# Determining the effect of soil on bush encroachment between 1993 and 2018 in the North West Province

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# ABSTRACT

Bush encroachment (BE) is a serious form of land degradation and South Africa alone has lost an estimated 8 million hectares (ha) of grazing or cultivation land due to BE. This consequently leads to decreased food security. To prevent BE, one needs to understand the drivers and mechanisms that control the process and to advise when and where certain management actions should be implemented. Unfortunately, the proposed drivers for BE in African savannas are still widely debated given that the causes for this process is still poorly understood. The focus of this study was to understand the effect of soil type and certain soil properties on BE in the North West Province (NWP) between 1993 and 2018.

For this study, the main driving factors of BE extent and spread were identified in the study area for the specified period by taking a GIS approach on provincial (NWP) and regional scales (four significant areas). Maps indicating the percentage (%) of woody cover for the years 1993, 1998 and 2018 were sourced from Symeonakis *et al*. (2020). The layers indicating the % woody cover in the NWP were used for calculating the spread of bush and bush spread maps were created for time frames, 1993-1998, 1998-2018 and 1993-2018. Potential driving factors of BE were sourced from various sources and used to analyse the bush spread and determine the driving factor/s of the specific bush spread from 1993 to 2018 on a provincial scale and regional scale. On a provincial scale, mean annual precipitation (MAP) was the main driving factor of BE, while in land-managed areas, land-use and MAP together with soil, were important driving factors of bush encroachment from 1993 to 2018. Therefore, soil can be regarded as a minor driving factor of BE in the NWP from 1993 to 2018.

Vegetation surveys were also carried out at the study sites, characterising different soil types, soil properties and degrees of BE. The belt-transect method was used for the vegetation survey to determine the composition, density, and structure (height classes) of the woody component (tree- and shrub species). Soil profiles were described per soil horizon, soil samples were taken within each transect, which were analysed at the laboratory to determine the soil particle distribution (soil texture), pH, electrical conductivity (EC), and water retention of the soil.

From the vegetation surveys, *Dichrostachys cinerea* and *Diospyros lycioides* were found to be the main woody encroacher species as *D. cinerea* occurred at all study sites with *D. lycioides* mainly occurring at the Kgomo-Kgomo study site. The other recognized woody encroacher species included *Grewia flava*, *Grewia flavescens*, *Senegalia mellifera*, *Vachellia karroo*, *Vachellia tortillis*, and *Ziziphus mucronata*.

Soil types and properties did not have a significant influence on all the woody species identified at each study site, but rather on specific encroacher species causing BE in the NWP. The results indicated that *D*. *cinerea* mostly occurred on soils with low clay content, while *G. flava* favoured soils with higher clay content. The highest extent of BE occurred at the Legkraal and Kgomo-Kgomo study sites, where the soil was characterised as deep soils with sandy loam texture. Species such as *Combretum apiculatum*, *Combretum inberbe*, and *Combretum hereroense*, occurred on shallow soils, while *Vachellia tortillis* preferred deep soil types. The encroacher species, *D*. *lycioides*, occurred on the subsoil with an alkaline pH, while both *D*. *lycioides* and *D*. *cinerea* preferred soils with EC higher than 25 mS/m. *D*. *lycioides* and *G*. *flava* both occurred in soils with high dry bulk densities (Pbs), especially at the Kgomo-Kgomo study site. The highest Pbs was also recorded at the Kgomo-Kgomo study site. It therefore seems that soil types with specific soil properties, influence the occurrence of specific woody species causing BE in the NWP.

It is recommended that land-managed areas that experience BE should in general be considered as important future restoration and/or research study sites. Areas where deep soils occur, with predominantly sandy or sandy loam textures, should be regarded as priority areas. Restoration actions that could be considered in the priority areas include the application of manual, mechanical, chemical, biological or a combination of these methods in BE areas to stimulate the growth of grasses. To improve soil condition for grass growth, soil organic matter in the form of livestock manure could be added to the topsoil instead of fertilizer, as fertilizers are usually too expensive for land managers. A knowledge, training and skills development program should also be impleemted for land managers. It is recommended that future research be conducted on determining the main driving factors of BE of other Provinces, such as Limpopo and Northern Cape and using different GIS methods for determining the main driving factors of BE on provincial and regional scale. Future research should also be done on the effect of other soil properties, such as soil temperature and soil organic matter, on woody species causing BE.

**Key words:** Bush encroachment, bush thickening, GIS, land use, North West Province, soil.

# ABBREVIATIONS

BE: Bush encroachment

BL: Bush lessening

BT: Bush thickening

DFFE: Department of Forestry, Fisheries and the Environment

EC: Electrical conductivity

FSP: Free State Province

MAP: Mean annual precipitation

MAT: Mean annual temperature

NC: No change

NWP: North West Province

Pb: Bulk density

PAW: Plant available water

PTE: Potentially toxic element

SAWS: South African Weather Service

TPAW: Total plant available water

VWC: Volumetric water content

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# CHAPTER 1 INTRODUCTION

## 1.1 Background and problem statement

Bush encroachment is a serious form of land degradation (Hoffman & Ashwell, 2001; Haussman *et al*., 2016; Devine *et al*., 2017; Kellner, 2020). South Africa alone has lost an estimated 8 million hectares (ha) of grazing or cultivation land due to bush encroachment (Stafford *et al*., 2017). This consequently leads to decreased food security. Bush encroachment is the process whereby the cover of indigenous woody plants (trees and shrubs) in a grassy ecosystem, increases substantially relative to the indigenous woody cover of a historical reference state (Turpie *et al*., 2019; Kellner, 2020). The increase in density and cover of the woody species result in dynamic changes in vegetation composition and structure over time, causing an imbalance in the grass-woody ratio (de Klerk, 2004; Wiegand *et al*., 2005; Harmse *et al*., 2016). Thus, bush encroachment alters the structure and functioning of an ecosystem and can lead to a decrease in ecosystem services, and eco-tourism appeal (Belayneh & Tessema, 2017). Ecosystem goods and services are the benefits obtained by mankind from the ecosystem, including biodiversity, groundwater recharge, and grazing capacity (Eldridge *et al*., 2011; Dreber *et al*., 2014; Fouché, 2017). A decrease of ecosystem services directly affects South Africa's economy (Van Wilgen *et al*., 2012; Haussmann *et al*., 2016; Harmse *et al*., 2016; Turpie *et al*., 2017; Kellner, 2020). Studies indicate that the value of the ecosystem services (water, grazing, and biodiversity) of South Africa is estimated at R152 billion annually (Van Wilgen *et al*., 2012). However, an estimated R6.5 billion of this amount is lost every year as a result of bush encroachment (Van Wilgen *et al*., 2012). Furthermore, the large-scale vegetation change reduces energy, carbon, and water budgets, which directly influences the people practising communal land management who are dependent on the ecosystem, especially in the rural areas (Devine *et al*., 2017). The loss of grassland and savanna habitat to bush encroachment is also a major concern for conservation managers (Wigley *et al*., 2009). In Africa, bush encroachment decreases landscape heterogeneity, reducing the diversity of invertebrates, birds, and large mammals (Devine *et al*., 2017).

The Department of Environmental Affairs (DEA), under the Natural Resource Management (NRM) and Expanded Public Works Programmes (EPWP), is responsible for the restoration of degraded lands (DEA, 2019). The NRM program incorporates a number of the "working for" programmes through labour-intensive projects, such as the Working for Water (WfW) programme (Van Wilgen *et al*., 2012). Other "working for" projects include: Working for Forests, Working for Ecosystems, Working for the Coast, Working for Land and Working for Wetlands (DEA, 2019). The WfW programme is one of South Africa's crucial programmes controlling invasive species (alien and indigenous) and leading to the conservation of natural resources, job creation, capacity building, and poverty elimination (McQueen *et al*., 2001; Magadlela & Mdzeke, 2004; Turpie *et al*., 2008; Coetzer & Louw, 2012; Mokgosi, 2018). This programme's overarching goal is to alleviate poverty by creating short- to medium-term jobs for unskilled workers through clearing alien and indigenous vegetation contributing to bush encroachment (McQueen *et al*., 2001; Coetzer & Louw, 2012). The fundamental principle of the WfW programme is to preserve water through the eradication of woody plants as part of the National Reconstruction and Development Programme (RDP) initiative (Turpie *et al*., 2008; Van Wilgen *et al*., 2012; Mokgosi, 2018). This programme has received international acknowledgement and has successfully cleared 2.7 million ha of bush encroached rangelands over the last 20 years (Magadlela & Mdzeke, 2004; Van Wilgen *et al*., 2012; Mokgosi, 2018). In 2018 the WfW programme yielded 62 thousand ha of land under restoration or rehabilitation, which exceeded the planned target with a variance of 93% (DEA, 2018).

A study done by Stafford *et al*. (2017) indicates that bush encroachment is a problem in the Limpopo, North West, KwaZulu-Natal, and Eastern Cape provinces of South Africa. Bush encroachment has already in 2001 influenced 42% of the savanna rangelands within these respective provinces (Hoffman & Ashwell, 2001, in Harmse, 2013). The analyses done by Stafford *et al*. (2017) and Skowno *et al*. (2016), indicates that bush encroachment is the most severe in the northern and western parts of the North West Province. High bush encroachment was also observed by Hudak and Wessman (2001), on a farm east of the Madikwe Game Reserve. According to Turpie *et al*. (2019), the western area of North West, specifically near Vryburg, is heavily encroached and forms part of the Ghaap Plateau Vaalbosveld of the Eastern Kalahari Bushveld Bioregion (Mucina & Rutherford, 2006). The savanna biome is characterised by a grassy ground layer and a distinct interlocking layer of woody plants (Mucina & Rutherford, 2006).

The grassy or herbaceous layer is used for grazing (mainly by cattle or game), which may lead to overgrazing, making this biome susceptible to the proliferation of woody plants (Mucina & Rutherford, 2006). The savanna biome, which is the largest of the nine (9) biomes in South Africa, is more prone to bush encroachment and therefore occurs in large regions of Limpopo, North West, and Northern Cape provinces (Mucina & Rutherford, 2006; Harmse, 2013; Turpie *et al*., 2019). Symeonakis and Higginbottom (2014) used multi-temporal Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) to map bush encroachment in the North West Province. They studied the extent of bush encroachment in the Dr Ruth Segomotsi Mompati District Municipality from 1989 to 2009 and found that the bush canopy cover in the area increased by 9%, within this time frame (Symeonakis & Higginbottom, 2014).

Bush encroachment is not caused by a particular species but is rather a change in the balance of the broader phenotypes of plants occurring in ecosystems (Turpie *et al*., 2019). Nevertheless, some species respond as drivers of bush encroachment more prolifically than others. The encroacher species present in the North West Province of South Africa are mainly *Vachellia karroo* (Sweet thorn) and *Senegalia mellifera* (Black thorn), which are indigenous to South Africa and are also present in other provinces, such as Limpopo and Gauteng (Haussmann *et al*., 2016; Fouché, 2017; Turpie *et al*., 2019). Encroachment of the woody species of the genus *Vachellia*, *Senegalia*, *Dichrostachys*, *Prosopis*, *Balanites*, and *Grewia* in arid and semi-arid rangelands are recorded from Africa, North-America, Asia, and Australia (Belayneh & Tessema, 2017; Fouché, 2017). Rangeland ecologists spend great effort in understanding the effects of abiotic and biotic drivers and their interactions savanna dynamics to better understand responses of the mentioned woody plants (Dreber *et al*., 2014).

To prevent bush encroachment, one needs to understand the drivers and mechanisms that control the process and to advise when and where certain management actions should be implemented. Unfortunately, the proposed drivers for bush encroachment in African savannas are still widely debated given that this process is still poorly understood (Wigley *et al*., 2009; Devine *et al*., 2017). However, certain factors including precipitation, increases in carbon dioxide ($CO_2$) emissions, management practices through herbivory (especially grazing), and the lack in fire events, have been identified by a variety of authors as the main causes for bush encroachment (Scholes & Archer, 1997; Ward, 2005; Wiegand *et al*., 2005; Scholes, 2009; O'Connor *et al*., 2014; Belayneh & Tessema, 2017; Skowno *et al*., 2017; Venter *et al*., 2018; Turpie *et al*., 2019). Geology and soil are two driving factors that influence bush encroachment in certain areas (Sankaran *et al*., 2005; Mills *et al*., 2017; Devine *et al*., 2017; Turpie *et al*., 2019). The proposed drivers fall into two broad categories: i.e. local and global (Devine *et al*., 2017; Venter *et al*., 2018). Global drivers include climate change (such as precipitation variability and temperature fluctuations), soil type (nutrient and water availability), and $CO_2$ enrichment (Devine *et al*., 2017; Venter *et al*., 2018), whereas local drivers include fire management practices and herbivory (Devine *et al*., 2017).

As mentioned, bush encroachment is also a major problem in the North West Province (Symeonakis & Higginbottom, 2014; Harmse *et al*., 2016; Turpie *et al*., 2019). Previous studies on the drivers of bush encroachment in the North West Province mainly focused only on fire suppression and herbivory (O'Connor *et al*., 2014). Only a few previous studies in certain areas included soil as a possible cause for bush encroachment (Sankaran *et al*., 2005; Mills *et al*., 2017; Devine *et al*., 2017; Turpie *et al*., 2019). The focus of this study were on the gap that exists regarding the effect of soil type on bush encroachment in the North West Province between 1993 and 2018.

## 1.2 Aims and objectives of the study

This study aimed to determine whether soil was a driving factor of bush encroachment in the North West Province (NWP) between 1993 and 2018, and whether different soil types and properties can be associated with the growth characteristics of the woody species causing bush encroachment (BE).

To reach the aims, the following objectives had to be met:

- Identify the main driving factors of BE extent and spread in the study area for the specified period. To achieve this objective, the following sub-objectives had to be met: (1) to collect and pre-process suitable GIS layers to represent potential driving factors of BE, (ii) to analyse the suitable GIS layers and calculate the BE spread in the NWP and (iii) to determine which potential driving factor/s corresponds the most with BE spread.
- Determine the effect of different soil types and physical properties on the BE attributes at selected sites, where bush encroachment occurred for the period, within the study area. To achieve this objective, the following sub-objectives had to be met: (i) to identify the main encroacher species, (ii) determine the extent of BE and (iii) to determine the effect of soil as a driving factor of BE.
- Make recommendations regarding the management of BE represented by certain soil types.

## 1.3 Hypothesis of the study

The hypothesis tested in this study was that soil type distribution is one of the driving factors of bush encroachment spread and extent in the North West Province during the period 1993 to 2018.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Introduction

The literature review includes a general overview regarding bush encroachment (BE), including BE establishment models, the occurrence of BE, and control technologies of BE in the North West Province (NWP). The main factors driving bush encroachment will also be discussed.

## 2.2 Bush encroachment establishment models

Bush encroachment (BE) has been defined by a variety of authors, as the increase in the density of woody vegetation in grassland and savanna ecosystems (De Klerk, 2004; Smit, 2004; Ward, 2005; Oldeland *et al*., 2010; O'Connor *et al*., 2014; Dreber *et al*., 2014). Other synonyms for BE include woody plant encroachment, brush encroachment, bush invasion, shrub encroachment, woody encroachment, and the increase in woody biomass (Scholes & Archer, 1997; Tews & Jeltsch, 2004; Wigley *et al*., 2009; O'Connor *et al*., 2014; Devine *et al*., 2017). The term invasion refers to the increase of shrubs (alien or indigenous woody species) that have not occurred in the area before (Dreber *et al*., 2014). All the definitions however, refer to the increase of indigenous and alien woody plant species, at the expense of grass cover and density in an area, where none or less woody plant species were previously present. The increase of indigenous and alien woody vegetation (trees, shrubs, and non-herbaceous shrubs) is important, as it is often associated with the decrease in forage productivity, biodiversity and specifically a decline in soil moisture availability (Huxman *et al*., 2005).

Several models have been developed to explain the initiation of BE. In earlier times, researchers proposed the two-layer model of Walter (Walter, 1939) and the one-layer model of Moir (Moir, 1954), to explain the locally-observed BE phenomenon (Belayneh & Tessema, 2017). Three other models were later developed to explain the occurrence of bush encroachment, i.e. the state-and-transition-, equilibrium-, and non-equilibrium rangeland models (Belayneh & Tessema, 2017). Currently, these five models are used to describe the initiation and main driving factors of BE. These five models will be briefly discussed below.

### 2.2.1 Walter's two-layer model

Roots determine the spatial distribution of water and nutrient uptake and can cause an increase or decrease in water- and nutrient availability (Smit, 2004). The two-layer model (Walter, 1939) describes that grass species out-competed trees in the grasslands of semi-arid savannas since they have higher growth and intercept moisture from the top layer of the soil, thus inhibiting trees from potentially absorbing moisture in the deeper soil layers (Walter, 1939; De Klerk, 2004; Ward *et al*., 2013; Belayneh & Tessema, 2017) (Figure 2.1). According to Ward *et al*. (2013), "this hypothesis relies on vertical niche partitioning and assumed that grasses are more water-use efficient than trees and use subsurface water while trees also have access to deeper water sources". The grass cover declines, where there is heavy grazing pressure in dryland rangelands, and the soil moisture becomes more available to deep-rooted woody species, leading to BE (Belayneh & Tessema, 2017). This condition allows woody plants (trees and shrubs) to benefit regarding moisture uptake, allowing them to dominate dryland environments. Walter's two-layer model implies that the main factor influencing BE is soil type, depth, moisture, and nutrient availability, such as nitrogen (N) and phosphorous (P) (Kraaij & Ward, 2006). Ward *et al*. (2013) predicted that within arid savannas, Walter's two-layer model would be able to predict root-niche partitioning, which would not be so clear within savannas systems because of other factors, such as impacts of herbivory, fire intensity, and physical soil disturbance that play larger roles in these systems. Figure 2-1 indicates the competition of woody vegetation and grass for resources in the upper and lower soil layers.

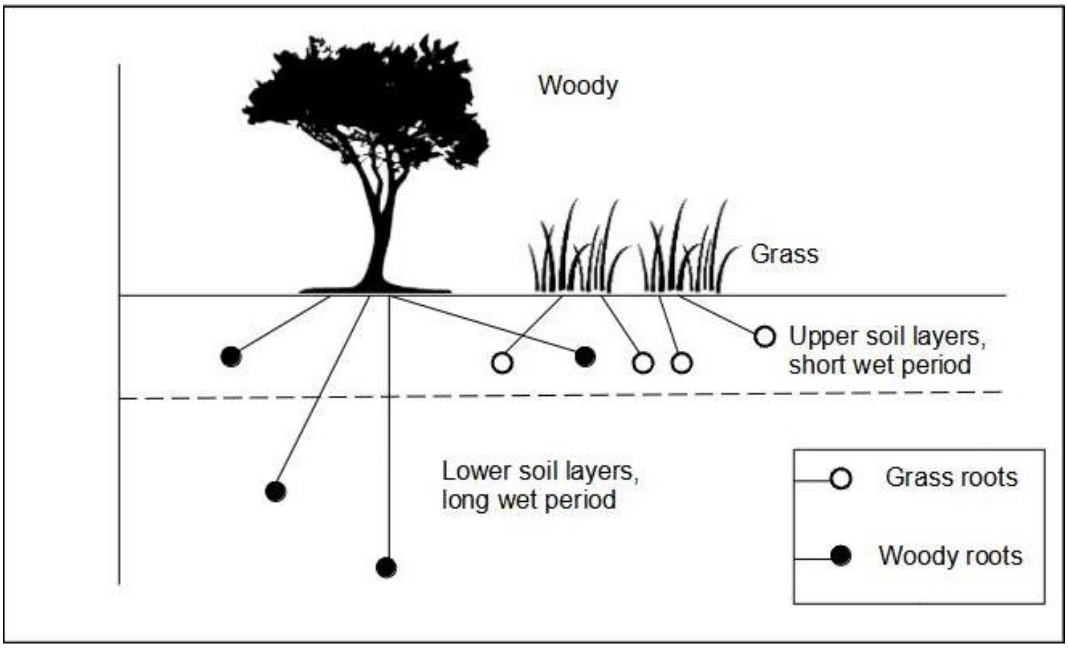



**Figure 2.1: Walter's two-layer model indicating root partitioning in the soil (modified from Ward *et al*., 2013).**

### 2.2.2 Moir's one-layer model

Moir's one-layer model (Moir,1954) states that a constant nitrogen loss through grass fires could limit grass growth and favours the growth of *Acacia* species (genus *Acacia* now called *Senegalia* and *Vachellia*), which are nitrogen-fixing (Adams, 1967; Belayneh & Tessema, 2017). This would lead to increasingly poor growth of grass vegetation in the grassland and savannah regions.

*Senegalia mellifera* (previously known as *Acacia mellifera*) however, might survive and add more nitrogen to the ecosystem over time (Adams, 1967). Brunt (1964) (in Adams, 1967) briefly tested this hypothesis but found that there was no significant difference in nitrogen status between the soils of *Acacia* woodlands and grasslands soils. Adding nitrogen to the topsoil however, does suppress the seedling establishment of *S*. *mellifera* (Ward, 2005).

### 2.2.3 State-and-transition model

This model describes ecosystems with more than one state and transitions taking place from one state to another due to external factors (biotic and abiotic), such as climatic impacts, change in vegetation composition, biodiversity, and impacts of management practices (Briske *et al*., 2003; De Klerk, 2004; Belayneh & Tessema, 2017). State-and-transition models are used to organize and communicate information regarding ecosystem change, especially due to rangeland management actions (Bestelmeyer *et al*., 2017). According to Stringham *et al*. (2003), "a state is a recognizable, resistant and resilient complex of two components", while "transitions" refer to the changing of one state to another, which may include the passing of a threshold (boundary in space and time between states). The transition between stable states can be reversible and are mostly initiated by natural events (i.e. climate, soil, erosion, and natural wildfires), or by management "actions", such as a change in grazing pressure and fire management (Briske *et al*., 2003; Belayneh & Tessema, 2017). State-and-transition models were developed to help managers make better decisions when managing vegetation for potential land uses, such as livestock foraging, erosion control, water infiltration, and wildfire risk. This model is used to develop predictions for how ecosystems respond to changes as previously mentioned (i.e. natural events and management actions) (Bestelmeyer *et al*., 2017). This model implies that BE is not a permanent phenomenon, but rather that a grassland or savanna could be changed to its grass-dominated state by favourable management or environmental conditions (De Klerk, 2004).

Belayneh and Tessema (2017) regard fire and erosion as natural events, but it can also be management actions, especially if the type of management influences the erosion and fire impacts. There is however no definite consensus on the type of driving factors that operate at various scales in diverse rangeland ecosystems (Ward, 2005; Belayneh & Tessema, 2017). Joubert *et al*. (2008) provide an example of a state-and-transition model describing BE in the semi-arid Highland savanna of Namibia (Figure 2.2). A summary of the proposed conceptual model of vegetation dynamics of the area is presented as a catalogue of states and transitions (Appendix A and B).

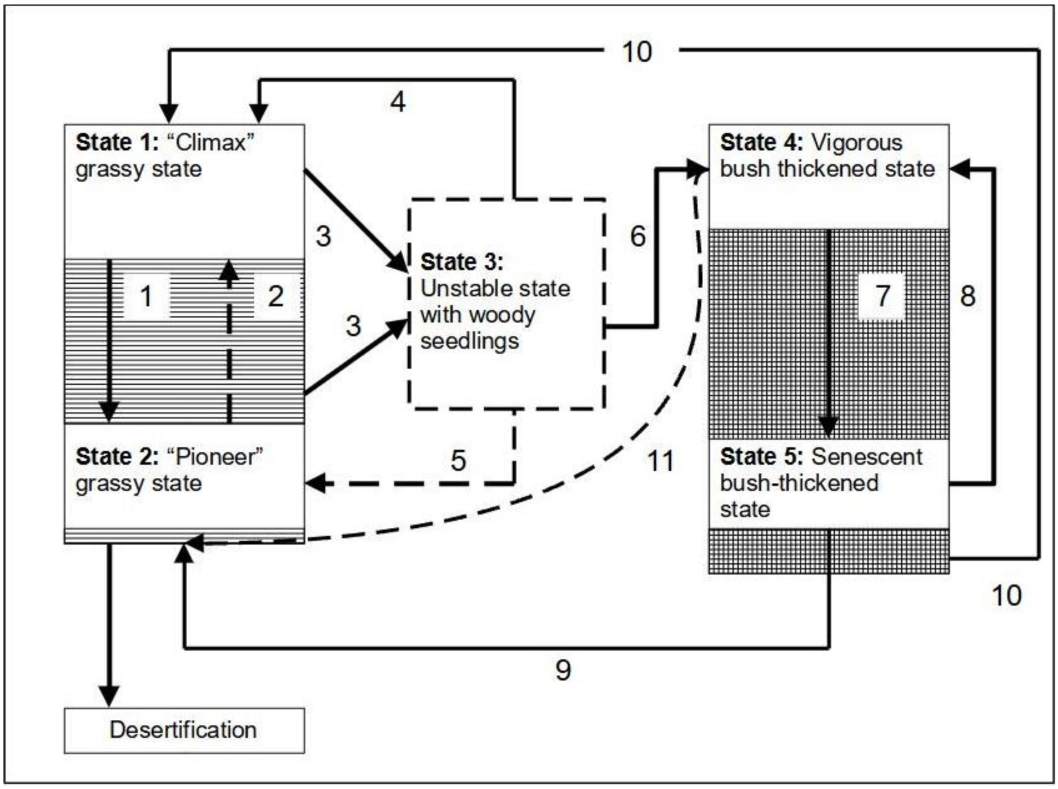



**Figure 2.2: Schematic representation of a conceptual state and transition model regarding bush encroachment in the Highland savanna of Namibia. Solid lines represent likely transitions and dashed lines represent less likely transitions (modified from Joubert *et al*., 2008).**

### 2.2.4 Equilibrium rangeland model

According to Belayneh and Tessema (2017), "the equilibrium rangeland ecosystem model suggests that rangelands respond to the environment under the influence of grazing sequentially and predictably". This model is based on the assumption that ecosystems has the capacity for internal regulation, including intense intra- and interspecific competition and plant-animal interactions (Briske *et al*., 2003). The equilibrium model hypothesises that woody–grass ratios are stable and that disturbances only slightly alter the ratios temporarily (Scholes & Archer, 1997; Belayneh & Tessema, 2017). Continuous and sustained heavy grazing, elevated carbon dioxide ($CO_2$), changes in soil nutrient composition and other soil parameters (i.e. increase in erosion and moisture availability), vegetation physiognomy, changes in species composition, fire events, and climatic changes in dryland ecosystem regions can initiate the encroachment of woody vegetation, by shifting the balance of woody–grass ratio to a more woody state which emulates into BE (Scholes & Archer, 1997; Sankaran *et al*., 2008).

