Hindley, 2004a; Tongway and Hindley, 2004b). These results were also found by other scientists, such as Dougill *et al.*, 2004; Neff *et al.*, 2005 and Mager, 2010. The deep, loose sandy soils of the Molopo region also played a role in low stability and above average infiltration scores found at all sites

The large IPs found between most of the nutrient accumulating patches played a very big role in the similar functionality scores received by all the BC and BT sites over both survey years. These large IP and the small nutrient accumulating patches played large a role in the low functionality scores achieved by the BC and BT sites. High grazing intensities and the lack of forage as a result of the drought are the two main contributing factors that caused the increase in IP size and the decrease in the size and the frequency of the nutrient accumulating patches.

The second objective was to assess the differences in soil chemical properties at patch scale, contrasting bush-thickened and controlled areas. This objective was met by collecting soil samples at the two dominant patches identified at each of the LFA transects conducted throughout both survey years as mentioned before. Seven different types of patches were identified during the study, six of these were nutrient accumulating patches. The patches included a non-nutrient accumulating patch: inter patch (IP), and six nutrient accumulating patches: grass patch (GP), grass litter patch (GLP), litter patch (LP), grass shrub patch (GSP), shrub patch (SP) and shrub litter patch (SLP). The two dominant nutrient accumulating patches found throughout the BC and BT sites were the GLP found predominantly in the BC sites and the SLP found only in the BT sites. A total of 324 soil samples were collected at these patches of which 99 were analysed and 84 used in the description of the results. The samples were dried and sieved by the laboratory (Eco-Analytica laboratory¹²) prior to analysis. The soil macronutrients, namely carbon (C), calcium (Ca), magnesium (Mg), nitrogen (N) and phosphorus (P), as well as soil micronutrients, such as sodium (Na), were determined. Other parameters that were analysed included the soil pH (KCl) and particle size distribution.

No significant differences could be found between the nutrient levels of the bush thickened (BT) and the bush controlled (BC) sites. The SLP of the BT sites and the GLP of the AC sites did however have much higher Ca, C and K concentrations compared to the patches of the other sites (referring to all the other BC sites: SB, SM, HC and 2HC). These high nutrient levels can be attributed to the nutrient deposition by the roots of the vegetation that occur close to the soil surface, the higher amount of litter, as well as the high densities of cryptogams found surrounding the SLP's and

¹² Eco-Analytica – North-West University, PO Box 19140, Noordbrug, 2522. Tel: 018 293 3900

the GLP's. Studies by Mager (2010) and Berkley *et al.* (2005) found that cryptogams and especially the cryptogams found in the Molopo region play a very important role in the soil nutrient content of arid landscapes as they have the ability to fix nitrogen and carbon. Cryptogams further also helps to stabilise the soil thus reducing the chances of erosion. The soils have the potential to be wind eroded due to the reduced vegetation cover. No signs of water erosion was observed.

The SLP's also had the highest Ca (mg/kg) and C (%) concentrations with the GLP's having very high Mg, K and P concentrations (mg/kg). Both these patches also had the highest pH (KCl) values of 5.6. The higher C (%) concentrations found at the SLP's in the BT sites compared to the C (%) concentrations of the GP's and GLP's of the BC sites coincides with findings made by (Smit and Rethman, 2000; Breshears, 2006; Maestre *et al.*, 2006; Eldridge *et al.*, 2009; Daryanto *et al.*, 2013; Eldridge and Soliveres 2014; Eldridge *et al.*, 2015), which states that the soil organic C will decrease with the removal of trees. They also state that the soil organic C concentrations found in the inter canopy zones are much lower than soil organic C concentrations of soil found below the canopy of a tree or shrub.

The results from the LFA's and soil analyses confirmed previous statements made by various scientist, that the Molopo has high infiltration rates and low nutrient and organic matter levels (Donaldson and Kelk, 1970; Thomas *et al.*, 2002; Gebremeskel and Pieterse, 2006).

The encroachment of the Molopo region is the result of poor management and over-grazing which decreased the grass layer and led to increased water percolation thus favouring woody establishment. Unfortunately the woody species establishing in these over grazed areas are undesired species which has very little benefit for the cattle and game farmers from the region, but are not harming the landscape function.

5.2 Recommendations

It is recommended that more and longer LFA transects be carried out at additional sites where certain control or management practices were carried out. This will increase the sample size and improve the statistical analysis. The latter is especially true for the number of soil samples and the analysis. More in-depth analysis could be done regarding the cation exchangeable capacity (CEC) and the electrical conductivity (EC) of the soils in the Molopo study sites chosen for this study. Additional soil samples can also be collected up to a depth of 10cm to determine if a difference in soil clay content can be found at deeper soil profiles.

It is further recommended that the LFA procedures are carried out also in higher rainfall years (such as the 2016/17 season), as especially the herbaceous vegetation could be in a much better condition which might lead to the identification of other LFA patch types and other LFA parameter results, especially aspects such as nutrient cycling. The data from drought stricken years can then be compared to the higher rainfall years. These comparisons would also explain how resilient the landscape is and how it responds to severe drought conditions.

Additional vegetation data that can be collected and be used to better explain the LFA data includes: measurements of distance between patches, grass densities using a quadrant method and the difference between the biomass production of the BT and BC sites. Enclosures experiments can also be conducted to determine the effect herbivore pressure and the different control methods has on the LFA indices and overall grass production.

Chapter 6

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Appendix

Appendix

Table A2: Particle Size Distribution of the 2015 soil samples

Sample no.	> 2mm (%)	Sand	Silt	Clay	LECO %N	LECO %C
		(% < 2mm)				
1501 IP LFA1 AC	0.0	98.5	1.2	0.4	0	0.35
1501 LFA1 LP AC	0.0	98.5	1.2	0.4	0	0.48
1501 LFA2 IP AC	0.0	98.5	1.1	0.4	0	0.38
1501 LFA2 LP AC	0.0	98.5	1.2	0.4	0	0.57
1502 LFA1 IP BE	0.0	98.5	1.2	0.4	0	0.41
1502 LFA1 SP BE	0.0	96.4	3.2	0.4	0	0.70
1502 LFA2 IP BE	0.1	98.5	1.2	0.4	0	0.35
1502 LFA2 SP BE	0.0	98.5	1.2	0.4	0	0.39
1503 LFA GLP AC	0.0	98.5	1.1	0.4	0	0.43
1503 LFA1 IP AC	0.0	98.5	1.1	0.4	0	0.37
1503 LFA2 GP AC	0.3	98.5	1.1	0.4	0	0.42
1503 LFA2 IP AC	0.1	98.5	1.1	0.4	0	0.35
1504 LFA IP BE	0.0	98.0	1.1	0.8	0	0.31
1504 LFA1 SP BE	0.0	98.0	1.1	0.8	0	0.47
1504 LFA2 IP BE	0.0	98.0	1.1	0.8	0	0.34
1504 LFA2 SP BE	0.0	98.0	1.1	0.8	0	0.50
1505 LFA1 IP BE	0.0	98.1	1.1	0.8	0	0.33
1505 LFA2 IP BE	0.0	98.0	1.1	0.8	0	0.31
1505 LFA1 SP BE	0.0	96.0	3.1	0.8	0	0.59
1505 LFA2 SP BE	0.0	98.0	1.1	0.8	0	0.43
1506 LFA2 GP AC	0.0	98.0	1.1	0.8	0	0.37
1506 LFA1 IP AC	0.0	98.0	1.1	0.8	0	0.37
1506 LFA2 IP AC	0.0	98.0	1.1	0.8	0	0.33
1506 LFA1 GP AC	0.0	98.0	1.1	0.8	0	0.42
1507 LFA1 GLP AC	0.0	98.0	1.1	0.8	0	0.45
1507 LFA1 IP AC	0.0	98.1	1.1	0.8	0	0.45
1507 LFA2 IP AC	0.0	98.0	1.1	0.8	0	0.36
1507 LFA2 GP AC	0.0	98.0	1.1	0.8	0	0.35
1508 LFA1 IP BE	0.0	94.8	2.4	2.8	0	0.29
1508 LFA1 SP BE	0.2	94.8	2.4	2.8	0	0.40
1508 LFA2 IP BE	0.0	94.8	2.4	2.8	0	0.28
1508 LFA2 SP BE	0.0	94.8	2.4	2.8	0	0.44
1521 LFA1 GP SB	0.0	94.9	2.4	2.7	0	0.41
1521 LFA2 GP SB	0.0	94.9	2.4	2.7	0	0.34
1521 LFA1 IP SB	0.1	94.9	2.4	2.7	0	0.31
1521 LFA2 IP SB	0.0	94.8	2.4	2.8	0	0.32