### 2.2.5 Non-equilibrium rangeland model

According to Belayneh and Tessema (2017), non-equilibrium rangeland ecosystems models are mostly determined by abiotic factors (i.e. variable precipitation), resulting in unpredictable and variable rangeland productivity. The non-equilibrium model hypothesises that savannas are unstable mixtures of woody and herbaceous (mainly grasses) vegetation that persist as a result of disturbances (Higgins *et al*., 2000). The non-equilibrium model is founded on the assumption that ecosystems possess a limited capacity for internal regulation, which implies that these systems are more vulnerable to external disturbances (Briske *et al*., 2003). This leads to unpredictable ecosystems and fluctuations in the woody–grass ratio, because the woody vegetation may overgrow the herbaceous species (mainly grasses) during the rainy seasons, whereas these species may dominate during the drier periods (Belayneh & Tessema, 2017). Disturbances and episodic recruitment provide the mechanism for woody–grass coexistence and changes in this paradigm (Gordijn, 2010). Drought is assumed to limit the establishment of tree seedlings, while fire and herbivory limit sapling growth. This unstable system may either tend towards open grassland or savanna woodland (a higher ratio of trees than grass) depending on precipitation (Higgins *et al*., 2000). Therefore, compared to arid savannas, mesic savannas are suggested to be governed by non-equilibrium dynamics that influence the woody–grass ratio (Higgins *et al*., 2000).

## 2.3 Bush encroachment in the North West Province

More recent studies have used satellite data to estimate the extent of BE in South Africa. Hudak and Wesmann (2001) studied BE in the Madikwe Game Reserve using two Systeme Probatoire d'Observation de la Terre (SPOT) panchromatic images. Simulated SPOT images were created and estimates of a percent (%) woody canopy cover were calculated from 1955 to 1996. The results indicated the absolute percent woody cover was 5.6% higher in 1996 compared with 1955, which translated into a relative increase of 30% over 41 years Hudak & Wesmann, 2001).

Recently, BE is monitored using remote sensing and specifically earth observation (EO) data (Symeonakis & Higginbottom, 2014). Symeonakis and Higginbottom (2014) studied BE in the NWP, specifically an area within the Dr Ruth Segomotsi Mompati District Municipality. They used Landsat imagery, along with Random Forest land cover classifications from 1989 to 2009, with an overall validation accuracy of 91%. The results indicate an increase of 9% cover by woody vegetation within 20 years from 1989 to 2009.

Symeonakis *et al*. (2016) created woody cover maps for the NWP for the years 1990, 1994, 1998, 2002, 2007, 2011, and 2015, using Landsat imagery and Random Forest land cover classifications. The results indicate that woody vegetation in the NWP increased slightly over 25 years, especially in areas near Vryburg, Zeerust, and Koster in the NWP (Symeonakis *et al*., 2016).

Stafford *et al*. (2017) used land cover data from 2010 to estimate the extent of BE of South Africa at a national scale. Stafford *et al*. (2017) produced a conservative estimate of BE of 8 million hectares (ha). Skowno *et al*. (2016) used multi-season Landsat data together with satellite L-band radar backscatter data to estimate the extent of woodlands and grasslands in South Africa in 1990 and 2013. The study suggested that over these 23 years over 5.7 million ha of grasslands have been replaced by woodlands, which can be regarded as an increase in BE in the NWP (Turpie *et al*., 2019).

Using the data from Skowno *et al*. (2016) and Stafford *et al*. (2017), BE hotspots can be identified, which includes the Vryburg and Kuruman areas situated within the NWP (Turpie *et al*., 2019). These hotspots are also in agreement with Symeonakis *et al*. (2016), who also found that the area around Vryburg showed a significant increase in woody cover from 1990 to 2015 (25 years).

## 2.4 The management and control of bush encroachment

As BE became a serious problem in semi-arid rangelands, land users, land managers and governments officials implemented better sustainable land-use management (SLM) strategies to prevent and/or reduce BE. Turpie *et al*. (2019) also indicated that pro-active measures are important for reducing existing and preventing further BE and proposed several ideas that should be implemented to reduce or prevent further BE. These include biological management (fire and herbivory), manual and mechanical thinning or clearing, chemical spraying, and income generation strategies through wood harvesting. Some of these strategies will be discussed below.

### 2.4.1 Biological clearing

The biological clearing of woody vegetation includes methods regarding the management of fire and herbivory, whereas biological control involves the deliberate introduction of invertebrates or diseases (such as wood fungi) and is aimed at reducing the effects (invasion and reproduction) of specific woody vegetation (Van Wilgen *et al*., 2004; De-bushing Advisory Service Namibia, 2017).

In certain instances, fire and/or herbivory are described as “biological clearing” methods to decrease the woody vegetation causing BE. Rangelands where BE occur are mainly burnt for (1) the removal of accumulated organic material (particularly in areas of high precipitation) and (2) to combat or prevent BE (Naudé, 2018). High-intensity fires are applied at the right time of year to prevent woody plant seedlings from surviving (Smit *et al*., 2010). When burning too early (early winter), the burnt surface is exposed to wind, frost, and sunlight, which leads to fertile surface material being lost (Naudé, 2018). It is also important for rangeland managers to burn areas consisting of dense stands of perennial grasses, as when rangelands consisting of primarily pioneer and/or subclimax species are burnt, the rangeland might further deteriorate. Intensive and frequent fires also often kill woody plants, preventing the establishment of a continuous canopy cover (Smit *et al*., 2010, in Hare *et al*., 2020).

Another biological control method to combat BE includes the use of browsing animals and management of grazing animals (Naudé, 2018). The common strategy of grazing management is to allow adequate rest for the veld through carefully-managed rotational grazing, rather than continuous grazing (Turpie *et al*., 2019). Continuous grazing refers to a system by which animals graze in one area without any barriers to their movement. Rotational grazing is usually applied using a system of fenced camps (paddocks) in which the livestock is "rotated" between pastures to meet the forage needed for livestock. Tainton (1999) and Smit (2004) have established two important approaches to either adapt the livestock system to the existing vegetation or to modify the vegetation to suit specific livestock systems. Where browsers form an important component of the livestock system, woody plant densities should be high and palatable, as browsing animals, such as goats, are well suited to control woody plants. This is because of the intensity and frequency with which they utilise the browse (Hare, 2020). Goats also have been used together with mechanical methods in the initial thinning of woody vegetation in a bush control programme (Smit *et al*., 1999, in Hare *et al*., 2020). Earlier studies have reported that after mechanical methods were used, plots were stocked with 1.2 to 2.2 Boer goats per hectare (ha-1) for commercial farmers who wished to increase the grass production by reducing bush (Hare *et al*., 2020).

### 2.4.2 Manual clearing

The manual clearing of woody species causing BE relies on "man-power" to remove unwanted bush (Naudé, 2018). Manual removal is carried out by using tools, such as hand saws, pruning loppers, bush axes, spades, and in advance cases chainsaws. This is done to remove woody vegetation causing BE (De-bushing Advisory Service Namibia, 2017). As manual control is labour intensive, it creates job opportunities, especially in communal areas (Nghikembua *et al*., 2020). Other advantages of manual control include that specific encroaching species and size-classes of plants can be targeted, limiting soil disturbances. A disadvantage of manual clearing of woody vegetation is that it may be time-consuming (De-bushing Advisory Service Namibia, 2017). This is a very selective method and has to be applied correctly, i.e. cutting off all the stems of a multi-stemmed shrub (Naudé, 2018). Manual clearing/control is often followed up by chemical methods.

### 2.4.3 Mechanical clearing

The clearing of woody vegetation causing BE by mechanical technologies involves the use of heavy machines, such as bulldozers, bush rollers, or bush cutters (De-bushing Advisory Service Namibia, 2017; Naudé, 2018). Wheel- and track-mounted heavy machines can be outfitted with saws, clippers, and leveraged scoops to help remove unwanted woody vegetation. This method is effective in clearing large areas of land in a relatively short amount of time, with bulldozers able to clear up to 8 ha/day (De-bushing Advisory Service Namibia, 2017). Mechanical clearing/control is faster than manual clearing, but it causes substantial soil disturbance, which may favour the establishment of woody seedlings (De Klerk, 2004). Smaller machines or “mini-heavies” have been designed to reach difficult areas and can manoeuver easier through dense thickets (De-bushing Advisory Service Namibia, 2017). These smaller machines are also more selective and can treat 3-5 ha of unwanted woody vegetation/day and with smaller wheels, cause less soil disturbance compared to the larger bulldozers. Unfortunately, mechanical clearing is very expensive (cost, maintenance, and fuel) and has to be operated by skilled operators, which is not always possible for landowners, especially in communal areas (Barac, 2003; De-bushing Advisory Service Namibia, 2017).

### 2.4.4 Chemical clearing

Chemical clearing/control involves the application of arboricides (herbicides specific for eliminating woody plant species) that are applied selectively to kill targeted plants only (De-bushing Advisory Service Namibia, 2017; Naudé, 2018). The chemical control of woody vegetation causing BE is a common practice applied in southern African rangelands, to decrease the density of the woody layer and stimulate the growth of the herbaceous layer by restoring the soil moisture content of the upper soil layers (see mentioned models) (Harmse *et al*., 2016). This control method is generally based on the size of the target area, funds available, and availability of a labour force that is trained to apply the arboricide (De Klerk, 2004). Arboricides are applied to the foliage, stems of woody plants, or to the soil around plants (Turpie *et al*., 2019). Chemical application is usually used for a very large area, where mechanical and manual clearing is not possible, as well as the tree density is such that animal access is severely restricted. Tebuthiuron or bromacil (chemical formula: $C_9H_{16}N_4OS$) is the active ingredient present in many arboricides commonly used by rangeland owners and bush clearing contractors (Harmse *et al*., 2016; Naudé, 2018). Other chemicals used include Picloram and Triclopyr or arboricides coming by trade names, such as Hyvar, Bushwhacker, Brush-free, Spike, Graslan, Grazer, Limpopo, Molopo, or Reclaim (De-bushing Advisory Service Namibia, 2017; Naudé, 2018). The drawback of chemical control is the decrease of soil health and the treated woody plants are “virtually un-harvestable”, after which it cannot be used to generate income (De Wet, 2015, in Turpie *et al*., 2019). Other disadvantages of chemical clearing/control include: (1) the arboricides can cause harm if it comes into contact with skin, eyes, mouth, and nostrils and (2) if spilled, arboricides can cause unwanted pollution in water sources (De-bushing Advisory Service Namibia, 2017). Compared to manual methods of bush clearing, chemical control is also very costly and less applied by local, poor communities (De-bushing Advisory Service Namibia, 2017).

## 2.5 Driving factors of bush encroachment

Previous studies have reported that the driving factors of BE mainly entail climate change (specifically erratic precipitation and elevated atmospheric $CO_2$), management of fire and herbivory impacts in rangelands due to different land-use strategies, geological bedrock, and weathering of underlying geology and soil types (Scholes & Archer, 1997; Barac, 2003; De Klerk, 2004; Sankaran *et al*., 2005; Ward, 2005; Abule *et al*., 2005; Gottfried *et al*., 2009; Bowman *et al*., 2011, Belayneh & Tessema, 2017; Turpie *et al*., 2019). It is often difficult to attribute a single factor causing BE, simply because most factors are spatially and time-correlated and depend on the management applied (Archer, 2010; Harmse *et al*., 2016; Belayneh & Tessema, 2017) (Figure 2.3). Sankaran *et al*. (2005) also stated that combined effects of more than one driving factor, such as variable precipitation combined with decreased fires and increased overgrazing (herbivory), may lead to BE.

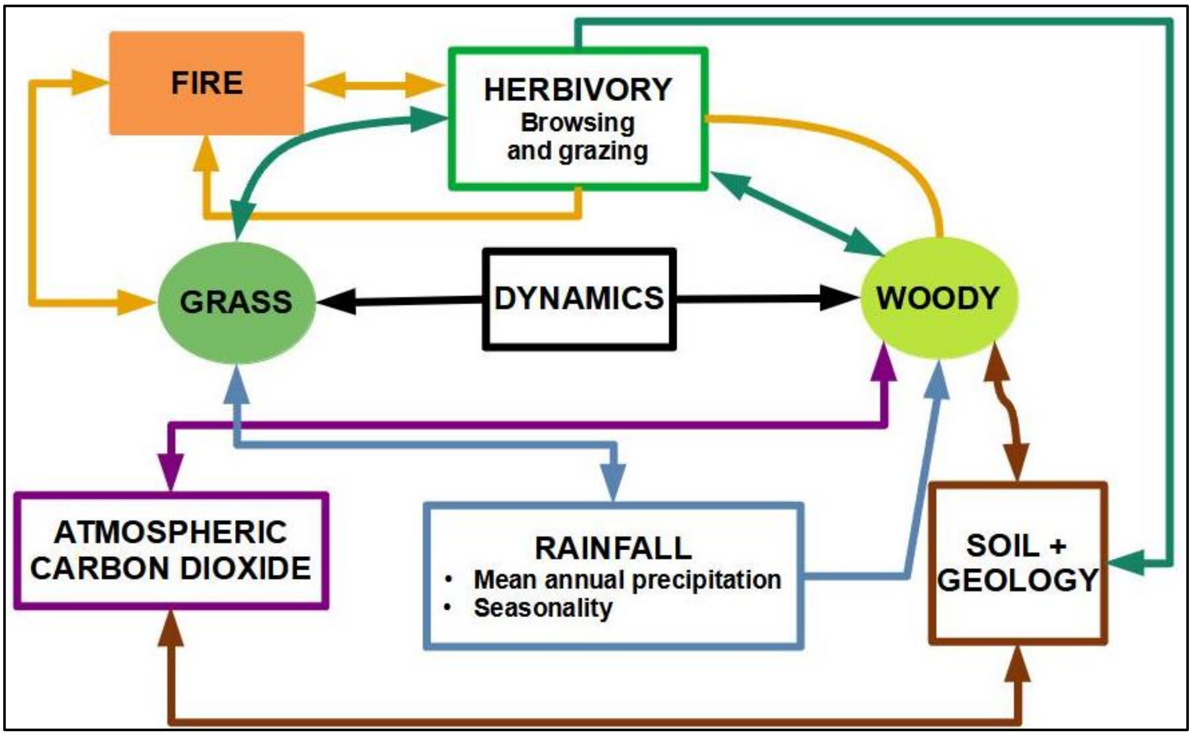



**Figure 2.3: Overview of the factors hypothesised to influence the woody–grass dynamics, which can lead to bush encroachment (modified from Turpie *et al*., 2019).**

### 2.5.1 Climate

#### 2.5.1.1 Precipitation

Seasonal and mean annual precipitation (MAP) are considered primary drivers of BE, which cannot be controlled by management strategies (Naudé, 2018). In arid and semi-arid environments, the woody cover and density tend to increase with the increase in MAP (Turpie *et al*., 2019). High precipitation leads to an increase in soil moisture availability, which allows woody plant seedlings to survive and grow into adult plants and ultimately cause woody thickets (Turpie *et al*., 2019). At local scales, a continual wet period (a high amount of MAP in multiple and consecutive years) can increase the cover and density of woody vegetation (Sankaran *et al*., 2005; Belayneh & Tessema, 2017). Dry savanna ecosystems are generally water-limited and BE is generally associated with erratic and high variability in precipitation (Sankaran *et al*., 2005; Kgosikoma & Mogotsi, 2013). Erratic and variable precipitation also influences woody–grass dynamics through its effects on plant recruitment, growth, and mortality (Briske, 2017). Certain woody species, such as *S. mellifera* need a minimum of three years of successive higher-than-average precipitation to recruit and grow successfully, and combined with other factors, such as heavy grazing and competition for water and nutrients in the soil, may lead to BE (Belayneh & Tessema, 2017).

Drought probability is also considered important, as droughts can increase encroacher seedling mortality (Turpie *et al*., 2019), which is due to highly irregular precipitation and the vanishing of palatable grasses through overgrazing, together with the decrease of water- and nutrients in the soil (Belayneh & Tessema, 2017). As the grasses are removed, this leads to less competition between grass and woody seedlings in the soil, which increases the establishment and growth of woody seedlings. During periods of drought, most of the grazing is depleted and soils are often denuded, which leads to the seedling of invader bushes to establish themselves because they are favoured by the initial absence of competition (De Klerk, 2004). Seasonal precipitation can increase the rate of fire frequency, which reduces the rate of woody vegetation growth (Archibald *et al*., 2009; Turpie *et al*., 2019). Turpie *et al*. (2019) state that deeper root systems have a higher competitive advantage for trees over grasses in dry environments, as the trees can access the subsoil water (Figure 2.1). Yu *et al*. (2017) studied the inter-annual variation in rainfall along the Kalahari Transect in southern Africa, indicating the interaction between grass and trees. In dry environments (MAP < 900-1000 mm), high inter-annual variability favours trees over shallow-rooted grasses, while the opposite is true in wetter environments (MAP < 900-1000 mm) (Yu *et al*., 2017). Therefore, Yu *et al*. (2017) found that wetter environments yield a competitive advantage for grasses (rapid growth rate), decreasing the chances of potential BE. The studies done by Yu *et al*. (2017), and Turpie *et al*. (2019) indicate the dynamic factors, such as precipitation, soil, and plant functional type, driving and controlling BE. This also shows the importance of the BE models (section 1.2), describing the initiation and occurrence of BE. Walter's (1939) two-layer model shows the competition for water and nutrients, between grass and woody vegetation that may lead to BE in soil layers of dry environments, while the non-equilibrium model indicates that ecosystems are vulnerable to external disturbances, such as erratic and variable precipitation, which may benefit woody seedlings to establish and may lead to BE (Higgins *et al*., 2000; Briske *et al*., 2003; Belayneh & Tessema, 2017).

#### 2.5.1.2 Temperature

Temperature is a factor that determines the geographic distribution of organisms (Nievola *et al*., 2017). Precipitation can also be directly influenced by temperature, which can alter MAP. As average temperatures at the earth's surface rise, more evaporation occurs, which increases overall precipitation. The change in temperature changes precipitation, which influences the growth and survival of woody species. The change in temperature and precipitation can disrupt a variety of natural processes, especially if the change occurs quicker than plant species can adapt. Way and Oren (2010) found that increased temperature generally increases tree growth, except for tropical trees. Most higher plants are classified as mesophiles, whose optimal growth range is between 10 to 30 $^{o}$C. Mesophiles are organisms (including woody plants) that grow at moderate temperatures (Biology Online, 2021). Donaldson (1969) (in De Klerk, 2004) found that *S. mellifera* does not tolerate excessively cold or warm humid conditions, since it does not occur naturally in these climatic areas. Smit (1990) (in De Klerk, 2004) found that frost-sensitive seedlings of Dichrostachys cinerea had a better chance for survival under dense bushes than in open grasslands. Therefore, temperature can be considered a minor driving factor of BE.

#### 2.5.1.3 Atmospheric carbon dioxide ($CO_2$)

Although data on atmospheric $CO_2$ will not be used for this study, it is important to understand the impact it has on vegetation globally. According to a variety of authors, the rising atmospheric $CO_2$ may have disproportionate effects on the growth of plants (Barac, 2003; Bond & Midgley, 2012; Devine *et al*., 2017; Turpie *et al*., 2019). The photosynthetic pathways (known as $C_3$, $C_4$, and CAM) may influence the ability of certain types of plants to grow and thrive in a world with elevated atmospheric $CO_2$ (Turpie *et al*., 2019). According to Devine *et al*. (2017), lower concentrations of $CO_2$ are competitively advantageous to $C_4$ plants. In areas with high atmospheric $CO_2$, $C_4$ plants have less of a competitive advantage over $C_3$, which indicates a plausible reason for the triggering of bush encroachment (Idso, 1992, in Devine *et al*., 2017). $C_4$ plants are generally not constrained by available atmospheric $CO_2$, whereas the $C_3$ plants are limited by the amount of $CO_2$ in the atmosphere. Most grass species in drier South African savannas follow a $C_4$ photosynthetic pathway, while woody species use a $C_3$ process.

Bond and Midgley (2012) proposed that with an atmospheric $CO_2$ increase over time, an associated increase in the ability of woody species to thrive and compete with $C_4$ grasses will develop. This is substantiated by the experiments done by Kgope *et al*. (2010). The experiments were done to indicate the effect of elevated atmospheric $CO_2$ on two typical African savanna tree species (*Vachellia karroo* and *Vachellia nilotica*). Kgope *et al*. (2010) found that the woody species presented an increase in growth after exposure to elevated $CO_2$, even after the species were subjected to fire damage and herbivory. Further experimentation and modelling however, may be required to fully understand the effect of atmospheric $CO_2$ on multispecies communities at landscape scales over time (Turpie *et al*., 2019). Three mechanisms have been recognised by a variety of authors, by which trees have an increased competitive advantage over grasses, as a result of increased $CO_2$ levels (Polley *et al*., 1997; Bond & Midgley, 2000; Ward, 2010; Gordijn, 2010). The separate and collective applications of these models assert that $C_3$ woody plants have a competitive advantage over $C_4$ grassy plants, with increasing $CO_2$ levels (Polley *et al*., 1997; Bond & Midgley, 2000; Ward, 2010; Gordijn, 2010). Therefore, they may explain one ($CO_2$) of the many drivers that have led to global BE (Ward, 2010).

### 2.5.2 Topography

Previous studies indicate that topography is a minor factor influencing bush encroachment, as it can influence vegetation distribution and structure (Nunes *et al*., 2019). According to Paudel and Vetaas (2014), slope aspects are likely to influence plant diversity and composition. Other topographic elements, such as elevation and position, also significantly influence plant distribution and attributes through the modification of the local environment (Yang *et al*., 2020). A study done by Sternberg and Shohany (2001) (in Yang *et al*., 2020) found a significant vegetation difference between opposite slopes in semi-arid regions and observed the strongest slope effects in areas with critical water limitation. The slope aspect, together with slope position can jointly influence vegetation structure.

Topography also strongly affects the spatial patterns of precipitation, by altering both the local wind patterns and condensation of perceptible water (Yang *et al*., 2011). A few studies have focused on how topography influences precipitation, whereas fewer studies have been done on the influence of precipitation on topography (Yang *et al*., 2011; Soomro *et al*., 2019). As ridges and mountains are barriers to the horizontal movement of air and force winds upwards and over their slopes. As the air rise, it also cools and is capable of holding less water. Therefore, topography can change the wind patterns, thereby changing precipitation patterns, which has a direct influence on bush encroachment. In semi-arid areas, slope aspect also significantly influences microclimate (i.e. air- and soil temperature, evapotranspiration and wind speed), soil properties (i.e. organic matter content, soil depth- and soil texture), and hydrological processes (i.e. runoff, hydraulic conductivity, and soil water retention) (Yang *et al*., 2020). This results in different or distinct vegetation types occupying opposite slopes. This indicates that topographic variables drive or inhibit encroachers species from surviving on specific slope aspects and positions, making it a minor driving factor.

### 2.5.3 Herbivory

The term "herbivory" refers to the consumption of plant material (both grass and woody) (Collin's Online Dictionary, 2020). Bush encroachment is affected by different aspects of herbivory, which include (1) the type of herbivory (either grazing or browsing), (2) impacts of herbivory on woody and herbaceous plants, and (3) competition between grazing and browsing herbivores.

- **Type of Herbivory**

As mentioned, most previous studies focused on how herbivory (specifically grazing pressure and overgrazing) is a driving factor of BE (Archer *et al*., 1995; Adler, 2001; Scholes, 2009; Devine *et al*., 2017; Belayneh & Tessema, 2017). Grazing pressure refers to "the relationship between the number of animal units or forages intake units, and the weight of forage dry matter unit area at any one point in time" (Tueller, 1992), while overgrazing refers to the mismanagement of rangeland and the removal of more grass than is optimal for maximum grass and animal production (Barac, 2003; Scholes, 2009). Importantly, grazing pressure and overgrazing both refer to the removal of grass through consumption by herbivorous animals. Browsing pressure can be defined as the percent of plants that are prevented by browsing from reaching their potential stature (Keigley & Frisina, 2011). Browsing pressure may also increase the chances of rangeland being dominated by woody plants. Recent studies have shown that the consumption of grass as well as woody plants, play key roles in driving BE (Barac, 2003; Dreber *et al*., 2014; Stevens *et al*., 2016; Skowno *et al*. 2016; Hempson *et al*., 2017; Turpie *et al*., 2019).

- **Impacts of herbivory on woody plants**

African savannas support the most diverse assemblages of browsing herbivores, grazing herbivores, and mixed-feeders in the world (McNaughton & Georgiadis, 1986; Gordijn, 2010). Herbivores may either directly or indirectly, alter woody species composition (McNaughton & Georgiadis, 1986; Gordijn, 2010). The overall plant response to herbivory suggests that it negatively affects the plant (Strauss *et al*., 2002; Gordijn, 2010), however, herbivory may also benefit plants by stimulating plant growth (Gordijn, 2010) and providing a seed dispersal agent

(Walters *et al*., 2005; Gordijn, 2010). Woody plants have developed chemical and physical traits to avoid herbivory (Gowda, 1998, Rohner & Ward, 1997; Gordijn, 2010). Some woody plants produce compounds (secondary metabolites) to deter herbivores by altering the taste and smell of the plant (Provenza, 1995; Gordijn, 2010). Physically, woody plants may grow in less desirable locations for herbivores, i.e. grow in the presence of more preferable species (Hjältén *et al*., 1993; Gordijn, 2010). Woody plants may also grow very tall, such that their canopy is inaccessible to smaller browsing herbivores, such as goats (Allcock & Hick, 2004; Gordijn, 2010). Spines and thorns are another physical development by certain woody plants to deter herbivores (Gordijn, 2010).

Different herbivores are however adapted to forage on woody plants by different methods (Gordijn, 2010). The most widely documented is the damage of elephants (*Loxodonta africana*) (Barac, 2003; Guldemond & van Aarde, 2008; Gordijn, 2010), from tree felling, root damage and removal, branch damage, and bark removal of trees and shrubs (Danell *et al*., 2006; Gordijn, 2010). Within conservation areas in Africa, elephants are known to increase the browsing (feeding on leaves, shoots) pressure, as they can uproot trees, which can lead to a more stable savanna state (Stevens *et al*., 2016, in Turpie *et al*., 2019). Skowno *et al*. (2016), found that woodland areas decreased 0.43% per year to a more savanna state, where elephants were present. The decrease in woody vegetation and associated decrease in tree canopy cover may allow grasses to receive more water and nutrients (Turpie *et al*., 2019). The utilisation of large trees by elephants, especially by debarking, can make these individual trees more susceptible to wood borer infestation and fire damage, which may lead to them being killed or toppled over (Van Wilgen *et al*., 2008; Smit *et al*., 2010).

- **Impacts of herbivory on herbaceous plants**

It is important to understand the impact of herbivores on herbaceous plants (grass) and the indirect consequences for woody plants in savannas (Van Langevelde *et al*., 2003; Smit, 2004; Gordijn, 2010). Defoliation (removal of leaves) without sufficient recovery periods indicates a decrease in grass vigour (strength and health) (Ferraro & Oesterheld, 2002). In return, the decrease in grass vigour leads to a reduction in growth rates and lateral tillers and leads to an increase in the competitive ability of woody plants and resources available for woody plant seedlings (De Klerk, 2004; Cramer *et al*., 2007; Riginos, 2009; Gordijn, 2010). Under intense grazing, less palatable pioneer grass species dominate and will eventually replace more palatable perennials with less palatable annuals (Westoby *et al*., 1989).

Another impact of herbivores is by trampling on grasses and forbs. Trampling refers to the mechanical effect of herbivores' hooves on the vegetative and edaphic components of an ecosystem (Danell *et* al., 2006; Savadogo *et al*., 2007; Gordijn, 2010). Trampling can damage and even destroy the roots or rhizomes of grass, reducing their vigour and creating gaps for woody plant germination. Grazing and trampling together may provide niche gaps for woody plants and increase their germination (Danell *et* al., 2006; Savadogo *et al*., 2007; Gordijn, 2010).

- **Competition between grazing and browsing herbivores**

Studies indicate that the competition between the indigenous herbivores (wildlife) and domestic grazing animals also has an impact on the occurrence of BE (Britz & Ward, 2007; Belayneh & Tessema, 2017; Hempson *et al*., 2017). According to Britz and Ward (2007), "the increase in the woody–grass ratio of savannas has been attributed to the replacement of the indigenous herbivores by domestic grazing animals". This has led to an increase in domestic grazing animals, consuming higher amounts of grass and increasing the grazing pressure of rangelands. According to Belayneh and Tessema (2017), "in the semi-arid savannas, plant composition is dependent upon the types of herbivore species and their grazing frequency and intensity". This statement is substantiated by the study done by Adler (2001) on the effects of grazing on the spatial heterogeneity of vegetation. High levels of grazing can cause a great decrease in aboveground grasses and herbaceous biomass (Belayneh & Tessema, 2017). The decrease in grass competition allows the woody vegetation to establish and increase more effectively. The effect of competition between grazing and browsing animals is also substantiated by Stevens *et al*. (2016), which states that the recent elimination of megafauna, such as elephants, and the overall reduction in mammal browsers can be the cause of wide-scale BE. As mentioned before, browser animals decrease woody vegetation, but with a decrease of browsers because of the replacement with livestock, hunting, and poaching (illegal capture and killing), fewer browser animals can feed on woody vegetation (Hempson *et al*., 2017). Thus, an area with many grazers and few browsers may have a higher chance of being encroached.

### 2.5.4 Fire

Bush encroachment is affected by different aspects of fire, which include (1) the management of fire, (2) types of fires, (3) intensity, seasonality, and frequency of fires, and (4) the response of woody vegetation to fire.

- **Management strategies**

Fire is one of the principal drivers of the structure of savanna ecosystems (Scholes and Archer, 1997) and a principal tool in managing savannas (Bond & Archibald, 2003; Hudak & Fairbanks, 2004; Gordijn, 2010; Smit *et al*., 2010; Naudé, 2018). Fires are typically used on savannas as a management tool to suppress woody cover (Parr & Andersen, 2006, in Devine *et* al., 2017). Fire may also manipulate both livestock and wildlife herbivory patterns (Archibald *et al*., 2005; Gordijn, 2010). The green growth in a burnt area may attract grazing herbivores and focus the impacts of these herbivores on the burnt area (Archibald *et al*., 2005; Gordijn, 2010).

If the grass fuel biomass allows for hot and frequent fires, it increases the capability of controlling woody plant densities by destroying their aboveground biomass (topkill) (Bond and Keeley, 2005; Lohmann *et al*., 2014). Intense and frequent burning regimes limit seedling and sapling establishment, and trees are often suppressed from reaching a reproductive stage (Bond & Midgley, 2000, in Devine *et al*., 2017). As encroachment progresses, there may also be a 'tipping point' as tree canopy cover increases over 45-50%, above which fires rarely occur. According to Scholes (2009) "to keep the trees in check, fires need to be sufficiently intense (> 3000 kW/m) and sufficiently often (< 5 years) to prevent young tree saplings from escaping the 'fire trap'". Once an area heavily encroaches, the fire regime cannot be reversed, and only chemical and mechanical methods can be used for bush clearing (Scholes, 2009). Fire is seen as a risky management regime, as owners fear the risk of damaging infrastructure and/or livestock, as well as removing grass (livestock fodder) (Lohmann *et al*., 2014).

- **Types of fire**

Fire-type is also a factor that may influence bush encroachment. Surface fires (most common) occur below tall tree canopies, whereas crown fires can occur in the canopies of tall trees (Snyman, 2002; Trollope *et al*., 2002; Gordijn, 2010). Head burns and back burns are two types of surface fires that have been used to manage bush encroachment (Trollope *et al*., 2002). Back fires move towards the general wind direction, while head fires move with the wind (Trollope *et al*., 2002). Back fires burn close to the ground and do the most damage to the herbaceous layer (Snyman, 2002). Head fires have a less burning effect on the herbaceous layer and a higher impact on the topkill of trees. Head fires have a longer flame length, resulting in more intense fires and higher damage to woody plants (Trollope *et al*., 2002).

- **Intensity, seasonality, and frequency of fires**

Fire intensity refers to the energy released when burning and may be practically measured by flame length and rate of spread (Bond & Keeley, 2005). Another term is "fire severity", which is also another measure that describes the impact of fires on ecosystems (Gordijn, 2010). High-intensity fires played a crucial role in maintaining open savannas in the past, but with the introduction of livestock farming, veld fires were suppressed (De Klerk, 2004). Fire intensity can decrease woody plants (Smit, 2004; Walters *et* al., 2004; Govender *et al*., 2006) and is positively related to the mortality of woody plant seedlings (Trollope & Tainton, 1986; Gordijn, 2010). The mortality of woody plants due to fire alone however, is low (Trollope & Tainton, 1986; Midgley *et al*., 2010). Studies suggest that increased fire intensities are correlated with greater topkill of woody plants (Trollope & Tainton, 1986). Taller plants with increased stem diameters however, are less vulnerable to stem death, compared to shorter plants (Balfour & Midgley, 2006). Trees with a height ≥ 4 m, show fewer amounts of topkill and are considered to have "escaped" the effects of fire (Trollope & Tainton, 1986; Higgins *et al*., 2000). Environmental factors, such as wind speed, slope, fuel load (grass biomass), type of fire, humidity, temperature, and season of burn may affect fire intensity (Trollope *et al*., 2002). Humidity can decrease fire intensity, whereas wind speed, temperature, and fuel load can increase fire intensity. A down slope would decrease the spread rate and intensity of the fire (Trollope *et al*., 2002). Fires in the wet season have a lower fuel load and higher relative humidity. Therefore, the season may also influence the fire intensity (Trollope *et al*., 2002).

Fire typically occurs in regions with between 450 and 1 800 mm of annual precipitation, particularly in dry seasons, because fire requires a source of ignition, as well as fuel to sustain spread across a landscape (Turpie *et al*., 2019). In southern Africa, the main burning season is usually from March to November (Archibald *et al*., 2008). The duration of the dry season will determine the amount of time that the fuel is dry and available to burn (Archibald *et al*., 2008). Weather conditions on the day of burning however will also determine the fuel moisture (Russell-Smith *et al*., 2007; Archibald *et al*., 2008). A longer dry season will decrease the relative humidity, directly decreasing the fuel moisture and increasing the chances of fire (Archibald *et al*., 2008). Smit *et al*. (2010) found that dry-season fires reduced woody plant cover more than wet-season fires.

Fire frequency measures the occurrence of fires in a specific area for a specific amount of time (Bond & Keeley, 2005). The effect of fire frequency is determined by "event-dependent" and "interval-dependent" factors (Bond & van Wilgen, 1996; Gordijn, 2010). "Event-dependent" effects are determined by factors at the time of the fire, i.e. fire type, fire intensity, and fuel load. "Interval-dependent" factors are mostly influenced by growing conditions between consecutive fires. Previous studies suggest that the response of woody plants to fire frequency is difficult to predict and dissimilar results have been found (Hoffmann, 1999; Higgins *et al*., 2007). Hoffmann (1999) observed that tree density decreased in the Brazilian Cerrado vegetation type with an increase in fire frequency, while Higgins *et al*. (2007) found that fire frequency had no influence on tree density in semi-arid and mesic savannas (Gordijn, 2010). Higgins *et al*. (2007) however, found that woody plant structure was influenced by fire frequency, with the dominance of smaller woody plants (≤ 2 m) increasing in annual and biennial fire treatments. Triennial treatments indicated the increase in the dominance of taller trees (≥ 2 m) (Higgins *et al*., 2007). Smit *et al*. (2010)

found that more frequent fires reduced woody plants more than less frequent fires. "Event-dependent" and "interval-dependent" factors are important to consider when controlling bush encroachment, as they may complicate the responses of woody plants to fire frequency (Pratt & Knight, 1971; Higgins *et al*., 2007; Munkert, 2009; Gordijn, 2010).

- **Woody vegetation responses to fire**

Fire is an important factor in regulating and changing the dynamics of a savanna–woodland ecosystem (Bond & Keeley, 2005; Gordijn, 2010). Previous studies suggest that savanna trees must have adaptations that allow them to survive frequent and intense fires (Balfour & Midgley, 2006; Gordijn, 2010). Bark and branch thickness is an example of woody plants adapting to survive intense fires (Hoffman *et al*., 2003). Studies suggest that woody plants with thicker bark and branches have a higher survival rate (Hoffman *et al*., 2003; Hoffmann & Solbrig, 2003).

In addition to causing woody plant mortalities, fire also reduces the height of woody plants (Hoffmann & Solbrig, 2003). Fire may cause woody plants to be in a "gulliver" state (Bond & van Wilgen, 1996) until a disturbance occurs that enables the escaping of the "fire trap" (Bond & Midgley, 2000; Gordijn, 2010). It is recorded that savanna trees generally mature at shorter heights compared to forest trees (Hoffman *et al*., 2003). This allows savanna trees to reach maturity faster and reproduce in the presence of frequent and intense fires (Hoffman *et al*., 2003).

### 2.5.5 The combined factor of herbivory and fire

The combined effect of herbivory and fire influence BE and can be divided into two aspects: the (1) history of herbivory and fire and (2) the effect of herbivory and fire on woody vegetation.

- **History of herbivory and fire**

The European cattle ranchers that settled in South Africa typically suppressed fire, either deliberately or because the sustained grazing pressure reduced grass fuel load (Archer, 1994; Scholes, 2009; Briske, 2017). At the same time, these ranchers also hunted natural browsers, such as kudu (*Tragelaphus strepsiceros*), giraffe (*Giraffa camelopardalis*), and elephant (*Loxodonta africana*), which led to the increase in tree cover and eventually BE (Archer, 1994; Smit, 2004; Scholes, 2009; Briske, 2017). This may indicate that both main factors, herbivory, and fire, are also a combined factor driving BE.

- **Effect of herbivory and fire on woody vegetation**

Herbivory, specifically the management of grazing, is a factor that directly affects the suppression of fire (Turpie *et al*., 2019). Prolonged and intense grazing of animals (such as goats and cattle) reduces the fuel load, thereby suppressing fire and potentially leading to BE (Madany & West, 1983; Britz & Ward, 2007). Ungulate herbivory is capable of changing the composition and structure of savannas and in combination with fire, can make a significant contribution in the control of encroaching bushes (De Klerk, 2004). Hempson *et al*. (2017) studied the effects of fire and herbivory on a xeric and mesic savanna (Figure 2.4).

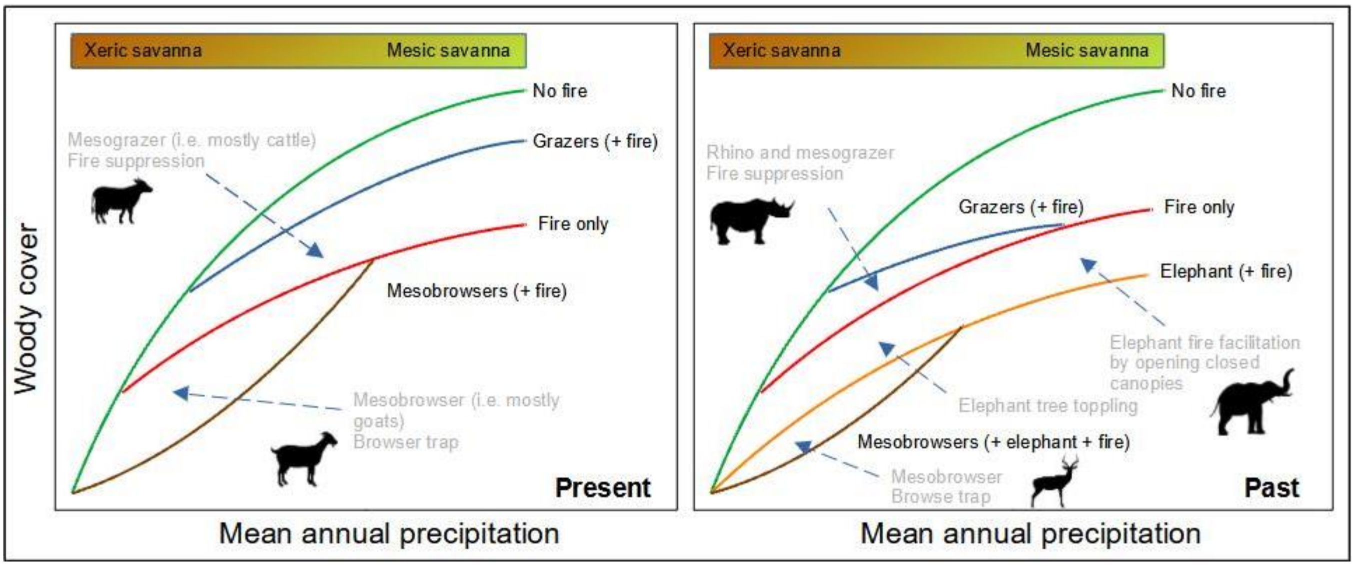



**Figure 2.4: Conceptual model of the effects of herbivore community distortion on woody cover and its direct influence on fire occurrence (modified from Hempson *et al*., 2017).**

From the conceptual model produced by Hempson *et al*. (2017), it is seen that the biomass and functional composition of herbivore communities are different now (left) than in the past (right). In the past, grazers and fire (blue line) suppressed fire by reducing the fuel loads, but elephants (orange line) and other mesobrowsers (brown line) were responsible for controlling the woody cover, by consuming or destroying the woody vegetation (Figure 2.4). In the present, there is an increase in grazing herbivores, accompanied by the suppression of fire. There is also the replacement of elephants with other mesobrowsers (goats), which have a much smaller impact on fire suppression (Figure 2.4) and this leads to the increase of woody cover.

### 2.5.6 Geology

According to Turpie *et al*. (2019), the assessment of underlying geology may be needed to form an effective strategy to combat BE across landscapes. Very few studies have been done on the influence of geology on BE, however studies have been done on the influence of geology on vegetation, which helps understand the influence geology may have on BE. The influence of geology on BE can be split into two basic areas (Cottle, 2004): the direct influence of rock type itself and the indirect role that it plays in soil formation and development of structures that influence vegetation at a range of scales.

There are however limited examples of the direct influence the rock type has on vegetation presence and distribution (Cottle, 2004). The influence of rock type generally relates to species that attach to a rock face (i.e. lichens and some vascular plants) or where direct contact with the rock forms an internal part of the life cycle (i.e. uptake of mineral nutrients) (Cottle, 2004). Studies have been done on certain rocks and geological features, such as sandstone, granite, basalt, and karst landscapes, which influences vegetation distribution and biodiversity (Cottle, 2004; Buitenwerf *et al*., 2012; Acharya *et al*., 2018). However, the main ecological factor determining the distribution and biodiversity of vegetation (including woody plants) will mainly be determined by factors such as climate, slope aspect, and management (Cottle, 2004).

The direct influence of geology on vegetation and specifically BE is mainly based on the influence of the bedrock. Bedrock has great potential to influence overlying vegetation by regulating the chemical and physical properties of the regolith (Hahm *et al*., 2014; Jiang *et al*., 2020). The "bedrock" is the source of most mineral nutrients, such as Fe and P, which subsequently shapes vegetation growth and composition (Jiang *et al*., 2020). The bedrock also contains potentially toxic elements (PTE's), such as lead and cadmium, which can inhibit vegetation growth (Zang *et al*., 2015; Jiang *et al*., 2020).

The weathering products of parent material may play a primary role in vegetation growth as the weathered material may inhibit or increase vegetation growth (Cottle, 2004). The weathered material is comprised of elements that may increase vegetation growth (such as P and N) or inhibit growth (such as Cd or Mn). According to Cottle (2004), most higher plants do not indicate rock preferences as to preferred habitats. It is mostly the weathered products of rocks, such as soils, that may influence vegetation type and distribution (Cottle, 2004). Importantly, soils reflect the type of parent material, both the physical properties such as texture, colour, and weatherability and in chemical composition (Cottle, 2004). Organism activity, slope, relief, climate, and time however are also main factors contributing to soil formation, which may affect BE (Monroe *et al*., 2007). Rock types weather to a different material that may influence vegetation growth in the soil. These rock types include: ultramafic, mafic, intermediate, and felsic.

- **Ultramafic, mafic, intermediate and felsic rocks**

The term "ultramafic" refers to the mineral content of more than 90% ferromagnesian silicate (Winter, 2014). Ultramafic rocks contain a high amount of Fe and Mg relative to silicon and include minerals such as olivine, pyroxene, amphibole, biotite, and serpentine (Boneschans *et al*., 2015).

Ultramafic rocks include peridotite, pyroxenite, and komatiite (Monroe *et al*., 2007; McCarthy & Rubidge, 2005). Mafic rocks contain 45–52% silica and include rocks such as basalt and gabbro (Monroe *et al*., 2007). Ultramafic and mafic rocks containing minerals such as olivine, pyroxene, and amphibole, weather to clay minerals and iron oxides (Huang & Wang, 2005). The weathered clay minerals include minerals such as smectite, kaolinite, halloysite, while the iron oxides include goethite and hematite (Cottle, 2004; Wilson, 2004; Huang & Wang, 2005). Pyroxenes and amphiboles are largely confined to the sand and silt fractions of soils (Huang & Wang, 2005). Soils developed from ultramafic and mafic soils tend to have low Ca concentrations and/or high Mg concentrations (Boneschans *et al*., 2015). Ultramafic soils will also generally have weak soil structure, low CEC, and low water retention (Boneschans *et al*., 2015). Ultramafic and mafic soils require vegetation to be well adapted to lack of moisture and nutrients, high exchangeable Ca: Mg rations, and high concentrations of PTE's (such as Cr, Co, and Ni) (Boneschans *et al*., 2015).

The term "intermediate" refers to rocks comprised of mafic and felsic minerals and include rocks, such as diorite and andesite, while "felsic" refers to minerals rich in silica (> 65%) and include rocks, such as granite and rhyolite (Monroe *et al*., 2007; Winter, 2014). Felsic rocks are rich in minerals containing a high amount of silicon, such as feldspars, micas, and quartz. Quartz and feldspars are the most abundant primary minerals in soils and are found in virtually all sediments (Huang & Wang, 2005). Micas are 2:1 phyllosilicates with tightly help, non-hydrated, interlayer cations balancing a high layer charge (Huang & Wang, 2005). Micas are abundant in many rocks, such as shales, slates, schists, gneisses, granites, and sediments derived from these rocks (Huang & Wang, 2005). The micas in soils are mainly inherited by soils from parent materials and are found in intermediate rocks, but are more extensive in felsic rocks (Huang & Wang, 2005). Micas weather to 2:1 clay minerals, such as vermiculite and smectite, which usually develop into swelling vertic soils (Wilson, 2004; Huang & Wang, 2005; Soil Classification Working Group, 2018). Feldspars are commonly present in the silt and sand fractions of young to moderately developed soils, representing various soil parent materials and soil-forming conditions (Huang & Wang, 2005). Feldspars are composed of macronutrients K and Ca, and play a substantial role in the overall K dynamics in soils (Huang & Wang, 2005). Quartz is present in essentially all soils and often constitutes the major portion of all sand and silt fractions (Huang & Wang, 2005). The weathering of a pure quartz sandstone yields no clay, whereas weathering of clay yields no sand (Monroe *et al*., 2007). The influence of soil texture on BE will be thoroughly explained in section 2.5.7.1**Error! Reference source not found.**. The weathering of parent material can also determine the soil depth, which influences the competition between woody vegetation and grass (Figure 2.1). The metamorphic rock quartzite (consisting mainly of metamorphosed quartz) will have thin soil over it, because it is chemically stable, while an adjacent body of granite will have a much deeper soil (Monroe *et al*., 2007).

- **Previous studies on geology and bush encroachment**

A study done by Buitenwerf *et al*. (2012), demonstrated that BE occurs rapidly on granite-based soils (sandy), but is mostly absent in basalt-based soils (clayey). The location sampled on granite soils however, was in unstable wet savanna (MAP of 737 mm/yr), whereas the basalt-based study site was a dry stable savanna (MAP of 537 mm/yr) (Buitenwerf *et al*., 2012). Although fire treatment was tested in this study, it had surprisingly no significant effect on tree density (Buitenwerf *et al*., 2012). The study done by Buitenwerf *et al*. (2012), precipitation was the main factor driving BE, although the geology presented significant results. Overall, the permeability of the geological bedrock and the weatherability of rocks present a key role in geology driving BE.