1522 LFA1 GSP SB	0.1	94.8	2.4	2.8	0	0.46
1522 LFA1 IP SB	0.0	94.9	2.4	2.7	0	0.32
1522 LFA2 GLP SB	0.2	94.0	3.2	2.7	0	0.34
1522 LFA2 IP SB	0.0	94.1	3.2	2.7	0	0.37
1523 LFA1 GSP SB	0.0	94.0	3.3	2.7	0	0.43
1523 LFA1 IP SB	0.0	94.0	3.2	2.7	0	0.35
1523 LFA2 GLP SB	0.1	94.0	3.3	2.7	0	0.39
1523 LFA2 IP SB	0.0	94.0	3.3	2.7	0	0.33
1524 LFA1 IP SB	0.0	94.1	3.2	2.7	0	0.31
1524 LFA2 IP BE	0.1	94.1	3.2	2.7	0	0.32
1524 LFA1 GLP BE	0.0	95.9	1.3	2.8	0	0.30
1524 LFA2 SLP BE	0.0	95.9	1.3	2.8	0	0.61
1525 LFA2 IP BE	0.0	98.5	1.1	0.4	0	0.32
1525 LFA1 IP BE	0.0	98.5	1.1	0.4	0	0.28
1525 LFA2 SLP BE	0.0	98.5	1.2	0.4	0	0.56
1525 LFA1 SLP BE	0.1	98.5	1.1	0.4	0	0.53
1526 LFA1 IP BE	0.0	96.5	1.1	2.4	0	0.34
1526 LFA1 SLP BE	0.0	96.5	1.1	2.4	0	0.62
1527 LFA1 IP SM	0.1	96.5	1.1	2.4	0	0.32
1527 LFA2 IP SM	0.2	96.5	1.1	2.4	0	0.35
1527 LFA1 GLP SM	0.1	96.5	1.1	2.4	0	0.36
1527 LFA2 GP SM	0.0	98.5	1.1	0.4	0	0.32

Table A3: Nutrient status of the 99 analysed soil samples

Sample no.	Ca	Mg	K	Na	P	pH (KCl)	EC (mS/m)
	(mg/kg)						
1501 LFA1 IP AC	278.5	55.5	98.5	0.5	11.1	5.56	18
1501 LFA1 LP AC	408.5	71.5	134.0	0.5	10.9	5.44	21
1501 LFA2 IP AC	338.0	58.5	106.5	0.5	8.7	5.79	19
1501 LFA2 LP AC	394.5	74.5	102.5	0.5	8.9	5.30	36
1502 LFA1 IP BE	325.5	54.0	205.5	0.5	9.7	6.64	26
1502 LFA1 SP BE	664.5	64.0	84.0	0.5	8.4	5.82	34
1502 LFA2 IP BE	211.5	31.5	44.0	1.0	12.1	4.31	8
1502 LFA2 SP BE	457.5	40.0	68.5	1.0	11.6	7.16	40
1503 LFA GLP AC	229.5	45.0	88.5	1.0	9.1	5.35	16
1503 LFA1 IP AC	207.0	64.0	88.5	0.5	8.7	5.90	18
1503 LFA2 GP AC	541.5	49.0	88.5	1.5	8.1	5.59	18
1503 LFA2 IP AC	184.5	46.0	70.0	1.5	9.5	5.09	14
1504 LFA IP BE	175.0	11.5	52.5	0.5	8.3	4.90	8
1504 LFA1 SP BE	542.5	52.5	78.0	1.5	7.7	5.35	18
1504 LFA2 IP BE	186.0	29.0	51.0	1.5	9.1	4.52	11
1504 LFA2 SP BE	394.5	55.5	121.0	1.0	9.3	6.11	32
1505 LFA1 IP BE	254.5	30.5	60.5	1.5	8.1	5.45	12
1505 LFA2 IP BE	144.0	31.5	52.5	1.5	7.7	4.55	10
1505 LFA1 SP BE	348.0	48.0	107.5	2.0	7.6	5.37	26
1505 LFA2 SP BE	308.5	45.5	110.5	2.0	7.6	5.48	20
1506 LFA2 GP AC	268.0	48.5	107.5	1.5	7.2	5.31	22
1506 LFA1 IP AC	202.5	34.5	85.5	1.5	8.0	5.05	17
1506 LFA2 IP AC	155.0	26.0	71.5	2.0	8.1	5.01	13
1506 LFA1 GP AC	244.0	37.5	101.0	4.5	7.3	5.54	24
1507 LFA1 GLP AC	280.5	56.0	148.0	3.0	8.6	5.78	28
1507 LFA1 IP AC	160.5	24.5	76.0	2.0	8.8	5.15	13
1507 LFA2 IP AC	201.5	37.0	82.0	1.0	8.1	4.84	18
1507 LFA2 GP AC	146.0	26.5	96.0	1.0	8.1	4.83	17
1508 LFA1 IP BE	124.0	23.0	39.5	0.5	8.9	6.34	6
1508 LFA1 SP BE	256.5	47.5	87.0	1.0	9.6	4.60	19
1508 LFA2 IP BE	326.0	41.5	37.0	1.5	10.0	5.30	8
1508 LFA2 SP BE	400.0	52.0	72.5	1.0	11.6	4.59	52
1521 LFA1 GP SB	158.5	20.0	34.5	1.0	8.1	6.27	6
1521 LFA2 GP SB	100.0	25.0	34.0	1.5	8.0	4.51	5
1521 LFA1 IP SB	49.0	15.0	22.5	2.0	8.8	4.43	4
1521 LFA2 IP SB	67.0	27.0	33.0	1.0	9.4	4.32	5
1522 LFA1 GSP SB	231.5	42.0	70.0	1.0	9.7	4.97	11
1522 LFA1 IP SB	104.5	20.5	60.5	1.0	9.6	4.47	10