A study done by Boneschans *et al*. (2015) on vegetation in the Vredefort Dome, South Africa, indicated that most woody species (including *Senegallia caffra* and *Vachellia robusta*) is mainly restricted to Na–Ca-rich felsic rock types, however, species such as *V*. *karroo* are unaffected and tend to dominate ultramafic rock outcrops, rich in Mg, Cr, Co, and Ni (Boneschans *et al*., 2015). Conversely, *V*. *karroo* was able to outcompete *S*. *caffra* and *V*. *robusta* on ultramafic and mafic rock types. Recognised encroacher species that were associated with ultramafic and mafic soil environments included *Asparagus suaveolens* and *V*. *karroo* (Boneschans *et al*., 2015; Turpie *et al*., 2019). Areas dominated by siliceous quartzite indicated lower soil pH and nutrients, with encroacher species including, *Grewia flava* and S. *caffra* present in these areas (Boneschans *et al*., 2015). The findings of *V*. *karroo* being more adapted to these soils indicate that certain species may be more adapted to specific geology and more prone to BE.

### 2.5.7 Soil

Previous studies indicate that soil types are accepted as an important driving factor of BE (Belayneh & Tessema, 2017; Devine *et al*., 2017; Turpie *et al*., 2019). Brady and Weil (2017) define soil as “a dynamic natural body composed of mineral and organic solids, gases, liquids and living organisms which can serve as a medium for plant growth”. In South Africa, soils are classified into respective soil forms and soil families, according to specific characteristics and properties (Soil Classification Working Group, 2018). The classification of soils according to a specific “soil type”, however, is a broader, widely used classification term throughout the world (Barrera-Bassols *et al*., 2006, in Brady & Weil, 2017). A soil type refers to a member of a soil series distinguished mainly by texture (Merriam-Webster’s Dictionary, 2020). Plant species composition is influenced by soil properties, such as nutrient status, pH, salinity, and texture (De Klerk, 2004). Soil types are characterised by important properties, such as water infiltration rate, runoff, and water-holding capacity that may play a role in driving and/or controlling BE (Breman & Kessler, 1995). Other soil properties, such as depth, and structure may also influence BE (Britz, 2004; Ward *et al.*, 2013). Because soil types are distinguished mainly through their texture, the main soil types are referred to as clayey, silty, sandy, loamy, and chalky soils.

#### 2.5.7.1 Soil texture

The texture of the soil refers to the size distribution of soil particles (Brady & Weil, 2017). According to Brady and Weil (2017), the particle sizes of soil can be classified as the following: gravel (> 2 mm), sand (< 2 mm – 0.05 mm), silt (< 0.05 – 0.002 mm), and clay (< 0.002 mm). Soil texture is an important characteristic because many other soil properties are influenced by texture, such as water-holding capacity, drainage rate, compatibility, aeration, and the flow of water through the soil profile (Easton, 2016; Brady & Weil, 2017). Soil texture may influence soil nutrients, thereby also influencing BE.

- **Influence of soil texture on plant nutrients**

Brady and Weil (2017) state that the larger the particle size means that pores cannot hold nutrients and water against the pull of gravity. Coarse soil texture is associated with large soil pores, while a fine soil texture is associated with small pores (Brady & Weil, 2017). Thus, the finer the particle size, the higher the retention of water and nutrients. As such, the number of clay particles in soil affects the amount of nutrients through its positive effect on the cation-exchange capacity (CEC) of soil. According to Whitehead (2000) (in Britz, 2004), the CEC determines the number of cations that can be absorbed in an exchangeable fashion in soil. Finer or clayey soils will have a higher CEC and organic matter than coarse or sandy soils (Brady & Weil, 2017).

Soil pores allow the soil to ventilate ($CO_2$ escaping and $O_2$ entering the root zone), as well as to absorb water and retain it where it can be used by plant roots (Brady & Weil, 2017). Thus, since plants use water continuously, the water-holding capacity of soils is essential for plant survival (Brady & Weil, 2017). Soil provides important cations and anions that act as determinants of the composition, structure, and productivity of vegetation (Smit, 2004) These important cations and anions include: calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), Nitrogen ($NH^{4+}$), potassium ($K^{+}$) phosphorous ($HPO_4^{2-}$), and sulphur ($SO_4^{2-}$). Soil also provides vegetation with micronutrients including: copper ($Cu^{2+}$), cobalt ($Co^{2+}$), iron ($Fe^{2+}$), manganese ($Mn^{2+}$), nickel ($Ni^{2+}$), zinc ($Zn^{2+}$), boron ($H_3BO_3$, $H_4BO_4^{-}$), chlorine ($Cl^{-}$), and molybdenum ($MoO_4^{2-}$) (Brady & Weil, 2017). Soil provides sodium ($Na^{+}$) in small amounts, which is essential for plants using the $C_4$ photosynthesis pathway (Brady & Weil, 2017:25). Although many other elements (such as fluorine ($F^{-}$) and barium (Ba) are taken up from soils by plants, they are not essential for plant growth.

- **Influence of soil texture on bush encroachment**

Kgosikoma and Mogotsi (2013) found that BE is more likely to occur in sandy soils with low clay content. As soil texture gets finer, there is a reduction in soil infiltration but an increase in soil moisture retention as clayey soils have a higher water-holding capacity compared to sandy soils (Brady & Weil, 2017). Dodd *et al*. (2002) also found that BE is more likely to occur on sandy soils. Dodd *et al*. (2002) used the model, presented by Sala *et al.* (1997), which is based upon two factors controlling bush and grass dominance: firstly, the seasonal correlation between monthly temperature and precipitation, and secondly the soil texture. Dodd *et al*. (2002) predicted that woody vegetation should dominate on very-coarse textured soils. The bush biomass was positively associated with topsoil having a high sand content, over medium-textured subsoil. Dodd *et al*. (2002) concluded that $C_3$ grasses and bush/shrubs are associated with sandy topsoil over medium-textured subsoil. There was also an association between $C_4$ grasses and half-shrubs with fine-textured soils. The findings by Dodd *et al*. (2002), support the conceptual model of Sala *et al.* (1997) at the regional scale and that bush dominance is mediated by coarse-textured soils.

According to Devine *et al*. (2017), "*low nutrient availability is a widely cited hypothesis for the lack of trees in savanna biomes, as poor soil quality limits tree growth*". A study by Mills *et al*. (2013) also indicates that areas with high nutrient availability are associated with a reduction in woody cover. The reduction in woody cover was however the result of competition with herbaceous vegetation (Mills *et al*., 2013). The woody–grass interaction is a very complex and dynamic system, as different factors facilitate both tree and grass growth. Devine *et al*. (2017) state that "*high precipitation and nutrient availability facilitate rapid tree growth, resulting in a transition to a forest system*". Although low precipitation and high nutrient availability facilitate palatable grass growth, which leads to increased herbivory and results in a savanna system (Lehman *et al*., 2011, in Devine *et al*., 2017). Studies by Mills *et al*. (2013) and Devine *et al*. (2017), confirm that the nutrient availability in the soil is important regarding whether grass or woody vegetation will establish and dominate. Schlesinger and Pilmanis (1998) concluded that in arid environments plant nutrients are concentrated in soil dominated by shrub/bush vegetation. According to Schlesinger and Pilmanis (1998), "*the establishment of shrub vegetation stimulates the processes leading to the formation of soil islands, allowing the persistence and regeneration of shrubs*". Soil islands are strong accumulations of plant nutrients and infertile soils between shrubs (Noy-Meir, 1985, in Schlesinger & Pilmanis, 1998). A broad-scale analysis of woody cover in African savannas revealed that less woody cover is found in soils with a high nitrogen concentration, indicating the importance of the nutrients in the soil (Kgosikoma & Mogotsi, 2013).

Importantly, soil moisture is one of the most crucial aspects determining which type of vegetation will function in soils. This is substantiated by Rodrigues *et al*., (2018), where water availability influences the observed vegetation formation in the savanna region, with the shortest woody individuals found in that region. Rodrigues *et al*., (2018) concluded that soil plays a more important role in the determination of structure and diversity in savanna habitats than in forest habitats. Forests occur over soils with higher nutrient- and water availability, while savannas tend to occur over soils with nutrient-poor soils (Rodrigues *et al*., 2018).

#### 2.5.7.2 Soil depth

Soil depth is an important soil characteristic that influences soil moisture and nutrients, and directly affects vegetation competition (Britz, 2004). The two-layer hypothesis (Figure 2.1) proposed by Walter (1939) (in Ward *et al*., 2013) explains how water is the limiting factor for plants, with the assumption that grasses use only topsoil moisture and nutrients, while woody plants use subsoil resources. Grasses have a fibrous root system of limited depth, which is well suited for exploiting soil resources in the upper 20–30 cm of the soil profile (Briske, 2017). As the grass is removed through overgrazing, less water is extracted from the topsoil and more water is available in the subsoil for woody plant growth (Wiegand *et al*., 2005). Importantly, the grass is generally favoured by fine-textured and shallow soils that retain water and nutrients near the surface (Briske, 2017). Woody plants are generally favoured by deep, coarse soils that facilitate percolation (further downward movement of water after infiltration) and nutrient leaching (Briske, 2017). Woody plants are limited in shallow soils, where bedrock or claypan horizons restrict the taproot extension (Briske, 2017). Because many woody species have a deep taproot and shallow lateral extensive root system (Scheck & Jackson, 2002), it allows them to capture water and nutrients in areas with low precipitation (Fravolini *et al*., 2005, in Briske, 2017). Therefore, woody plants with this dimorphic root system can exploit a wide range of growing season conditions (Scott *et al*., 2006, in Briske, 2017).

According to Cole (1982) (in Britz, 2004) on a global basis, the height and spacing of the woody and grassy components of savanna vegetation are influenced by soil moisture conditions within the soil profile. According to Dye and Walker (1980) (in Britz, 2004:35) soil structure and depth, also significantly influences species competition. Dye and Walker (1980) (in Britz, 2004), found that on deep soils (with sufficient rooting depth), perennial grasses occurred in abundance, and woody vegetation could establish successfully. Shallow soils, however would limit root growth, making such soils less suitable for woody plants and less prone to encroachment (Britz, 2004).

Soil depth may also influence temperature, as the insulating properties of soil protect the deeper section of the root system from extreme temperatures (Brady & Weil, 2017). According to Jordan *et al*. (2005), “turfgrass growth, health, and appearance are greatly affected by its environment”. The supra-optimal temperature (35 ºC and above) in the rootzone, increases root mortality, while it decreases the number of roots and nutrient content of the roots and shoots (Huang & Xu, 2000, in Jordan *et al*., 2005). Phytotoxic substances can be caused by chemical spills, herbicide application, or produced by plant roots or micro-organisms (Brady & Weil, 2017). Soil protects plants from such substances by ventilating gases, decomposing organic toxins, or by suppressing toxin-producing organisms (Brady & Weil, 2017).

#### 2.5.7.3 Soil structure

Soil structure is influenced by the aggregation of soil particles, as well as the amount of organic matter present (Britz, 2004). Both, soil structure and organic matter determine the amount and availability of soil moisture in a given area at any given time. The effects of soil structure and organic matter content of soil on savanna vegetation are seen in African savannas (Britz, 2004). According to Cole (1982) (in Britz, 2004) parkland vegetation (large, scattered trees in a grass layer) with deep-rooted, woody species (such as *Vachellia erioloba*), are the dominant woody species and confined to deep sandy soils. Cole (1982) (in Britz, 2004) also stated that the dominance of the woody plants is explained by the roots of the woody plants able to extract water from the water table. Different root structures allow some woody plants (such as *V. erioloba*), to have a competitive advantage over other woody plants, and outcompetes them from such areas (Britz, 2004:35).

Plant root growth and morphology can also be influenced by soil structure, specifically by the bulk density. Soil bulk density expresses the ratio of the mass of dry soil to the total volume occupied in the soil (Easton, 2016). Soil structure determines the bulk density of soil and the ease with which roots can penetrate the soil. The higher the bulk density for a given class, the more compact the soil (Britz, 2004). Thus, the more poorly defined the structure and less pore space, the lower the root penetration, as well as lower levels of oxygen for root respiration. It is important to note that compaction is a negative term when referring to root growth, but slight compaction may benefit plant growth as it improves the capillary movement of water to seeds (Kozlowski, 1999). In arid savannas, the herbaceous layer largely disappears under high tree densities, leaving large areas of bare soil surfaces (Smit, 2004). Crust formations will often form, as the soil is compacted and little organic material is present in the soil, which leads to reduced infiltration and causes substantial losses of water due to runoff (Smit, 2004).

# CHAPTER 3 GEOGRAPHIC INFORMATION SYSTEM (GIS)

## 3.1 Introduction

Geographical information system (GIS) analysis has frequently been used to determine the driving factors of land degradation, such as soil erosion, soil salinization, waterlogging, deforestation and desertification (FAO, 1994; Kakembo, 1997; Van Zijl *et al*., 2013; Belayneh & Tessema, 2017). Encroachment by bush is recognized as a major factor that aggravates degradation of rangelands, specifically in dry land areas of the world (Belay *et al*., 2013). In this chapter, GIS will be used to determine the driving factors of bush encroachment (BE) and bush thickening (BT) in the North West Province (NWP) of South Africa.

## 3.2 Materials and methods

### 3.2.1 Summary

Maps indicating the percentage (%) of woody cover in the NWP, for the years 1993, 1998 and 2018 were sourced from Symeonakis *et al*. (2020). Unfortunetely, woody cover maps of other provinces were not available to be used for this study. The layers indicating the % woody cover in the NWP were used for calculating the spread of bush (bush encroachment, bush thickening and bush lessening) and bush spread maps were created for time frames, 1993-1998, 1998-2018 and 1993-2018. Potential driving factors of BE were sourced from various sources and used to analyse the bush spread and determine the driving factor/s of the specific bush spread from 1993 to 2018 on a provincial scale. Four smaller areas were identified based on the significant spread of bush and the same analyses was done for determining the driving factor/s of specific bush spread from 1993 to 2018 on significant areas.

### 3.2.2 Site description

The NWP is one of the nine provinces of South Africa (Figure 3.1) and is located between 22 and 28 degrees longitude east of the Greenwich Meridian and between 24 and 28 degrees latitude south of the equator (Cowley, 1985). The NWP is situated in the north-western part of South Africa and shares borders with Botswana and four other provinces, namely Northern Cape-, Free State-, Gauteng- and Limpopo provinces (NWREAD, 2015). With a size of 104 882 ha, it is the sixth largest province in South Africa and is consists primarily of arid and semi-arid savanna areas (NWREAD, 2014). The land-use of the province is dominated by agriculture (Botai *et al*., 2016). Other dominant land-use also include communal- and commercial livestock and wildlife (Jordaan *et al*., 2019). A recent report by Stats SA (2021) indicates that the NWP has an estimated population of 4.15 million people. The mean annual precipitation (MAP) of the NWP is between

300 and 750 mm, while the mean annual temperature (MAT) ranges between 16 to 21 ºC (Schulze, 2007). The altitude above sea level ranges between 900 and 1 900 m. The vegetation types of the province consist mainly of the Central Bushveld, Dry Highveld Grassland and Eastern Kalahari Bushveld bioregions (Mucina & Rutherford, 2006).

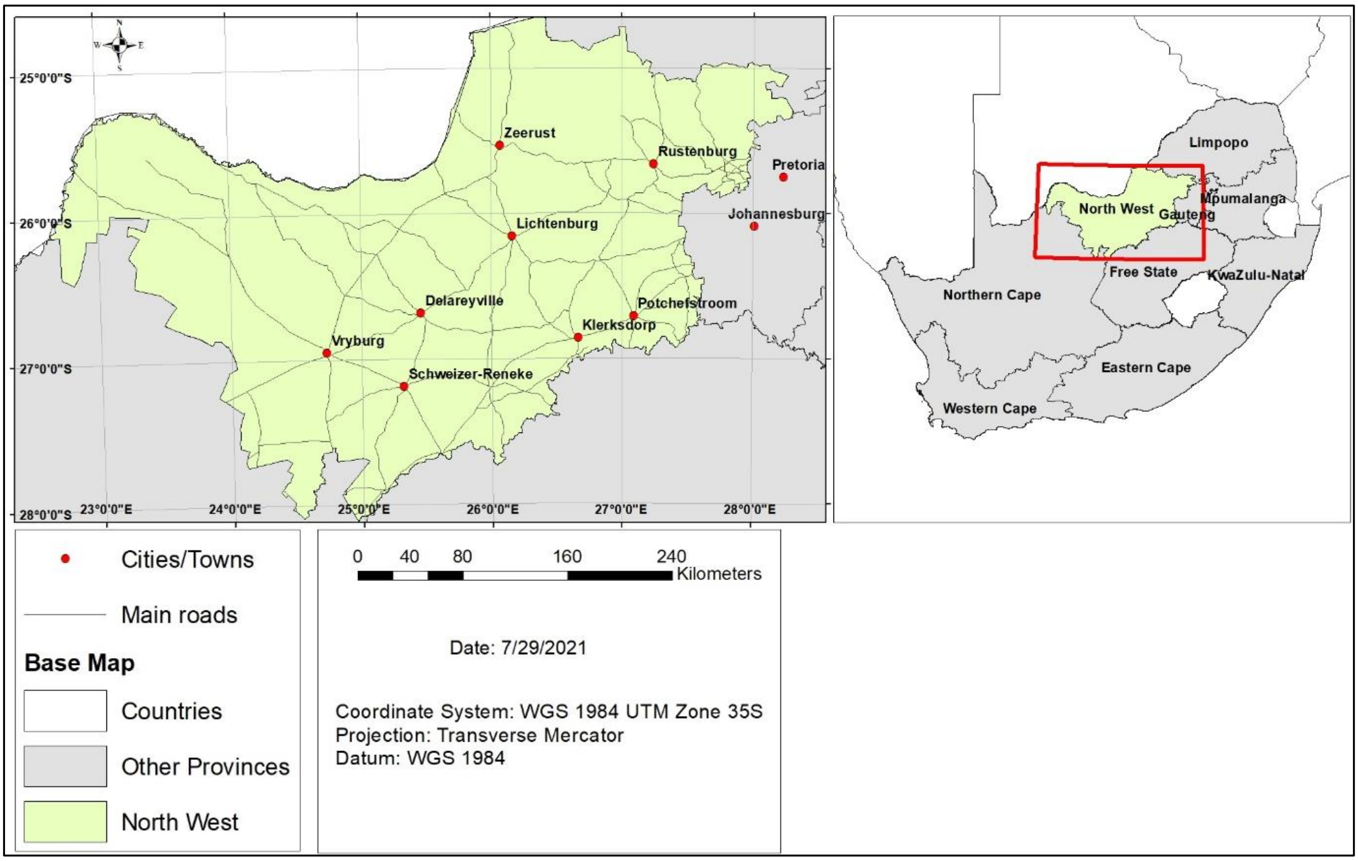



**Figure 3.1: A map indicating the location of the North West Province in South Africa.**

### 3.2.3 Obtaining and pre-processing GIS data

#### 3.2.3.1 Bush spread

For the maps sourced from Symeonakis *et al*. (2020), a manually annotated point data set was used and two datasets were estimated by Random Forest Classifier and U-Net models. The best performing regression models was used and the woody cover percentage (%) were calculated for the NWP for the different epochs. The resolution of these data sets was 30 m × 30 m and resampling did take place (Symeonakis *et al*., 2020).

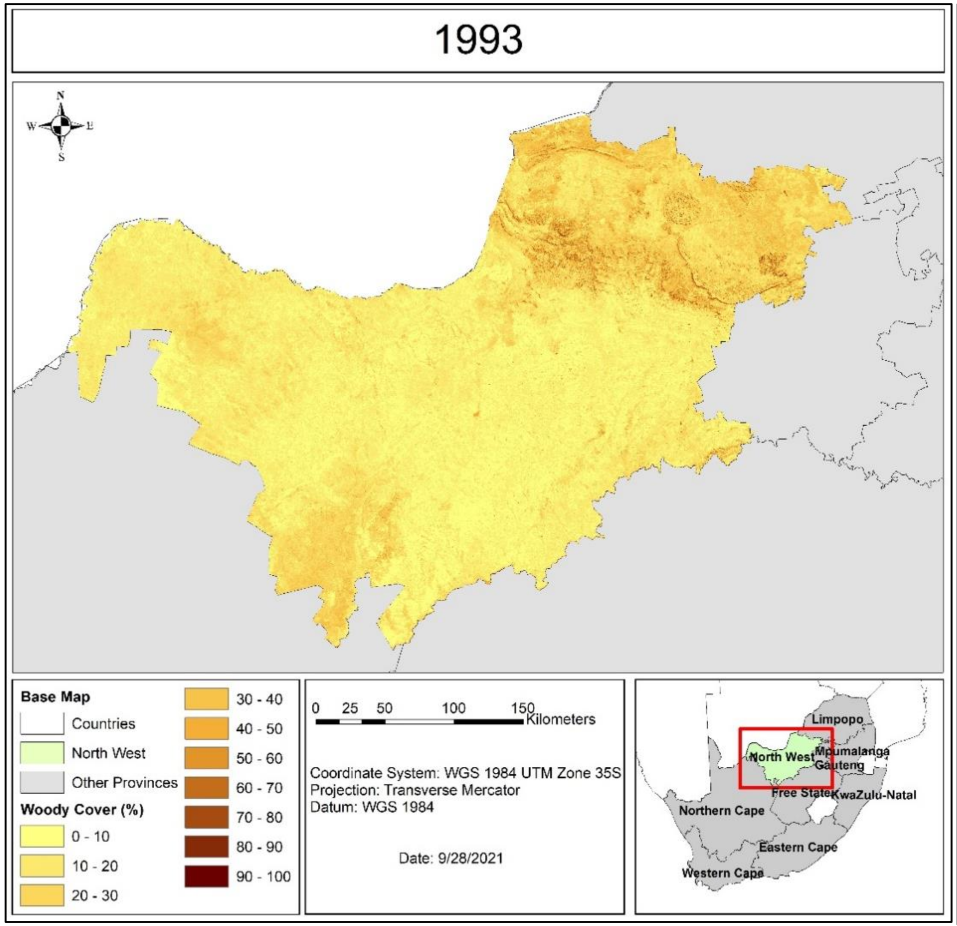
Figure 3.2 (a-c) presents maps that showed the % woody cover in the NWP (sourced from Symeonakis *et al*. (2020)), which were used to calculate the bush spread for time frames 1993-1998, 1998-2018 and 1993-2018. This data was analysed on a provincial scale, and four significant areas where there was considerable change in the bush spread was also identified, using the constraints as seen in Table 3.1.

**Table 3.1: The bush spread and corresponding constraints for the NWP.**

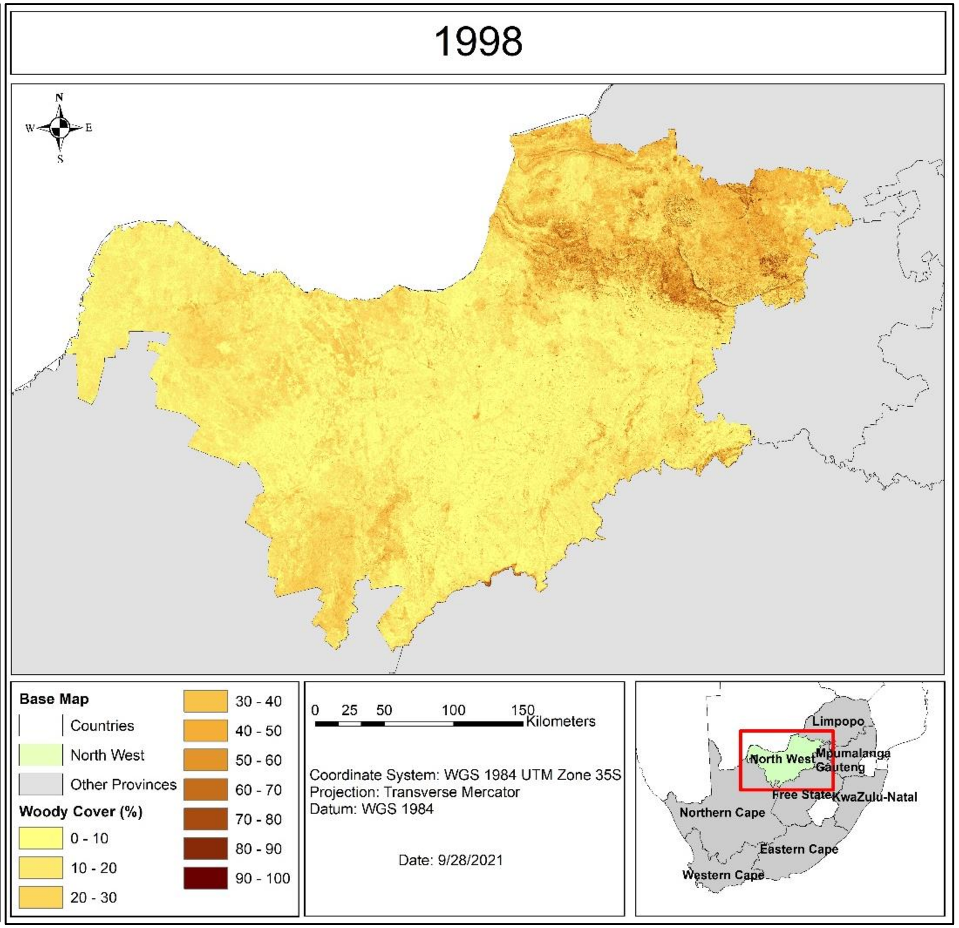
| Bush spread | Constraints |
|---|---|
| **No change (NC)** | Any change between -2 – 2 % woody cover |
| **Bush encroachment (BE)** | 0 – 10 % woody cover in earlier year, that showed any increase > 2 % woody cover over the time period |
| **Bush thickening (BT)** | > 10 % woody cover in earlier year, that showed any increase > 2 % woody cover over the time period |
| **Bush lessening (BL)** | Any decrease > -2 % woody cover over the time period |

The selection of the specific bush spread constraints is described below.

- No change (NC): areas that experienced little to no change of bush spread (increase or decrease) over the time period. The -2 – 2% woody cover class was selected as almost no data was found between -1 and 1% woody cover class, which was originally considered for the "no change" category.
- Bush encroachment (BE): areas with few to none woody plants that experienced the proliferation or establishment of woody (encroacher) plants. The 0 – 10 % woody cover class was selected for the earlier year, as this indicated few to none woody plants in an area and with the > 2% woody cover increase for this class seen as the establishment of woody plants in that area.
- Bush thickening (BT): areas with already established woody plants that grew larger and denser (thickened) over time. Areas with > 10 % woody cover was selected as already established woody plants and an increase of > 2% woody cover indicated the growth or thickening of these established woody plants.
- Bush lessening (BL): areas where woody plants were removed through natural or anthropogenic causes. Areas that showed any decrease > 2 % woody cover over the time period was seen as bush lessening.


1993
N
W
E
S
Base Map
Countries
North West
Other Provinces
Woody Cover (%)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
0 25 50 100 150
Kilometers
Coordinate System: WGS 1984 UTM Zone 35S
Projection: Transverse Mercator
Datum: WGS 1984
Date: 9/28/2021
Limpopo
North West
Mpumalanga
Gauteng
Free State
KwaZulu-Natal
Northern Cape
Eastern Cape
Western Cape

(a)


1998
N
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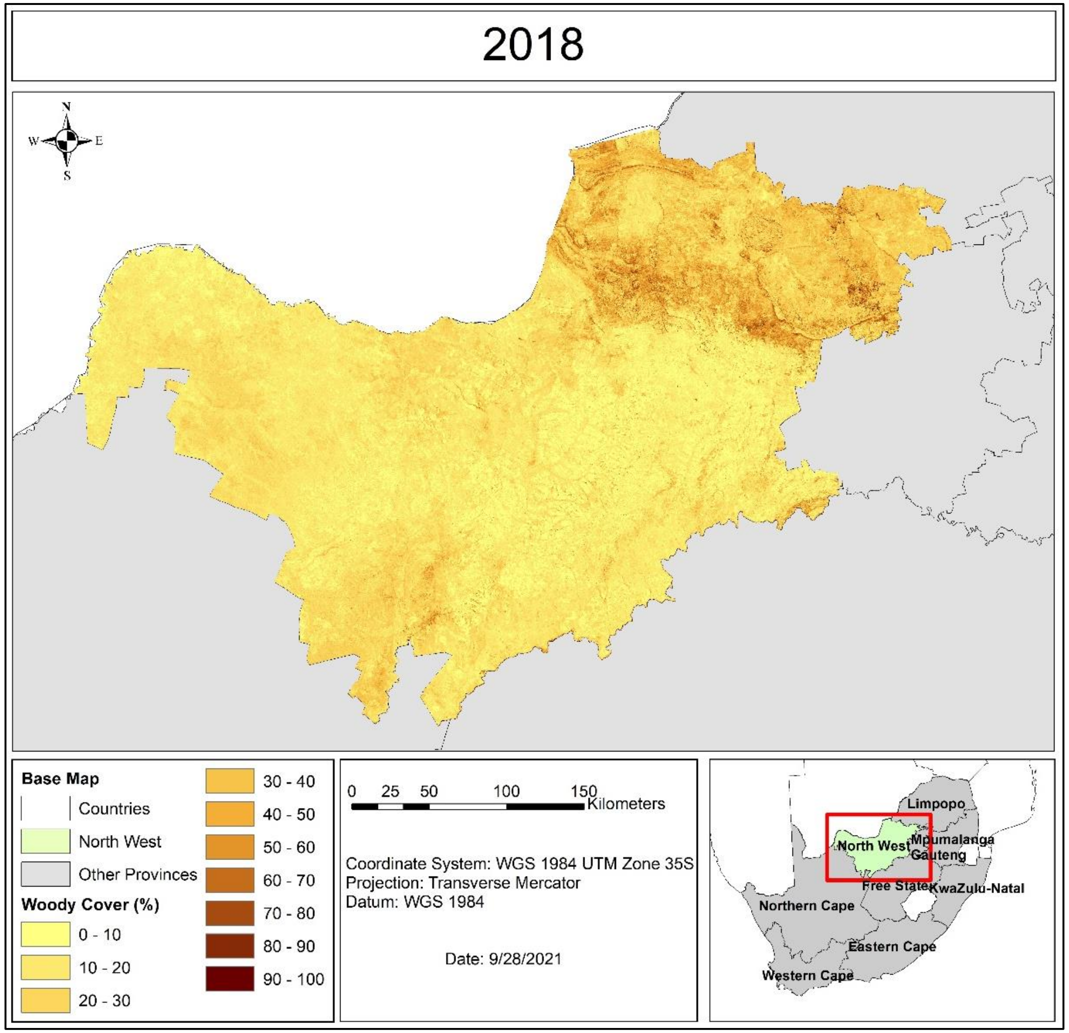
Base Map
Countries
North West
Other Provinces
Woody Cover (%)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
0 25 50 100 150
Kilometers
Coordinate System: WGS 1984 UTM Zone 35S
Projection: Transverse Mercator
Datum: WGS 1984
Date: 9/28/2021
Limpopo
North West
Mpumalanga
Gauteng
Free State
KwaZulu-Natal
Northern Cape
Eastern Cape
Western Cape

(b)




(c)

**Figure 3.2: A map indicating the % woody cover in the NWP for (a) 1993, (b) 1998 and (c) 2018 (from Symeonakis *et al*., 2020).**

#### 3.2.3.2 Potential driving factors of bush encroachment

Spatial data representing potential drivers of BE was obtained from various sources (Table 3.2) and clipped for the NWP using the "Clip" tool in ArcMap 10.8.1 (ESRI, 2020). After the "clipping procedure", all the layers (raster and vector) representing potential drivers of BE, still contained map units of the entire South Africa and had to be obtained for the NWP. The map units to be used in the analysis were obtained by using the "Dissolve" tool, to aggregate specific polygons for vector layers, while for raster layers, the continuous data were manually classified into specific classes. All vector layers were then converted to raster layers, using the "polygon to raster" tool. All the layers (presenting different resolutions) were then converted to American Standard Code for Information Interchange (ASCII) files, using the "Raster to ASCII" tool, to enable the layers to be imported into SAGA 2.1.4 (Conrad *et al*., 2015). Within SAGA 2.1.4, the layers were projected ("Projection" tool) to a common projected co-ordinate system (WGS 84 UTM Zone 35S), and resampled ("Resample" tool) to the grid extent and 30 m pixel size of the % woody cover layers provided by Symeonakis *et al*. (2020).

**Table 3.2: The maps of potential driving factors of bush encroachment that were obtained and pre-processed to be used for the GIS analysis.**

| Driver | Map/Layer | Reference | Format | Map Units |
|---|---|---|---|---|
| **Topography** | SRTM 30 m DEM | USGS, 2021 | Continuous Raster | 100 m increments |
| **Climate** | Mean annual precipitation (MAP) | Schulze, 2007 | Continuous Raster | 50 mm/ year increments |
| **Climate** | Mean annual temperature (MAT) | Schulze, 2007 | Continuous Raster | 1 ºC increments |
| **Land-use** | National Land Cover maps | Thompson, 2018 | Classed Raster | SALCC1 |
| **Soil** | Broad Land Types (South African Broad Land Types) | Land Type Survey Staff, 1972-2006 | Vector | Extensive land types |
| **Vegetation** | SANBI vegetation map | SANBI, 2012 | Vector | Bioregions |
| **Geology** | 1: 1 000 000 Geological map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland | Council for Geoscience, 2019 | Vector | Geological categories |

#### 3.2.3.2.1 Provincial scale

Table 3.2 indicates the potential driving factors of BE that were obtained and pre-processed for the analysis on provincial scale. Topography was represented by altitude above sea level (m), as derived from the SRTM 30 m DEM (USGS, 2021) (Figure 3-3) and 100 m increments were used for increments. Climate was represented by MAP and MAT as derived from Schulze (2007) (Figure 3.4). The MAP map units were divided in 50 mm per year increments, while the MAT map units were divided in 1 ºC increments. The South Africa National Land Cover (SANLC) maps (Thompson, 2018) (Figure 3.5) was used to represent land-use and the South African Land Cover Category 1 (SALCC1) was used as the map units (Table 3.3), as it was deemed to be the appropriate scale for this regional study. The South African Land Types (Land Type Survey Staff, 1972-2006) (Figure 3.5) represented the soil layer and 'Extensive' land types were chosen for the map units. An extensive land type refers to the first letter of the land type code, i.e A-I (Table 3.4). The SANBI vegetation map (SANBI, 2012) was used to represent the vegetation layer (Figure 3.6) and bioregions (Table 3.5) used as map units, as they were regarded as being on the correct scale for the provincial study. The Geological map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland (Council for Geoscience, 2019) (Figure 3.6), was used to represent geology as a potential driving factor of BE in the NWP. The map units (Table 3.6 and Table 3.7) were assigned manually to each polygon, in a new field added to the attribute table in ArcMap 10.8.1. The map units and their associated descriptions were derived from the dominant, as well as most abundant rock type in the geological formations and groups of the NWP (Council for Geoscience, 2019), and are described using common, well-defined geological terms (Winter, 2014).

**Table 3.3: The map units of the South African National Land Cover (SANLC) map (Thompson, 2018), representing land-use as potential driver of bush encroachment.**

| Map Unit | SALCC1 | Description |
|---|---|---|
| **Forested Land** | Forested land | Natural wooded land and planted forests |
| **Shrubland** | Shrubland | Shrubs and karroo vegetation, including fynbos |
| **Grassland** | Grassland | Natural grassland |
| **Wetlands** | Wetlands | Herbaceous and woody wetlands, including mangroves |
| **Barren Land** | Barren Land | Eroded terrestrial and coastal areas, including rock surfaces, dry pans and bare riverbed material |
| **Cultivated Land** | Cultivated | Fields cultivated for food production |
| **Built-up Land** | Built-up | Residential, recreational, commercial and industrial areas |
| **Mined Land** | Mines & Quarries | Mining areas, including pits, quarries, tailings dams and resource dumps |

**Table 3.4: Description of the 'extensive' land types (Land Type Survey Staff, 1972-2006) representing the soil layer as potential driver of bush encroachment.**

| Map Unit | Description |
|---|---|
| **A** | Freely-drained, red and/or yellow, eutrophic, mesotrophic or dystrophic, apedal soils with humic topsoils; comprise >40% of the land type |
| **B** | Red and yellow, eutrophic, mesotrophic or dystrophic, apedal soils with plinthic subsoils (plinthic soils comprise >10% of land type) |
| **D** | Either red or non-red duplex soils (sandier topsoil abruptly overlying more clayey subsoil); comprise >50% of land type; plus >10% occupied by black or red clays |
| **E** | Black or red clays comprise >50% of land type |
| **F** | Shallow soils (Mispah and Glenrosa forms) predominate |
| **I** | Rock outcrops comprise >60% of land type |

**Table 3.5: Description of the bioregions (SANBI, 2012) representing the vegetation layer in the NWP.**

| Map Unit | Description |
|---|---|
| **Alluvial Vegetation** | Vegetation present at streams and rivers |
| **Central Bushveld** | Contains the highest number of vegetation types and covers most of the high-lying plateau west of the main escarpment, from the Magaliesburg in the south to the Soutpansberg in the north |
| **Dry Highveld Grassland** | Constitutes the western belt (Graaff-Reinet and Aliwal North to Mafikeng) of the Grassland biome, mainly with a MAP below 600 mm |
| **Eastern Kalahari Bushveld** | Is the largest savanna bioregion and is on average at the highest altitude |
| **Inland Saline Vegetation** | Vegetation present at saline areas |
| **Mesic Highveld Grassland** | Is the largest Grassland Bioregion and has the highest number of vegetation types |
| **Zonal and Intrazonal Forests** | Natural woodlands and forests |

**Table 3.6: Description of the map units of geology (Winter, 2014 & Council for Geoscience, 2019) with the associated rocks.**

| Map Unit | Description | Rocks |
|---|---|---|
| **Ultramafic** | Abundant igneous rocks that are composed of 90% mafic minerals | Pyroxenite, peridotite, lherzolite, harzburgite |
| **Mafic** | Abundant igneous rocks that have a high Fe and Mg composition | Basalt, Gabbro, Norite |

**Table 3.7: Description of the map units of geology (Winter, 2014 & Council for Geoscience, 2019) with the associated rocks (Continued).**

| Map Unit | Description | Rocks |
|---|---|---|
| **Intermediate** | Abundant igneous rocks that are composed of equal felsic and mafic minerals | Andesite and syenite |
| **Felsic** | Abundant igneous rocks that are composed predominantly of felsic minerals | Granite and rhyolite |
| **Sedimentary** | Abundant rocks that formed through accumulation or deposition | Sandstone, mudstone, siltstone, shale, banded-iron formation, dolomite, conglomerate |
| **Metamorphic** | Abundant igneous or sedimentary rocks that formed through metamorphoses | Amphibolite, gneiss, chert, quartzite, greenstone |
| **Meta-sedimentary** | Formation and groups comprising of both abundant metamorphic and sedimentary rocks | Any metamorphic and sedimentary rocks |
| **Meta-igneous** | Formation and groups comprising of both abundant metamorphic and igneous rocks | Any metamorphic and igneous rocks |

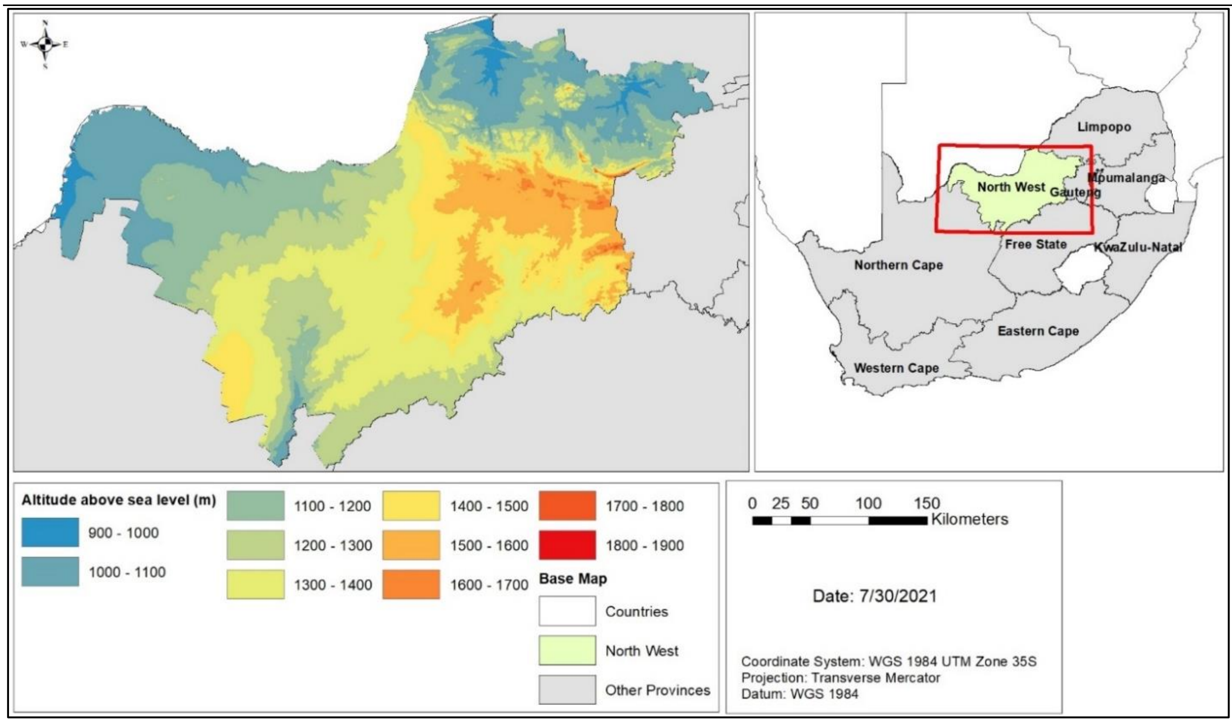



**Figure 3.3: The altitude above sea level (m) as representation of topography of the NWP (USGS, 2021).**

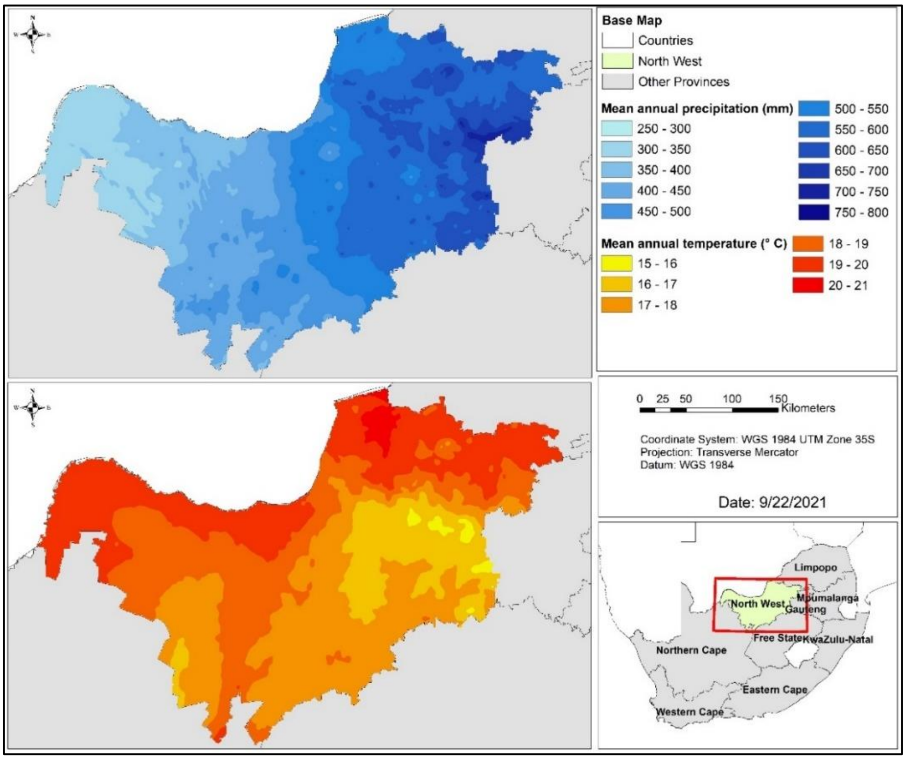



**Figure 3.4: A map presenting the mean annual precipitation (MAP) (mm) and mean annual temperature (MAT) (° C) of the NWP (Schulze, 2007).**

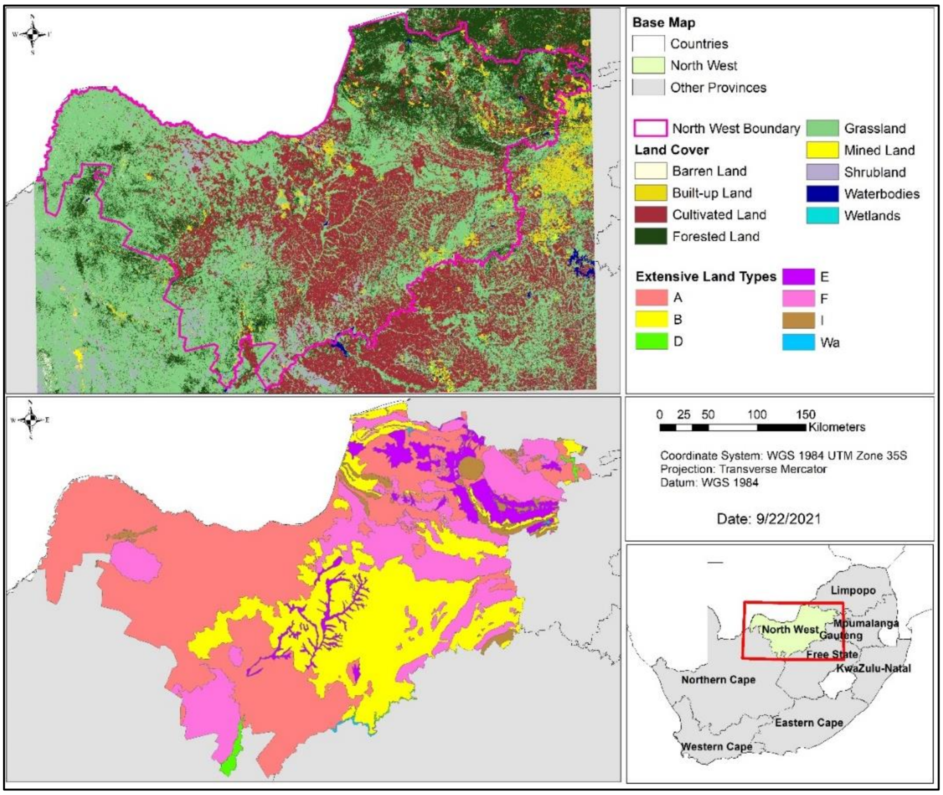



**Figure 3.5: A map presenting the land-use (SALCC1) (Thompson, 2018) and extensive land types (Land Type Survey Staff, 1972-2006) of the NWP.**

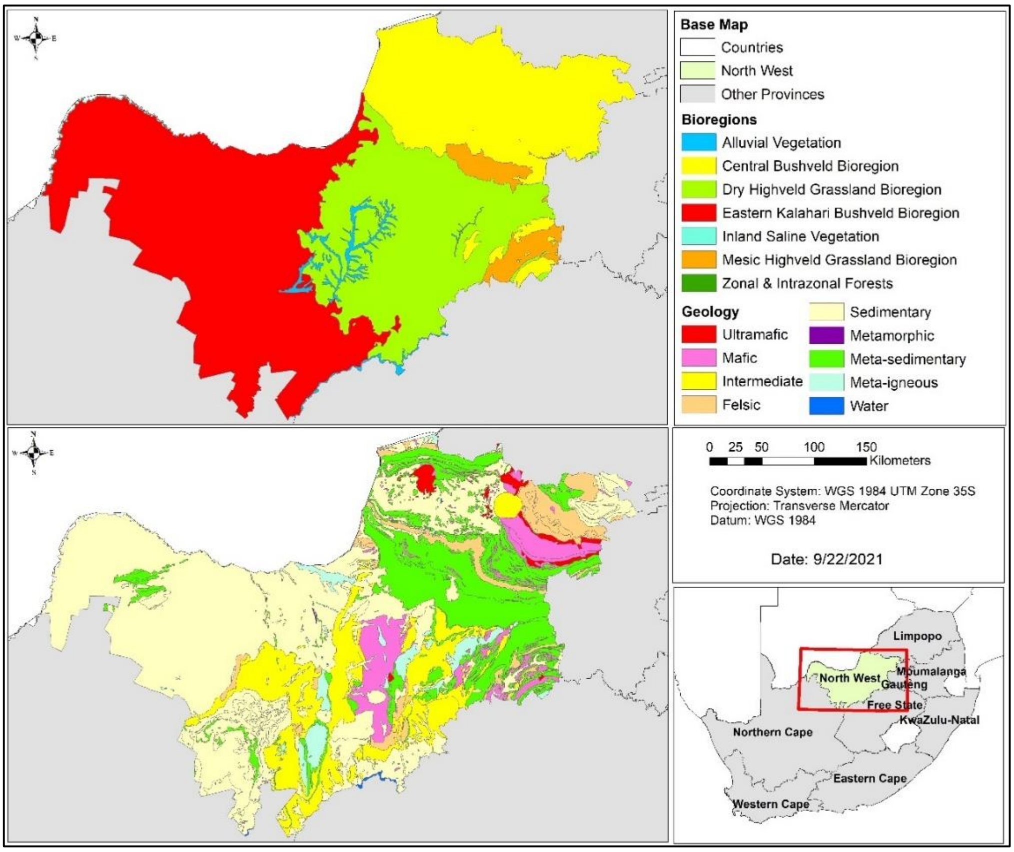



**Figure 3.6: A map presenting the bioregions (SANBI, 2012) and geology (Winter, 2014 & Council of Geoscience, 2019) of the NWP.**

#### 3.2.3.2.2 Significant areas

Significant areas were selected based on the visual severity of bush spread (Figure 3.9 (a-c)) of certain areas in the NWP from 1993-1998, 1998-2018 and 1993-2018 (Table 3.8). The significant areas were named after the nearest city/town or landmark and were called: Taung (town), Mafikeng (city), Pilanesberg (Pilanesberg National Park) and Rustenburg (city). The significant areas were selected using the “Create Features” tool, in ArcGIS 10.8.1, which was used to manually create polygons over the most severe parts of the nearest city/town or landmark. The polygon boundary ended where the visual severity of bush spread ended. Figure 3.7 shows the locality of the significant areas that were selected based on the severity of bush spread for time frames, 1993-1998, 1998-2018 and 1993-2018.