1522 LFA2 GLP SB	134.0	27.0	46.0	1.0	10.1	4.51	6
1522 LFA2 IP SB	109.5	19.5	38.0	0.5	9.8	4.24	4
1523 LFA1 GSP SB	267.0	31.0	76.5	0.5	12.2	5.08	11
1523 LFA1 IP SB	181.0	25.0	48.5	1.0	9.9	4.73	6
1523 LFA2 GLP SB	230.5	28.0	53.5	1.0	11.5	5.38	10
1523 LFA2 IP SB	173.0	19.0	42.5	1.5	9.6	4.54	5
1524 LFA1 IP SB	101.5	6.0	13.5	1.0	9.4	4.28	4
1524 LFA2 IP BE	105.0	3.5	24.0	1.0	10.3	4.35	4
1524 LFA1 GLP BE	109.0	2.5	20.0	2.0	8.3	4.66	6
1524 LFA2 SLP BE	479.0	29.0	68.5	1.5	9.1	6.11	22
1525 LFA2 IP BE	192.0	17.5	31.0	25.5	9.8	5.28	9
1525 LFA1 IP BE	76.5	5.0	11.5	29.5	8.9	4.35	3
1525 LFA2 SLP BE	343.5	28.0	55.5	1.0	10.5	6.28	31
1525 LFA1 SLP BE	282.5	30.5	66.5	1.0	9.9	6.03	24
1526 LFA1 IP BE	109.5	7.0	17.0	1.0	11.3	4.46	5
1526 LFA1 SLP BE	216.0	19.0	54.0	2.0	9.9	5.02	13
1527 LFA1 IP SM	128.0	39.0	46.5	1.0	10.0	4.71	7
1527 LFA2 IP SM	163.5	28.0	41.5	2.0	10.9	4.78	8
1527 LFA1 GLP SM	154.5	29.0	45.5	1.0	11.4	4.56	7
1527 LFA2 GP SM	181.5	25.0	41.0	2.0	8.5	5.13	13
1528 LFA2 IP SM	114.5	65.0	51.5	0.5	14.9	4.28	8
1528 LFA2 GLP SM	93.5	74.0	52.5	0.5	12.8	4.38	9
1529 LFA1 IP SM	93.5	53.0	62.0	6.0	10.1	4.33	6
1529 LFA1 GLP SM	85.0	43.0	66.5	4.0	9.0	4.35	9
1529 LFA2 IP SM	95.5	53.5	59.5	4.5	9.0	4.60	8
1529 LFA2 GLP SM	120.5	50.5	64.5	1.5	7.8	4.66	15
1531 LFA1 IP 2HC	148.5	80.0	64.5	3.5	7.7	4.81	17
1531 LFA1 GLP 2HC	268.0	81.0	75.0	3.0	10.0	5.34	22
1532 LFA1 IP 2HC	129.0	76.5	68.5	0.5	7.7	5.05	23
1532 LFA1 GLP 2HC	161.5	98.5	58.0	2.5	10.1	5.10	18
1532 LFA2 IP 2HC	163.5	91.5	67.5	15.0	7.2	4.60	13
1532 LFA2 GLP 2HC	142.0	94.5	59.5	1.0	6.7	4.91	16
1535 LFA1 IP HC	145.5	57.0	40.5	0.5	7.3	4.59	10
1535 LFA1 GLP HC	140.0	70.5	56.5	0.5	7.7	4.85	17
1536 LFA2 IP HC	75.5	63.0	56.0	0.5	8.4	4.42	9
1536 LFA2 GLP HC	83.0	76.5	74.0	1.5	7.3	5.15	15
1537 LFA1 IP HC	151.0	75.0	49.0	0.5	8.4	5.37	12
1537 LFA1 GLP HC	222.0	97.5	63.5	0.5	8.5	5.73	17
1541 LFA1 IP BE	108.5	84.0	36.5	0.5	9.9	4.74	7
1541 LFA1 GLP BE	107.0	90.5	47.0	0.5	8.0	4.94	10
1541 LFA2 IP BE	82.0	84.5	30.5	0.5	9.6	4.49	7
1541 LFA2 GLP BE	108.0	114.5	46.0	1.0	8.9	4.84	13
1538 LFA1 IP BE	149.0	47.5	50.5	0.5	8.8	4.90	13