The same potential driving factors of BE (from Table 3.2) were also used for the analysis of the significant areas. However, for the soil layer, broad land types (Land Type Survey Staff, 1972-2006) (Table 3.9) were chosen for the map units, while for the vegetation layer, vegetation units (SANBI, 2012) (Table 3.10 and Table 3.11) were used as map units, as they were regarded as being on the correct scale for the focused, significant areas. Improved detail on MAP as a driving factor of BE was included by using long-term precipitation data obtained from the South African Weather Service (SAWS) (2021).

**Table 3.8: The most severe bush spread of the significant areas for time frames, 1993-1998, 1998-2018 and 1993-2018. The most severe bush spread includes bush encroachment (BE), bush thickening (BT) and bush lessening (BL).**

| | Time frame | | |
|---|---|---|---|
| **Significant area** | **1993-1998** | **1998-2018** | **1993-2018** |
| **Taung** | BE and BT | BE and BT | BE and BT |
| **Mafikeng** | BL | BE and BT | BE and BT |
| **Pilanesberg** | BT | BL | BT and BL |
| **Rustenburg** | BT | BL | BT and BL |

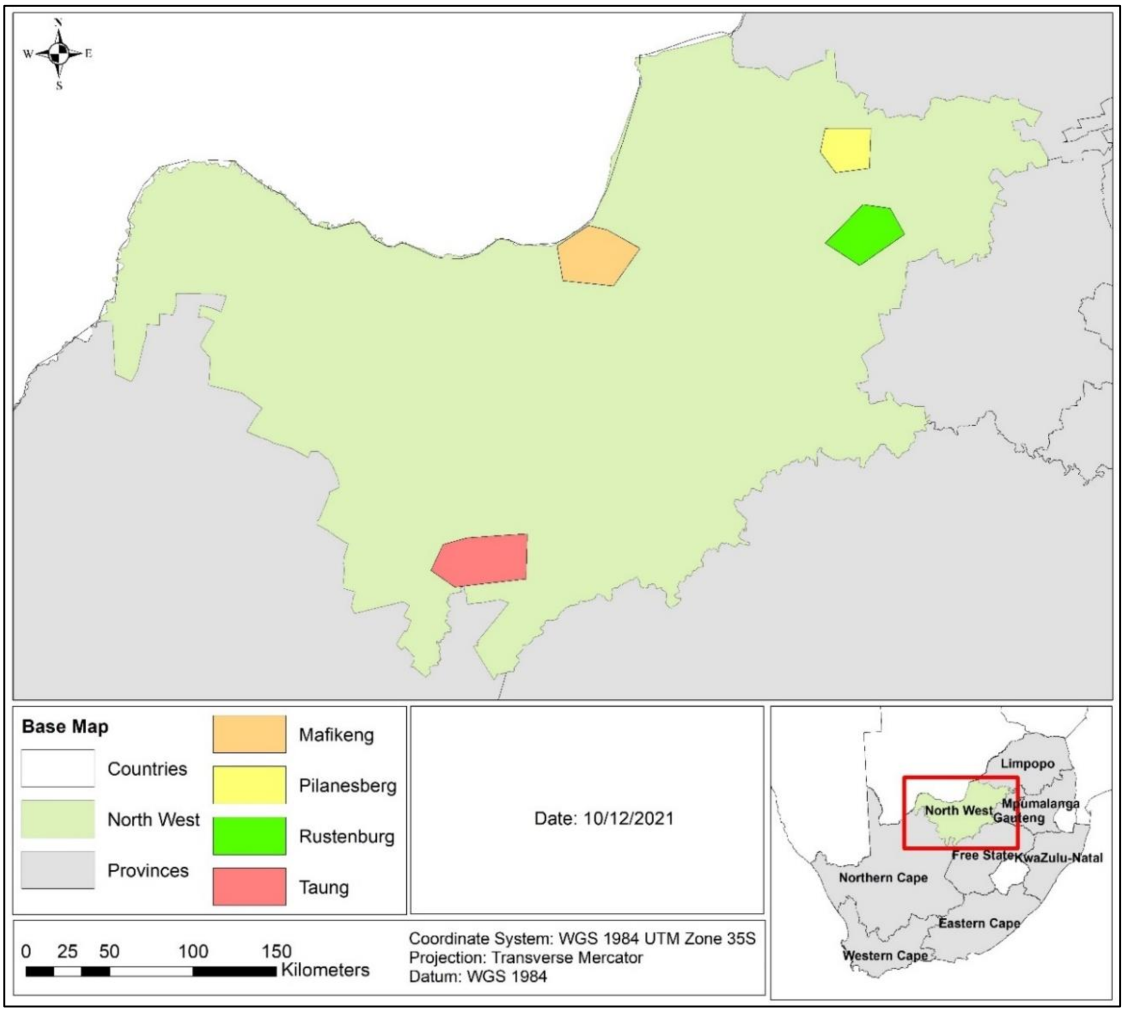



**Figure 3.7: A map indicating the locality of the selected significant areas that were based on the severity of bush spread for time frames, 1993-1998, 1998-2018 and 1993-2018. The significant areas include: Mafikeng (orange), Pilanesberg (yellow), Rustenburg (green) and Taung (red).**

**Table 3.9: Description of the broad land types (Land Type Survey Staff, 1972-2006) representing the soil layer as potential driver of bush encroachment.**

| Map Unit | Description |
|---|---|
| **Ae** | Freely drained, red, eutrophic, apedal soils comprise >40% of the land type (yellow soils comprise <10%) |
| **Ah** | Freely drained, red and yellow, eutrophic, apedal soils comprise >40% of the land type (red and yellow soils each comprise >10%) |
| **Bc** | Red and yellow, eutrophic, apedal soils with plinthic subsoils (plinthic soils comprise >10% of land type, red soils comprise >33% of land type) |
| **Bd** | Red and yellow, eutrophic, apedal soils with plinthic subsoils (plinthic soils comprise>10% of land type, red soils comprise <33% of land type) |
| **Dc** | Either red or non-red duplex soils (sandier topsoil abruptly overlying more clayey subsoil) comprise >50% of land type; plus >10% occupied by black or red clays |
| **Ea** | Black or red clays comprise >50% of land type |
| **Fa** | Shallow soils (Mispah & Glenrosa forms) predominate; little or no lime in landscape |
| **Fb** | Shallow soils (Mispah & Glenrosa forms) predominate; usually lime in some of the bottomlands in landscape |
| **Fc** | Shallow soils (Mispah & Glenrosa forms) predominate; usually lime throughout much of landscape |
| **Ib** | Rock outcrops comprise >60% of land type |

**Table 3.10: Description of the map units of vegetation (SANBI, 2012) found at the significant areas of the NWP.**

| Map Unit | Description |
|---|---|
| **Carletonville Dolomite Grassland** | Slightly undulating plains dissected by prominent rocky chert ricges. Species-rich grasslands forming a complex mosaic pattern dominated by many species |
| **Central Sandy Bushveld** | Low, undulating areas, sometimes between mountains, and sandy plains and catenas supporting tall, deciduous *Terminalia sericea* and *Burkea Africana* woodland on deep sandy soils, and broad-leaved *Combretum* woodland on shallow, rocky soils |
| **Dwaalboom Thornveld** | Plains with layer of scattered low-medium high, deciduous microphyllous trees and shrubs, and an almost continuous herbaceous layer dominated by grass species |
| **Ghaap Plateau Vaalbosveld** | Flat plateau with well-developed shrub and open tree layer |
| **Gold Reef Mountain Bushveld** | Rocky hills and ridges often west-east trending with denser woody vegetation often on the south-facing slopes associated with distinct floristic differences. Tree and shrub layer are often continuous |

**Table 3.11: Description of the map units of vegetation (SANBI, 2012) found at the significant areas of the NWP (continued).**

| Map Unit | Description |
|---|---|
| **Kimberley Thornveld** | Plains often slightly irregular with well-developed tree layer dominated by *Acacia* species |
| **Klerksdorp Thornveld** | Plains or slightly irregular undulating plains with open to dense *V. karroo* bush clumps in dry grassland |
| **Mafikeng Bushveld** | Well-developed tree and shrub layers |
| **Marikana Thornveld** | Open Vachellia karroo woodland, occurring in valleys and slightly undulating plains and some lowland hills. Shrubs are denser along drainage lines and rocky outcrops or areas protected from fire |
| **Moot Plains Bushveld** | Open to closed, low, often thorny savanna dominated by *Acacia* species in the bottomlands and plains |
| **Norite Koppies Bushveld** | A low, semi-open to closed woodland up to 5 m tall, consisting of dense deciduous shrubs and trees with very sparse undergrowth on shallow soils, with large areas covered by vegetation |
| **Northern Afrotemperate Forest** | Low, relatively species-poor forests of Afromontane origin and some of them still showing clear Afromontane character |
| **Pilanesberg Mountain Bushveld** | Broad-leaved deciduous bushveld with trees and shrubs with grass layer on slopes of mountains and hills |
| **Schmidtsdrif Thornveld** | Mostly a closed shrubby thornveld dominated by *S. mellifera* and *V. tortilis*. Vegetation is sometimes very disturbed due to overgrazing by goats and other browsers |
| **Schweizer-Reneke Bushveld** | Plains, slightly undulating plains and some hills, supporting open woodland with a fairly dense shrub layer, with *Acacia* trees dominant |
| **Waterberg-Magaliesberg Summit Sourveld** | Higher slopes and summit positions including crests and steep rocky scarps and cliff faces, covered with grassland dominated by wiry tussock grasses |
| **Western Highveld Sandy Grassland** | Flat to gently undulating plains with short, dry grassland, with some woody species occurring in bush clumps |
| **Zeerust Thornveld** | Deciduous, open to dense short thorny woodland, dominated by *Acacia* species with herbaceous layer of mainly grasses |

### 3.2.4 GIS analysis

#### 3.2.4.1 Bush spread

The change in % of woody cover for the time frames 1993-1998, 1998-2018 and 1993-2018, were calculated by subtracting the later years' woody cover from the earlier years' value, using the

“Raster Calculator” tool in ArcGIS 10.8.1. These new layers indicate the % woody cover change, which occurred between the different years. To determine specific bush spread that occurred for each time frame, the % woody cover layers for the years 1993, 1998 and 2018 (Symeonakis *et al*., 2020) and % woody cover change layers were superimposed on the same grid extent in SAGA 2.1.4. Thereafter, the layers were exported as text files using the “Export Grid to XYZ” tool. Python 3 (Van Rossum & Drake, 1995) and the Matplotlib Package (Hunter, 2007) were used to calculate each bush spread and the % distribution of each bush spread, for each time frame, by using the specific constrains (Table 3.1).

The calculated bush spread for each time frame (1993-1998, 1998-2018 and 1993-2018) were exported as three comma-separated values (CSV) files, using Python 3 and Matplotlib Package and included the X- and Y-coordinates of each data point (all 114 million). The CSV files were imported into FME desktop software 2021.1 (Safe Software Inc., 2020) and this software were used to convert the three CSV files to shapefiles (seven for each CSV file), using the “Writers” tool, in order for bush spread maps to be created. The shapefiles (containing all points) were imported into SAGA 2.1.4 and were converted to raster data (30 m pixel size), using the “Point Cloud to Grid” tool. The seven rasters were then merged, using the “Mosaicking” tool and the single (merged) file exported as a ASCII file, which was imported into ArcGIS 10.8.1. In ArcGIS 10.8.1, the symbology was changed to match the specific bush spread and the bush spread maps created.

#### 3.2.4.2 Determining drivers of bush encroachment

The % woody cover layers for the years 1993, 1998 and 2018 (Symeonakis *et al*., 2020), % woody cover change layers and potential driving factors of BE layers were all superimposed on the same grid extent in SAGA 2.1.4. The bush spread was calculated as explained in 1.2.4.1 and thereafter, Python 3, PhiK code (Baak *et al*., 2020) and the Matplotlib Package were used to calculate the correlation of the potential driving factors of BE with one another and with the bush spread for each time frame. Thereafter, a correlation matrix was created of each bush spread for each time frame, using Python 3 and the Matplotlib Package. The correlation matrixes were exported as CSV files and Microsoft Excel were used to manually combine all the correlation matrixes into just three (representing each time frame).

The correlation calculation of the potential driving factors of BE with one another and with bush spread are explained as follows:

Each of the 114 million pixels contained a specific map unit for each potential driving factor and a specific bush spread value for all three time frames. As the layers were exported as a text file, the format of the map data (raster data) changed from pixels to data points. The data points (containing values of two variables, i.e. bush spread and land cover) were then used to fill the cells of contingency tables (similar to Baak *et al*., 2020) for each variable pair (i.e. bush spread and land cover). However, the amount of data points in the cells of a contingency table do not present true correlation. Therefore, a correlation coefficient $\Phi_K$ needed to be calculated, which would indicate the true correlation of the variables with one another. Values from an "expected" contingency table were needed to calculate a correlation coefficient $\Phi_K$ and therefore, Equation 3-1 was used to calculate the expected contingency tables from the already created or "observed" contingency tables. For equation 1, the sum of values for each row (i) and sum of values for each column (j) for each "observed" contingency table (O) were calculated, divided by the amount of data points (N) in the contingency table.

Values from the columns (j) (i.e. bush spread) and rows (i) (i.e. land cover) of the observed contingency table (O) and expected contingency table (E) were then used in Equation 3-2 (Baak *et al*., 2020) to calculate a $\chi^2$ value. The $\chi^2$ values and $\Phi_K$ code (equations 12-17 in Baak *et al*., 2020) was then used to calculate the correlation coefficient $\Phi_K$, for each contingency table, representing the correlation between each variable pair. Finally, a correlation matrix was created, presenting the true correlation (correlation coefficient $\Phi_K$) between each variable pair. The correlation coefficient $\Phi_K$ and corresponding criteria (Table 3.12) were selected based on similar criteria from Baak *et al*. (2020). From Table 3.11, only correlation coefficients $\Phi_K > 0.39$ (Moderate and higher) were regarded as significant and were accepted as a very likely driver of the specific bush spread.

**Equation 3.1:** $$\boldsymbol{E_{ij}} = \frac{(\sum_{n=1}^{k} \boldsymbol{O_{ij}})(\sum_{m=1}^{r} \boldsymbol{O_{mj}})}{\boldsymbol{N}}$$

Where $E$ is the expected contingency table, $O$ is the observed contingency table, $i$ and $j$ is the columns and rows of the contingency tables, $N$ is the amount of data points in the observed contingency table, $\boldsymbol{n}$ is the index for the columns, $\boldsymbol{m}$ is the index for the rows, $\boldsymbol{k}$ is the amount of columns and $\boldsymbol{r}$ is the amount of rows.

**Equation 3.2:** $$\boldsymbol{\chi^2} = \sum_{i,j} \frac{(\boldsymbol{O_{ij}} - \boldsymbol{E_{ij}})^2}{\boldsymbol{E_{ij}}}$$

Where $\chi^2$ is Pearson's chi-squared test, $E$ is the expected contingency table, $O$ is the observed contingency table and $i$ and $j$ is the columns and rows of the contingency tables.

**Table 3.12: The correlation coefficient ranges and the corresponding criteria (from Baak *et al*., 2020).**

| Correlation coefficient $\Phi_K$ range | Correlation criteria |
|---|---|
| **0.00** | None |
| **0.001 – 0.19** | Insignificant |
| **0.20 – 0.39** | Slight |
| **0.40 – 0.59** | Moderate |
| **0.60 – 0.79** | Good |
| **0.80 – 0.99** | Great |
| **1** | Perfect |

#### 3.2.4.3 Significant areas

The "create feature" tool (ESRI, 2016) was used to select the area boundaries and create four polygons. Within the created polygons, bush spread and bush spread distribution (%) were calculated (3.2.4.1) and the driving factors of BE determined (3.2.4.2). For the long-term precipitation data, the MAP were calculated for each year and thereafter, the mean MAP calculated for each time frame, using Microsoft Excel.

### 3.2.5 Analysis of variance (ANOVA)

To determine whether the % woody cover of the different years, 1993, 1998 and 2018, were statistically different, a one-way analysis of variance (ANOVA) and a normality test (kruskal- wallis H test) was done. The same was also done for the different years of the significant areas.

## 3.3 Results and discussion

### 3.3.1 Provincial scale

#### 3.3.1.1 Bush spread

Figure 3.8 (a-c) presents maps that showed the change of woody cover (%) in the NWP for time frames, 1993-1998, 1998-2018 and 1993-2018. The north-eastern part of the province presented a significant increase (20 – 60 % woody cover) for the first time frame (1993-1998), while this part presented a significant decrease (- 20 – -80 % woody cover) for the second time frame (1998-2018). The central and southern part of the province mostly showed slight increase (0 – 10 % woody cover) or slight decrease (0 – -20% woody cover) for the first time frame (1993-1998), while these parts showed moderate increase (10 – 40 % woody cover) for the second time frame

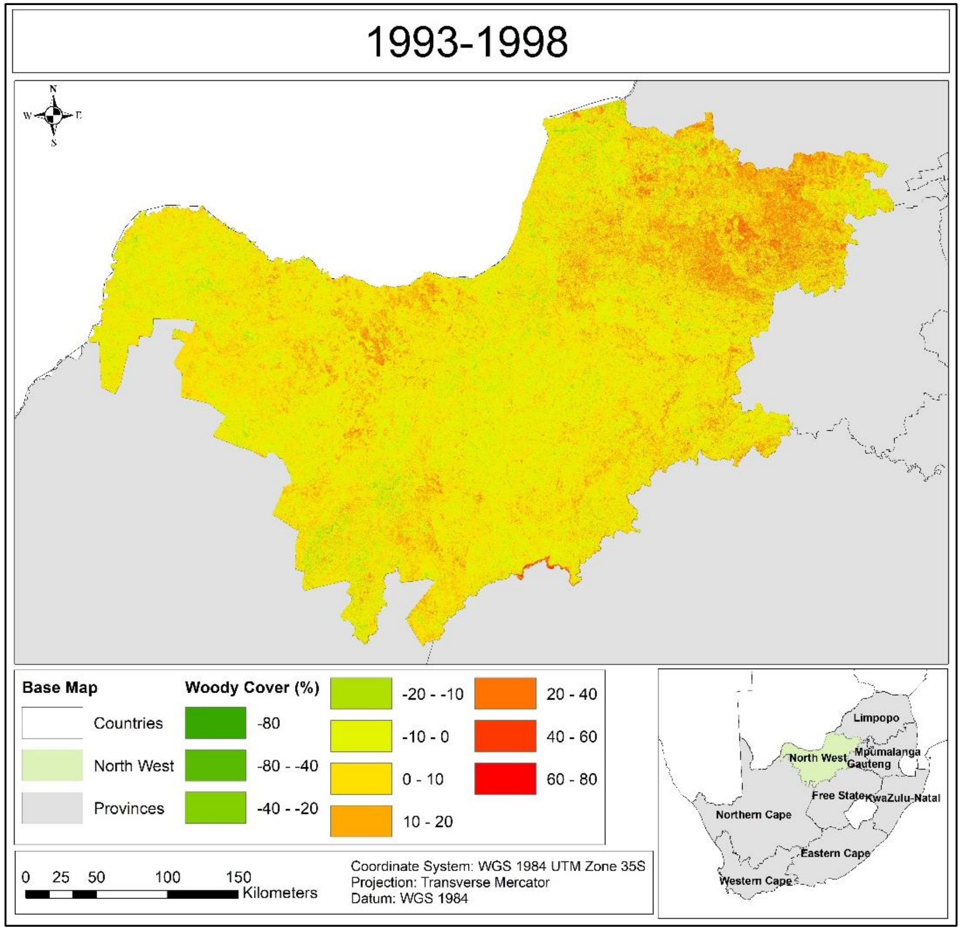
(1998-2018) (Figure 3.8 (a-b). From Figure 3.8 (c) it is clear that there was a significant increase (10 – 60 % woody cover) in the north-eastern, central and southern parts of the province from 1993 to 2018.

Figure 3.9 (a-c) presents maps that showed the bush spread in the NWP for the time frames, 1993-1998, 1998-2018 and 1993-2018. Bush spread was expressed as bush lessening (BL), bush encroachment (BE), bush thickening (BT) and no change (NC), all in % woody cover. For the first time frame (1993-1998), BT was the most severe in the north-eastern, western and south-western parts of the province, while BE was slightly severe in the western part of the province (Figure 3.9 (a)). BL and NC were commonly seen in the central and south-eastern parts of the province for the first time frame (1993-1998). For the second time frame (1998-2018), BT were severe in the northern, south-western and western parts of the province, while BE were severe in the central, southern and south-western parts of the province (Figure 3.9 (b)). BL and NC were severe in the eastern and north-eastern parts of the province for the second time frame (1998-2018). For the third time frame (1993-2018), BT were very severe in the western, northern and north-eastern parts of the province, while BE were very severe in the western, central and southern parts of the province (Figure 3.9 (c)). BL and NC were most severe in the south-eastern and north-western parts of the province for time frame three (1993-2018).

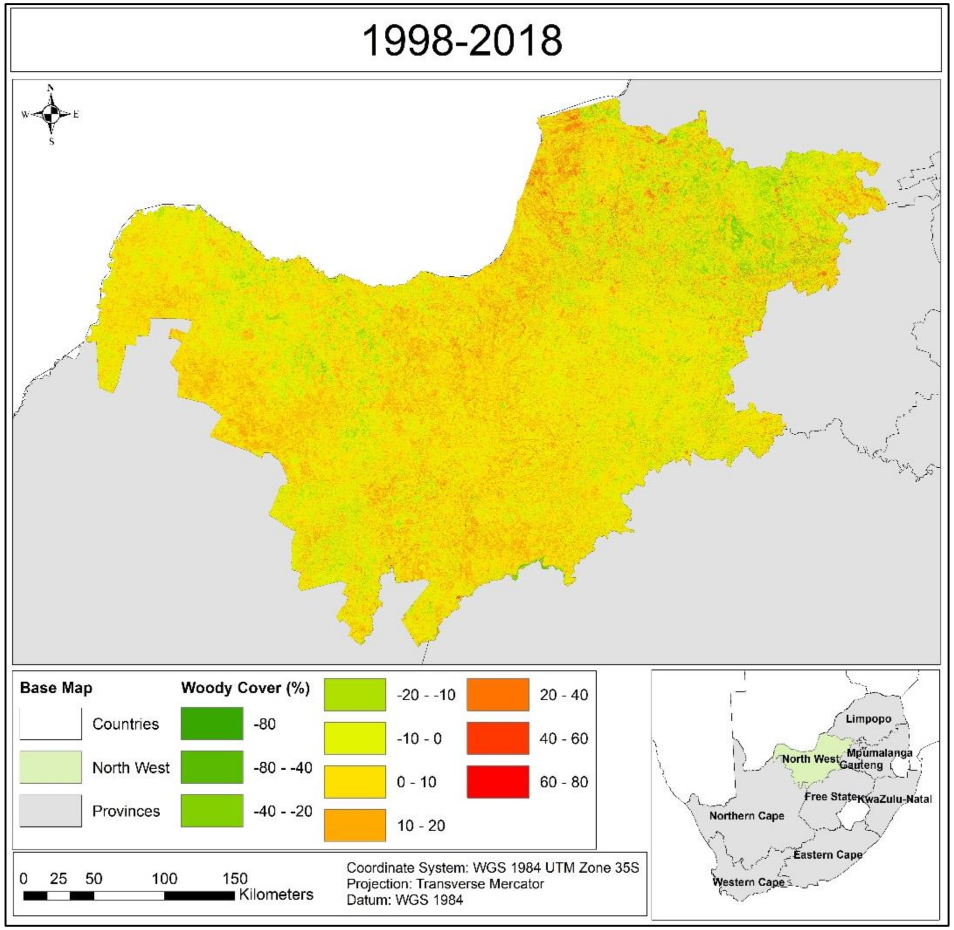
Table 3.13 indicates the data distribution (%) of the different bush spread of the NWP for time frames, 1993-1998, 1998-2018 and 1993-2018. The NWP had similar distribution of bush spread from 1993 to 2018 (Table 3.13). From time frame one (1993-1998) to time frame two (1998-2018) BE present a 7% increase, while BT present a 3% decrease. BL was slightly higher for time frame two (1998-2018) compared with time frame one (1993-1998), while NC decreased with 6% from time frame one (1993-1998) to time frame two (1998-2018) (Table 3.13).

**Table 3.13: The data distribution (%) of the different bush spread of the NWP for time frames, 1993-1998, 1998-2018 and 1993-2018.**

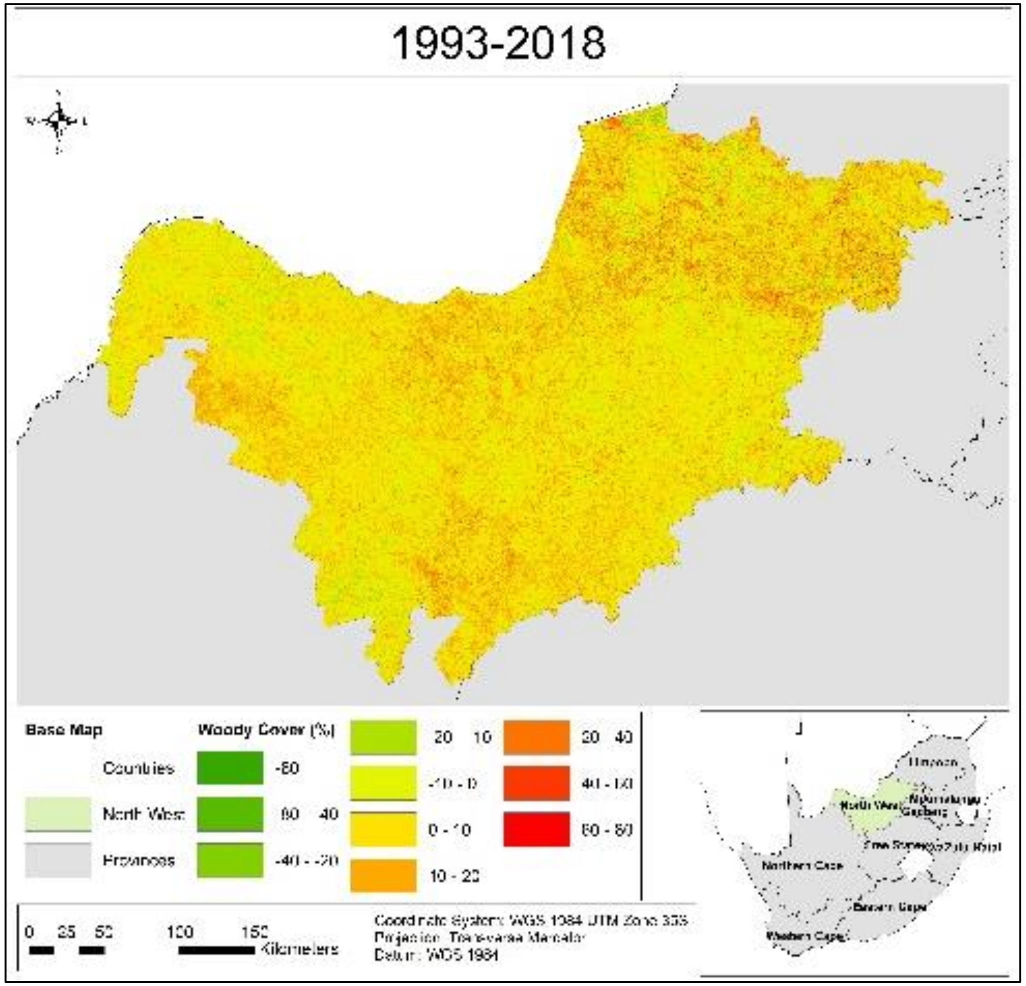
| | **Time frame** | | |
|---|---|---|---|
| **Bush spread** | **1993-1998** | **1998-2018** | **1993-2018** |
| **Bush encroachment (BE)** | 15 | 22 | 22 |
| **Bush thickening (BT)** | 31 | 28 | 28 |
| **No change (NC)** | 26 | 20 | 21 |
| **Bush lessening (BL)** | 28 | 30 | 29 |


1993-1998
Base Map
Countries
North West
Provinces
Woody Cover (%)
-80
-80 - -40
-40 - -20
-20 - -10
-10 - 0
0 - 10
10 - 20
20 - 40
40 - 60
60 - 80
0 25 50 100 150
Kilometers
Coordinate System: WGS 1984 UTM Zone 35S
Projection: Transverse Mercator
Datum: WGS 1984
Limpopo
North West
Mpumalanga
Gauteng
Free State
KwaZulu-Natal
Northern Cape
Eastern Cape
Western Cape

(a)

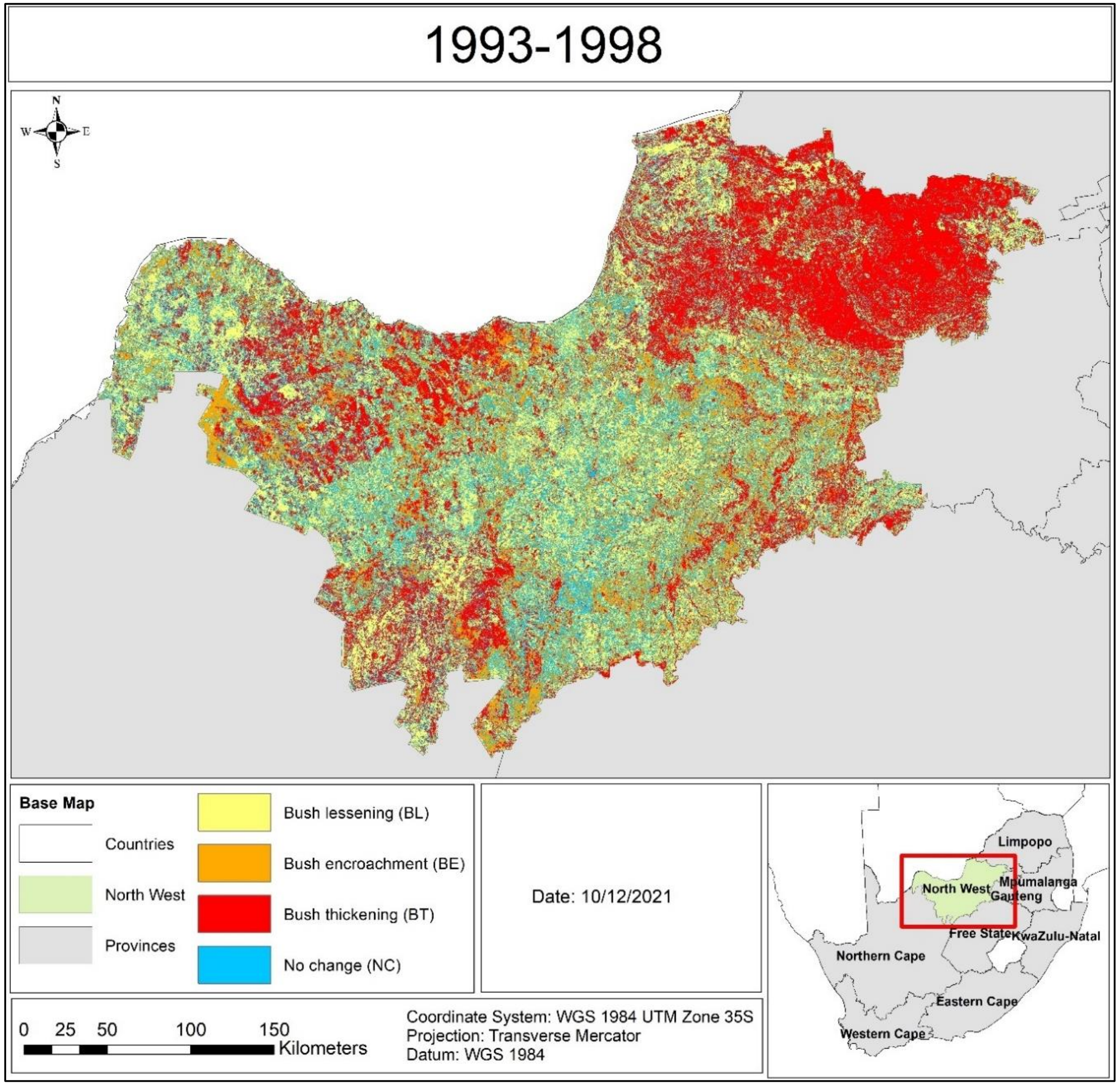

1998-2018
Base Map
Countries
North West
Provinces
Woody Cover (%)
-80
-80 - -40
-40 - -20
-20 - -10
-10 - 0
0 - 10
10 - 20
20 - 40
40 - 60
60 - 80
0 25 50 100 150
Kilometers
Coordinate System: WGS 1984 UTM Zone 35S
Projection: Transverse Mercator
Datum: WGS 1984
Limpopo
North West
Mpumalanga
Gauteng
Free State
KwaZulu-Natal
Northern Cape
Eastern Cape
Western Cape

(b)

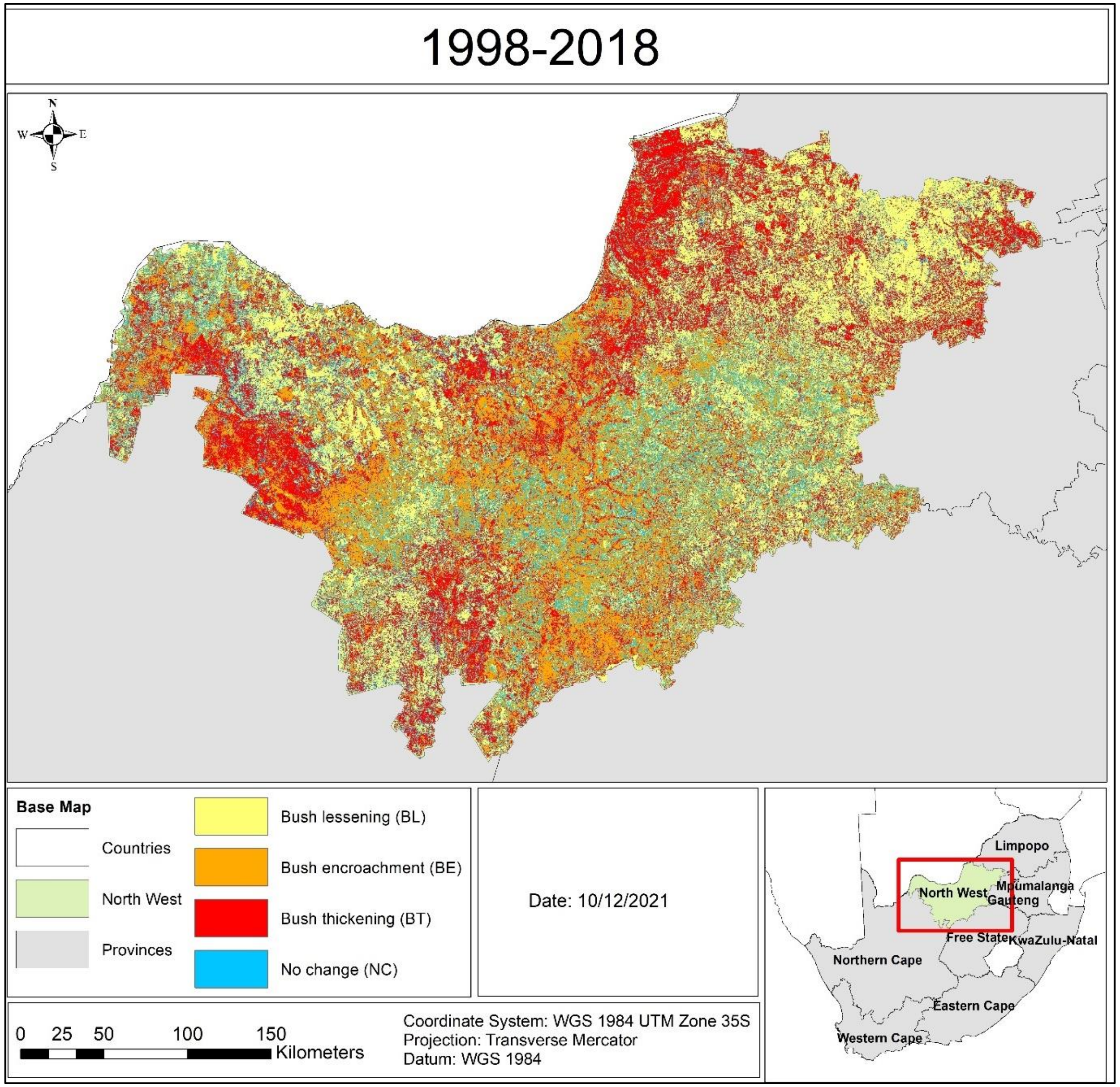



(c)

**Figure 3.8: A map indicating the change of woody cover (%) in the NWP for time frames (a) 1993-1998, (b) 1998-2018 and (c) 1993-2018.**

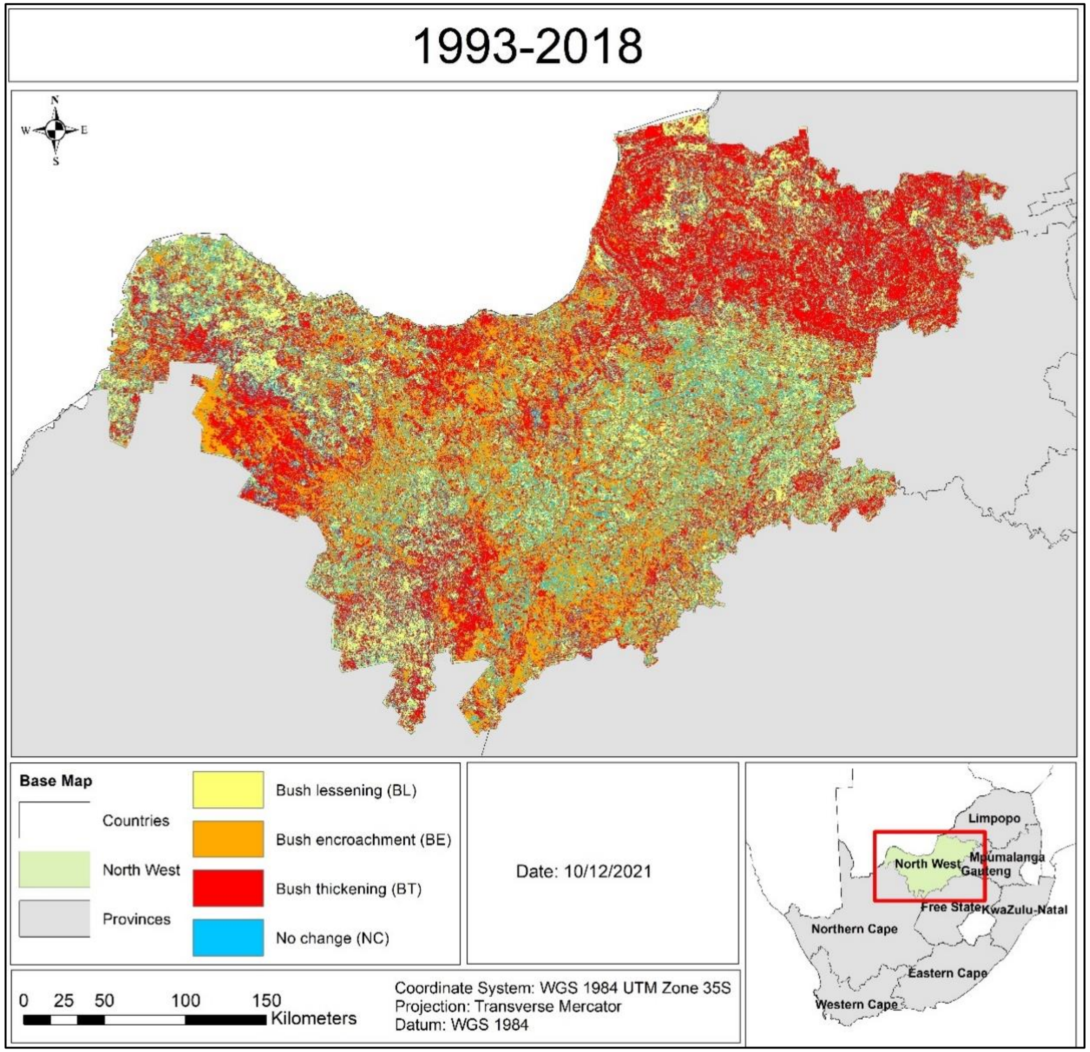

1993-1998
N
W
E
S
Base Map
Countries
North West
Provinces
Bush lessening (BL)
Bush encroachment (BE)
Bush thickening (BT)
No change (NC)
Date: 10/12/2021
Limpopo
North West
Mpumalanga
Gauteng
Free State
KwaZulu-Natal
Northern Cape
Eastern Cape
Western Cape
0 25 50 100 150
Kilometers
Coordinate System: WGS 1984 UTM Zone 35S
Projection: Transverse Mercator
Datum: WGS 1984

(a)



1998-2018
N
W
E
S
Base Map
Countries
North West
Provinces
Bush lessening (BL)
Bush encroachment (BE)
Bush thickening (BT)
No change (NC)
Date: 10/12/2021
0 25 50 100 150
Kilometers
Coordinate System: WGS 1984 UTM Zone 35S
Projection: Transverse Mercator
Datum: WGS 1984
Limpopo
North West
Mpumalanga
Gauteng
Free State
KwaZulu-Natal
Northern Cape
Eastern Cape
Western Cape


(b)




(c)

**Figure 3.9: A map indicating the bush spread in the NWP for time frames (a) 1993-1998, (b) 1998-2018 and (c) 1993-2018. The bush spread in the NWP included: bush lessening (yellow), bush encroachment (orange), bush thickening (red) and no change (blue) indicated almost no bush spread.**

#### 3.3.1.2 Determining drivers of bush encroachment

Tables 3.14 – 3.16 shows the correlation matrixes, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors and bush spread of the NWP for time frames, 1993-1998, 1998-2018 and 1993-2018. The potential factor that showed the highest correlation with each bush spread was indicated as bold. The significant correlation coefficients $\Phi_K$ were indicated as bold.

**Table 3.14: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the NWP for time frame 1993-1998. The significant correlation coefficients $\Phi_K$ were indicated as bold.**

| **1993-1998** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Bioregions** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.12 | 0.00 | 0.00 | 0.12 | 0.15 | 0.33 | 0.07 |
| **BT** | **0.45** | 0.00 | 0.00 | **0.43** | 0.22 | 0.17 | 0.19 |
| **NC** | 0.03 | 0.00 | 0.00 | 0.03 | 0.05 | 0.04 | 0.01 |
| **BL** | 0.08 | 0.00 | 0.00 | 0.14 | 0.12 | 0.07 | 0.04 |

**Table 3.15: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the NWP for time frame 1998-2018. The significant correlation coefficients $\Phi_K$ were indicated as bold.**

| 1998-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Bioregions** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.19 | 0.00 | 0.00 | 0.19 | 0.15 | 0.37 | 0.08 |
| **BT** | **0.45** | 0.00 | 0.00 | **0.44** | 0.23 | 0.15 | 0.20 |
| **NC** | 0.04 | 0.00 | 0.00 | 0.03 | 0.04 | 0.03 | 0.02 |
| **BL** | 0.21 | 0.00 | 0.00 | 0.25 | 0.24 | 0.13 | 0.12 |

**Table 3.16: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors with bush spread of the NWP for time frame 1993-2018. The significant correlation coefficients $\Phi_K$ were indicated as bold.**

| 1993-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Bioregions** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.10 | 0.00 | 0.00 | 0.10 | 0.12 | 0.29 | 0.04 |
| **BT** | **0.46** | 0.00 | 0.00 | **0.45** | 0.24 | 0.16 | 0.21 |
| **NC** | 0.02 | 0.00 | 0.00 | 0.02 | 0.05 | 0.02 | 0.02 |
| **BL** | 0.15 | 0.00 | 0.00 | 0.19 | 0.13 | 0.09 | 0.07 |

Topography and MAT showed no correlation with all bush spread for all time frames. For the first time frame (1993-1998), BE showed a slight correlation (0.33) with land cover and insignificant correlations (< 0.20) with the other potential driving factors (Table 3.13). BT showed moderate correlations (0.45 and 0.43) with MAP and bioregions, and slight correlation (0.22) with land types, but insignificant correlations (< 0.20) with land cover and geology. NC showed insignificant correlations (< 0.20) with all the other potential driving factors (Table 3.14). BL showed the highest correlation (0.14) with bioregions, but all potential driving factors showed insignificant correlations (< 0.20) with BL (Table 3.14).

For the second time frame (1998-2018), BE showed a slight correlation (0.37) with land cover and insignificant correlations (< 0.20) with the other potential driving factors (Table 3.14). BT showed moderate correlations (0.45 and 0.44) with MAP and bioregions, and slight correlations (0.23 and 0.20) with land types and geology, but showed insignificant correlation (0.15) with land cover. NC showed insignificant correlations (< 0.20) with all the other potential driving factors (Table 3.15). BL showed the highest correlation (0.25) with bioregions and showed slight correlations (0.24 and 0.21) with land types and MAP, but all potential driving factors showed insignificant correlations (< 0.19) with BL (Table 3.15).

For the third time frame (1993-2018), BE showed a slight correlation (0.29) with land cover and insignificant correlations (< 0.20) with the other potential driving factors (Table 3.16). BT showed moderate correlations (0.46 and 0.45) with MAP and bioregions, and showed slight correlations (0.24 and 0.21) with land types and geology, but showed insignificant correlation (0.16) with land cover. NC showed insignificant correlations (< 0.20) with all the other potential driving factors (Table 3.16). BL showed the highest correlation (0.25) with bioregions and showed slight correlations (0.24 and 0.21) with land types and MAP, but all potential driving factors showed insignificant correlations (< 0.20) with BL (Table 3.16).

Table 3.17 is derived from Tables 3.14 – 3.16, indicating the potential driving factors of BE that showed significant correlations with the different bush spread for time frames, 1993-1998, 1998-2018 and 1993-2018. No change (NC) was not included as all correlations were insignificant (< 0.1) with the potential driving factors of BE.

**Table 3.17: The potential driving factors of BE that showed significant correlation with the different bush spread of the NWP for time frames, 1993-1998, 1998-2018 and 1993-2018.**

| | **Time frame** | | |
|---|---|---|---|
| **BE spread** | **1993-1998** | **1998-2018** | **1993-2018** |
| **Bush encroachment (BE)** | None | None | None |
| **Bush thickening (BT)** | MAP, bioregions | MAP, bioregions | MAP, bioregions |
| **Bush lessening (BL)** | None | None | None |

Regarding the bush spread, BE and BL did not show any significant correlations, although BE did show the highest correlations with land cover for all three time frames. Bush thickening (BT) showed the highest and most significant correlations with MAP and bioregions for all three time frames (Table 3.17). From the initially created correlation matrixes (CSV files), bioregions also showed a good correlation (0.73) with MAP for all three time frames.

**Discussion on potential drivers of bush encroachment in the North West Province**

- **Bush encroachment (BE)**

Although BE showed the highest correlation with land cover for all three time frames, they were only slight (< 0.40) (Table 3.14 – 3.16). However, the high correlation might have indicated a slight influence of land-use (represented by land cover) for BE in the NWP from 1993 to 2018. According to Wigley *et al*. (2009), land-use practices can change the structure and functioning of savanna ecosystems. Botai *et al*. (2016) studied droughts in the NWP and Free State Province (FSP), from 1985 to 2015, and concluded that drought occurrences occurred from 2005 to 2015, primarily in the NWP. As the NWP had significant drought from 2005 to 2015 (Botai *et al*., 2016), it likely influenced the land-use in the province, which in turn, could have led to the increase in BE. Jacobs (2000) stated that low MAP (< 600 mm) had a great impact on land-use, making cultivation very risky with lower yields, especially in the communally-managed areas, which led to that communities reverting to pastoralism and livestock production (Jacobs, 2000). Previous studies indicated that overgrazing facilitates BE in semi-arid environments, with livestock removing grass, which can lead to higher woody seedling establishment (Archer *et al*., 1995; Adler, 2001; Scholes, 2009; Devine *et al*., 2017; Belayneh & Tessema, 2017). The possible high number of livestock in the NWP, as well as the low MAP, could have led to overgrazing in many parts of the province, which might have led to the proliferation of woody plant seedlings leading to BE and explained the slight correlation between BE and land cover in the NWP from 1993 to 2018. However, as the correlation between BE and land cover were not significant, no definite driver of BE in the NWP from 1993 to 2018 were found at provincial scale.

- **Bush thickening (BT)**

As mentioned, the NWP consists primarily of arid and semi-arid areas (NWREAD, 2014), which is prone to droughts and in 2016 the province was even declared as a drought disaster area (Botai *et al*., 2016). Pachuari *et al*. (2014) (in Yang and Crews, 2020) also stated that semi-arid regions will be more susceptible to future climate change, which is anticipated to increase MAP variability. Although the time frames of Botai *et al*. (2016) are not the same for this studies' time frames, it still presents substantial value on MAP variability from 1993 to 2018.

The increased precipitation variability might have greatly increased the density of woody plant and grass competition for water and nutrients (Ward *et al*., 2005; Wiegand *et al*., 2005). The latter phenomenon can be described by the fact that established woody plants generally have a deeper root system and therefore have the ability to acquire water in drought periods, whereas grass roots only extent down to 30 cm in the soil (Ward *et al*., 2005). This indicates that precipitation variability likely favoured the increase of woody plants and allowed them to outcompete grass and grow thicker in the NWP. Although, the effect of fire occurrences was not part of this study, it might also have contributed to the correlation between BT and MAP. Fires generally occur in areas where the precipitation is highly seasonal and once the grass layer has increased in its biomass during the wet season becomes dry enough to burn, it will decrease due to fire occurrences, which may lead to BT (Turpie *et al*., 2019). The decrease in the grass layer can also be caused by the trampling and higher foraging of livestock and wildlife in the communal- and commercial land-use systems in the NWP (Jordaan *et al*., 2019). The high number of livestock in the province likely led to overgrazing (Scholes, 2009), decreasing the fuel load (Turpie *et al*., 2019), thereby decreasing the number of fires in the NWP. Bond *et al*. (2003) (in Turpie *et al*., 2019) has also suggested that most grassy biomes, with > 750 mm MAP, could also shift from a grassland to a thicket (woodland) in the long absence of fire. This phenomenon could have occurred in the small portion of the province, with a MAP of < 750 mm (Schulze, 2007) (Figure 3.4).

The four largest bioregions (Central Bushveld, Dry Highveld Grassland, Eastern Kalahari Bushveld and Mesic Highveld Grassland) in the NWP have been identified as bush encroachment/thickening zones (Turpie *et al*., 2019). Not only have these bioregions been identified as encroachment/thickening zones, but studies over the last 23 years also indicated that grasslands have been replaced by woodlands (Turpie *et al*., 2019). Since the MAP was < 600 mm (Mucina & Rutherford, 2006) in these four bioregions and were likely influenced by overgrazing, leading to a decrease in aboveground biomass (Scholes, 2009), it could have influenced the competition between herbaceous plants (grass) and woody plants for water and nutrients in the soil, causing a decrease in fire events and an increase in BT. This indicates that the significant correlation between BT and bioregions, were likely caused by the influence of MAP, which increased the susceptibility of the bioregions in the NWP for bush thickening.

Therefore, the lower MAP, likely decreased competition between woody plants and grasses, benefitting the growth of woody plants and with the absence of fire, can increase in BE and BT may occur in the four bioregions in the NWP from 1993 to 2018.

- **Bush lessening (BL)**

As BL only had slight correlations with land types and MAP for the three time frames (Table 3.13 – 3.16), the significant areas indicated slightly better results (see 1.3.2.2.2) on the driving factors of BL.

### 3.3.2 Significant areas

#### 3.3.2.1 Bush spread

Table 3.18, 3.19 and 3.20 indicates the calculated data distribution (%) of the different bush spread of the significant areas for time frames, 1993-1998, 1998-2018 and 1993-2018.

For the first time frame (Table 3.18), the Pilanesberg and Rustenburg areas showed the highest distribution of BT, while the Taung and Mafikeng areas showed the highest distribution of BL, BE and NC. For the second time frame (Table 3.19), the Pilanesberg and Rustenburg areas showed the highest distribution of BL, while the Taung and Mafikeng areas showed the highest distribution of BE, BT and NC. For the third time frame (Table 3.20), the Pilanesberg and Rustenburg areas showed the highest distribution of BL and BT, while the Taung and Mafikeng areas showed the highest distribution of BE and the Mafikeng area showed the highest distribution of NC.

**Table 3.18: The data distribution (%) of the different bush spread of the significant areas for the first time frame (1993-1998).**

| | Bush spread | | | |
|---|---|---|---|---|
| **Significant area** | **Bush lessening (BL)** | **Bush encroachment (BE)** | **Bush thickening (BT)** | **No change (NC)** |
| **Taung** | 18 | 19 | 38 | 25 |
| **Mafikeng** | 40 | 14 | 16 | 30 |
| **Pilanesberg** | 16 | 1 | 68 | 15 |
| **Rustenburg** | 8 | 1 | 81 | 10 |

**Table 3.19: The data distribution (%) of the different bush spread of the significant areas for the second time frame (1998-2018).**

| | Bush spread | | | |
|---|---|---|---|---|
| **Significant area** | **Bush lessening (BL)** | **Bush encroachment (BE)** | **Bush thickening (BT)** | **No change (NC)** |
| **Taung** | 21 | 17 | 42 | 20 |
| **Mafikeng** | 12 | 34 | 38 | 16 |
| **Pilanesberg** | 50 | 1 | 33 | 16 |
| **Rustenburg** | 54 | 1 | 30 | 15 |

**Table 3.20: The data distribution (%) of the different bush spread of the significant areas for the third time frame (1993-2018).**

| | Bush spread | | | |
|---|---|---|---|---|
| **Significant area** | **Bush lessening (BL)** | **Bush encroachment (BE)** | **Bush thickening (BT)** | **No change (NC)** |
| **Taung** | 15 | 27 | 41 | 17 |
| **Mafikeng** | 15 | 27 | 38 | 20 |
| **Pilanesberg** | 38 | 1 | 43 | 18 |
| **Rustenburg** | 30 | 1 | 57 | 12 |

### 3.3.2.2 Determining drivers of bush encroachment

#### 3.3.2.2.1 Taung and Mafikeng areas

Both, the Taung and Mafikeng areas showed severe bush encroachment (BE) and bush thickening (BT) for all three time frames. As a result, these two areas were grouped together for indicating the drivers of BE and BT from 1993 to 2018.

- **Taung**

Table 3.21 – 3.23 show the correlation matrix, that indicated the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors and bush spread of the Taung area for time frames, 1993-1998, 1998-2018 and 1993-2018. The significant correlation coefficients $\Phi_K$ were indicated as bold.

**Table 3.21: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Taung area for time frame 1993-1998. The significant correlation coefficients $\Phi_K$ were indicated as bold.**

| 1993-1998 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.14 | 0.18 | 0.17 | 0.23 | 0.27 | 0.23 | 0.17 |
| **BT** | 0.19 | 0.22 | 0.20 | 0.22 | 0.25 | 0.25 | 0.09 |
| **NC** | 0.05 | 0.05 | 0.05 | 0.07 | 0.11 | 0.04 | 0.06 |
| **BL** | 0.22 | 0.25 | 0.26 | 0.36 | 0.13 | 0.15 | 0.21 |

**Table 3.22: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Taung area for time frame 1998-2018. The significant correlation coefficients $\Phi_K$ were indicated as bold.**

| 1998-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.26 | 0.28 | 0.27 | **0.43** | **0.40** | 0.34 | 0.22 |
| **BT** | 0.20 | 0.24 | 0.22 | 0.17 | **0.41** | 0.21 | 0.14 |
| **NC** | 0.04 | 0.04 | 0.06 | 0.04 | 0.05 | 0.10 | 0.04 |
| **BL** | 0.12 | 0.10 | 0.11 | 0.13 | 0.10 | 0.12 | 0.10 |

**Table 3.23: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors with bush spread of the Taung area for time frame 1993-2018. The significant correlation coefficients $\Phi_K$ were indicated as bold.**

| 1993-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.16 | 0.21 | 0.20 | 0.31 | **0.47** | 0.23 | 0.11 |
| **BT** | 0.18 | 0.15 | 0.17 | 0.07 | 0.19 | 0.39 | 0.17 |
| **NC** | 0.07 | 0.07 | 0.06 | 0.06 | 0.08 | 0.03 | 0.08 |
| **BL** | 0.15 | 0.17 | 0.18 | 0.25 | 0.14 | 0.15 | 0.24 |

For the first time frame (1993-1998), BE showed slight correlations with vegetation units (0.23), land types (0.27) and land cover (0.23) and insignificant correlations (< 0.20) with the other potential driving factors (Table 3.21). BT showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for MAP and geology, which showed insignificant correlations (< 0.20). NC showed insignificant correlations (< 0.20) with all the other potential driving factors (Table 3.21). BL showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for land types and land cover, which showed insignificant correlations (< 0.20).

For the second time frame (1998-2018), BE showed moderate correlations with vegetation units (0.43) and land types (0.40) and showed slight correlations (0.20 – 0.39) with the remaining potential driving factors (Table 3.22). BT showed a moderate correlation (0.41) with land types and slight correlations (0.20 – 0.39) with the other potential driving factors, except for vegetation units and geology, which showed insignificant correlations (< 0.20). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.22). BL showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.22).

For the third time frame (1993-2018), BE showed a moderate correlation (0.47) with land types and slight correlations (0.20 – 0.39) with the other potential driving factors, except for MAP and geology, which showed insignificant correlations (< 0.20) (Table 3.23). BT showed a slight correlation (0.39) with land cover, and showed insignificant correlations (< 0.20) with all the other potential driving factors (Table 3.23). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.23). BL showed slight correlations (0.25 and 0.24) with vegetation units and geology, but all potential driving factors showed insignificant correlations (< 0.20) with BL (Table 3.23).

- **Mafikeng**

Table 3.24 – 3.26 show the correlation matrix, that indicated the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors and bush spread of the Mafikeng area for time frames, 1993-1998, 1998-2018 and 1993-2018. The significant correlation coefficients $\Phi_K$ were indicated as bold.

**Table 3.24: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Mafikeng area for time frame 1993-1998. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1993-1998 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.16 | 0.17 | 0.18 | 0.21 | 0.28 | 0.28 | 0.07 |
| **BT** | 0.28 | 0.32 | 0.34 | 0.18 | 0.29 | 0.23 | 0.31 |
| **NC** | 0.05 | 0.04 | 0.06 | 0.07 | 0.05 | 0.03 | 0.05 |
| **BL** | 0.06 | 0.16 | 0.15 | 0.13 | 0.13 | 0.14 | 0.09 |

**Table 3.25: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Mafikeng area for time frame 1998-2018. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1998-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.16 | 0.23 | 0.21 | 0.30 | 0.36 | 0.30 | 0.13 |
| **BT** | 0.15 | 0.25 | 0.33 | 0.22 | 0.29 | 0.36 | 0.39 |
| **NC** | 0.05 | 0.04 | 0.05 | 0.07 | 0.06 | 0.05 | 0.04 |
| **BL** | 0.13 | 0.17 | 0.19 | 0.17 | 0.14 | 0.11 | 0.04 |

**Table 3.26: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors with bush spread of the Mafikeng area for time frame 1993-2018. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1993-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.16 | 0.22 | 0.21 | 0.27 | 0.26 | 0.32 | 0.10 |
| **BT** | 0.09 | 0.18 | 0.20 | 0.22 | 0.20 | 0.30 | 0.19 |
| **NC** | 0.06 | 0.02 | 0.03 | 0.03 | 0.03 | 0.02 | 0.04 |
| **BL** | 0.10 | 0.22 | 0.28 | 0.22 | 0.11 | 0.09 | 0.14 |

For the first time frame (1993-1998), BE showed slight correlations with vegetation units (0.21), land types (0.28) and land cover (0.28) and insignificant correlations (< 0.20) with the other potential driving factors (Table 3.24). BT showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for vegetation units, which showed insignificant correlations (< 0.20). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.24). BL showed insignificant correlations (< 0.20) with all the potential driving factors of BE.

For the second time frame (1998-2018), BE showed slight correlations with vegetation units (0.30), land types (0.36) and land cover (0.30) and showed slight correlations with MAT (0.23) and topography (0.21), but showed insignificant correlations (< 0.20) for MAP and geology (Table 3.25). BT showed slight correlations (0.20 – 0.39) with all the other potential driving factors, except for MAP, which showed insignificant correlations (< 0.20). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.25). BL showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.25).

For the third time frame (1993-2018), BE showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for MAP and geology, which showed insignificant correlations (< 0.20) (Table 3.26). BT showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for MAP, MAT and geology, which showed insignificant correlations (< 0.20) (Table 3.26). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.26). BL showed slight correlations with MAT (0.22), topography (0.28) and vegetation units (0.22), but all other potential driving factors showed insignificant correlations (< 0.20) with BL (Table 3.26).

Table 3.27 indicates the potential driving factors of BE that showed significant correlations with the different bush spread of the Taung and Mafikeng areas for time frames, 1993-1998, 1998-2018 and 1993-2018.

**Table 3.27: The potential driving factors of BE that showed significant correlations with the different bush spread of the Taung and Mafikeng areas for time frames, 1993-1998, 1998-2018 and 1993-2018.**

| | Time frame | | | | | |
|---|---|---|---|---|---|---|
| **Bush spread** | **1993-1998** | | **1998-2018** | | **1993-2018** | |
| | **Taung** | **Mafikeng** | **Taung** | **Mafikeng** | **Taung** | **Mafikeng** |
| **Bush lessening (BL)** | None | None | None | None | None | None |
| **Bush encroachment (BE)** | None | None | Vegetation units, land types | None | Land types | None |
| **Bush thickening (BT)** | None | None | Land types | None | None | None |

For the Taung and Mafikeng areas, only the Taung area showed significant correlations. Bush encroachment (BE) showed the highest and most significant correlations with vegetation units and land types for the second time frame (1998-2018) and significant correlations with land types for the third time frame (1993-2018) (Table 3.27). From the initially created correlation matrixes (CSV files), vegetation units showed a moderate correlation (0.53) with land types for the second time frame (1998-2018).

**Discussion on potential drivers of bush encroachment in the Taung and Mafikeng areas**

- **Bush encroachment (BE)**

Only the Taung area showed that BE showed significant correlation with land types for the second and third time frames (1998-2018 and 1993-2018), while BE showed significant correlations with vegetation units and land types for the second time frame (1998-2018). Plant species composition is influenced by soil properties, such as nutrient status, pH, salinity, depth and texture (De Klerk, 2004). This might indicate the significant correlation between BE and land types, as well as between land types and vegetation units.

The soil of the Taung area mainly consisted of the Ae and Ah broad land types, which were characterised by red and yellow freely-drained soils (Table 3.8). As these broad land types were freely-drained and of a sandy texture, it was likely very favourable for root growth (Britz, 2004; Ward *et al*., 2013, Kgosikoma and Mogotsi, 2013). This is also substantiated by studies from Dodd *et al*. (2002) and Briske (2017), who concluded that shrub and tree dominance are characterised by deep, coarse-textured soils that facilitate percolation. In these arid and semi-arid environments, such as the NWP, woody plants outcompete grass for topsoil moisture and nutrients, through the influence of overgrazing. As the grass is removed through overgrazing, less water is extracted from the topsoil and more water is available in the subsoil for woody plant growth (Wiegand *et al*., 2005), which increase the establishment of woody seedlings. As the Taung area have a low MAP (< 450 mm) (Figure 3.4) and are predominantly communally managed (Mokgosi, 2018), overgrazing was very likely to occur. This led to the decrease of grass and with the absence of competition, allowed woody seedlings to establish and grow, which explains the significant correlation between BE and land types.

The vegetation units of the Taung area includes: Ghaap Plateau Vaalbosveld, Kimberley Thornveld, Schmidtsdrif Thornveld and Schweizer-Reneke Bushveld. As seen from Table 3.9 and 3.10, all these vegetation units are characterised by the presence of shrubs and trees of the *Acacia* genus (now *Senegalia* and *Vachellia* genus). As mentioned, plant species composition is influenced by soil properties, such as texture and depth (De Klerk, 2004). The plant composition of the vegetation units was also very likely influenced by the sandy, well-drained soils of the Taung area, as shrubs and trees are able to outcompete grass for topsoil moisture and nutrients (Ward *et al*., 2005). The description of the Schmidtsdrif Thornveld also indicates the presence of two prolific encroacher species (Turpie *et al*., 2019), namely *S. mellifera* and *V. tortilis* (Table 3.10). As the Taung area was predominantly communally managed (Mokgosi, 2018), and the vegetation composition of the area is likely dominated by encroacher species, this area was likely very susceptible for overgrazing and the establishment of woody seedlings. This also further substantiates the reason why the bioregions in the NWP is considered as bush encroachment zones and indicating the importance of predominantly communally managed areas.

Therefore, as these soils were sandy and freely-drained and herbivory (overgrazing) very likely present, this decreased the competition of woody plant seedlings with grass for nutrients and water in the topsoil, which favoured the establishment of woody seedlings. However, the low MAP, together with the overgrazing of livestock likely contributed more to the establishment of woody seedlings, with low MAP and overgrazing decreasing the grass and competition. Thus, the low MAP, together with land-use (overgrazing) were the main drivers of BE, with soil being a minor driver of BE.

- **Bush thickening (BT)**

Only the Taung area showed that BT had significant correlation with land types for the second time frame (1998-2018). Similar to BE, BT were also likely influenced by the deep, sandy soil, together with the influence of MAP and overgrazing.

As the soil of the Taung area mainly consisted of the Ae and Ah broad land types, and indicated freely-drained and of a sandy texture, it was likely very favourable for root growth. As established, woody plants generally have a deeper root system, and have the ability to acquire water in drought periods, whereas grass roots only extent down to 30 cm in the soil (Ward *et al*., 2005). The increased precipitation variability (Botai *et al*., 2016) likely favoured the competitiveness of woody plants over grass for water and nutrients (Ward *et al*., 2005; Wiegand *et al*., 2005) in the soil. As mentioned, trampling can also damage and even destroy the roots or rhizomes of grass, reducing their vigour and creating gaps for woody plant germination. Therefore, defoliation (removal of leaves) by livestock without sufficient recovery periods, greatly decrease grass vigour (strength and health) (Ferraro & Oesterheld, 2002), and in return, the decrease leads to a reduction in growth rates and lateral tillers, which leads to an increase in the competitive ability of woody plants (Cramer *et al*., 2007; Riginos, 2009; Gordijn, 2010). Overgrazing, as well as trampling, likely decreased grass in both these areas, which increased bush densities and transformed susceptible grazing lands into dense thickets, that resulted in unsuitable rangelands for browsing and grazing animals (Gordijn, 2010).

Thus, the low MAP, together with land-use (overgrazing) were the main drivers of BT, with soil being a minor driver of BT.

#### 3.3.2.2.2 Pilanesberg and Rustenburg areas

Both, the Pilanesberg and Rustenburg areas showed severe bush thickening (BT) for the first time frame (1993-1998) and severe bush lessening (BL) for the second time frame (1998-2018). As a result, these two areas were grouped together for indicating the drivers of BT and BL from 1993 to 2018.

- **Pilanesberg**

Table 3.28 – 3.30 show the correlation matrix, that indicated the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors and bush spread of the Pilanesberg area for time frames, 1993-1998, 1998-2018 and 1993-2018. The significant correlation coefficients $\Phi_K$ were indicated as bold.

**Table 3.28: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Pilanesberg area for time frame 1993-1998. The significant correlation coefficients $\Phi_K$ were indicated as bold.**

| 1993-1998 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.17 | 0.18 | 0.16 | 0.25 | 0.05 | 0.17 | 0.08 |
| **BT** | 0.24 | 0.22 | 0.27 | 0.19 | 0.34 | 0.14 | 0.36 |
| **NC** | 0.03 | 0.04 | 0.05 | 0.05 | 0.04 | 0.11 | 0.03 |
| **BL** | 0.17 | 0.17 | 0.15 | 0.24 | 0.14 | 0.25 | 0.07 |

**Table 3.29: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Pilanesberg area for time frame 1998-2018. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1998-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.19 | 0.20 | 0.21 | 0.22 | 0.19 | 0.25 | 0.32 |
| **BT** | 0.24 | 0.23 | 0.26 | 0.31 | 0.35 | 0.27 | 0.31 |
| **NC** | 0.03 | 0.05 | 0.05 | 0.06 | 0.03 | 0.19 | 0.03 |
| **BL** | 0.23 | 0.25 | 0.17 | 0.16 | 0.16 | 0.14 | 0.16 |

**Table 3.30: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors with bush spread of the Pilanesberg area for time frame 1993-2018. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1993-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.20 | 0.21 | 0.20 | 0.15 | 0.17 | 0.15 | 0.08 |
| **BT** | 0.14 | 0.15 | 0.09 | 0.26 | 0.10 | 0.15 | 0.09 |
| **NC** | 0.04 | 0.06 | 0.04 | 0.03 | 0.03 | 0.08 | 0.04 |
| **BL** | 0.13 | 0.12 | 0.10 | 0.09 | 0.09 | 0.10 | 0.07 |

For the first time frame (1993-1998), BE showed a slight correlation with vegetation units (0.25) and insignificant correlations (< 0.20) with the other potential driving factors (Table 3.28). BT showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for vegetation units and land cover, which showed insignificant correlations (< 0.20). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.28). BL showed slight correlation with vegetation units (0.24) and land cover (0.25), but showed insignificant correlations (< 0.20) with all the potential driving factors of BE.

For the second time frame (1998-2018), BE showed slight correlations with all potential driving factors, except for MAP and land types, which showed insignificant correlations (< 0.20) (Table 3.29). BT showed slight correlations (0.20 – 0.39) with all the potential driving factors, with land types that showed the highest correlation (0.35). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.29). BL showed slight correlations with MAP (0.23) and MAT (0.25), but showed insignificant correlations (< 0.20) with all the other potential driving factors (Table 3.29).

For the third time frame (1993-2018), BE showed slight correlations (0.20 – 0.39) MAP (0.20) and MAT (0.21), but showed insignificant correlations (< 0.20) with the other potential driving factors (Table 3.30). BT showed a slight correlation (0.26) with vegetation units, but showed insignificant correlations (< 0.20) with all other potential driving factors (Table 3.30). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.30). BL showed insignificant correlations (< 0.20) with all the potential driving factors of BE.

- **Rustenburg**

Table 3.31 – 3.33 show the correlation matrix, that indicated the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors and bush spread of the Rustenburg area for time frames, 1993-1998, 1998-2018 and 1993-2018. The highest correlation coefficient $\Phi_K$ were indicated as bold.

**Table 3.31: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Rustenburg area for time frame 1993-1998. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1993-1998 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.17 | 0.22 | 0.21 | 0.23 | 0.26 | 0.13 | 0.23 |
| **BT** | 0.24 | 0.39 | **0.40** | 0.36 | 0.39 | 0.37 | **0.63** |
| **NC** | 0.04 | 0.05 | 0.05 | 0.02 | 0.06 | 0.06 | 0.02 |
| **BL** | 0.20 | 0.22 | 0.17 | 0.16 | 0.19 | 0.20 | 0.12 |

**Table 3.32: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.00 and 1) between the potential driving factors with bush spread of the Rustenburg area for time frame 1998-2018. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1998-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.15 | 0.24 | 0.29 | 0.15 | 0.27 | 0.11 | 0.19 |
| **BT** | **0.40** | **0.46** | **0.49** | 0.30 | **0.44** | 0.39 | 0.36 |
| **NC** | 0.04 | 0.03 | 0.03 | 0.04 | 0.14 | 0.05 | 0.01 |
| **BL** | 0.16 | 0.25 | 0.20 | 0.24 | 0.21 | 0.26 | 0.24 |

**Table 3.33: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors with bush spread of the Rustenburg area for time frame 1993-2018. The highest correlation coefficient $\Phi_K$ were indicated as bold.**

| 1993-2018 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bush spread** | **Potential driving factors of BE** | | | | | | |
| | **MAP** | **MAT** | **Topography** | **Vegetation units** | **Land Types** | **Land Cover** | **Geology** |
| **BE** | 0.31 | 0.28 | 0.26 | 0.13 | 0.29 | 0.28 | 0.27 |
| **BT** | 0.16 | 0.22 | 0.22 | 0.20 | 0.27 | 0.24 | 0.24 |
| **NC** | 0.02 | 0.03 | 0.03 | 0.03 | 0.01 | 0.04 | 0.02 |
| **BL** | 0.22 | 0.19 | 0.20 | 0.16 | 0.20 | 0.30 | 0.21 |

For the first time frame (1993-1998), BE showed slight correlations (0.20 – 0.39) with all potential driving factors, except for MAP and land cover, which showed insignificant correlations (< 0.20) (Table 3.31).

BT showed a good correlation (0.63) with geology and a moderate correlation (0.40) with topography, while BT showed slight correlations (0.20 – 0.39) with all other potential driving factors (Table 3.31). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.31). BL showed slight correlations with MAP (0.20), MAT (0.22) and land cover (0.20), but showed insignificant correlations (< 0.20) with all the potential driving factors of BE.

For the second time frame (1998-2018), BE showed slight correlations (0.20 – 0.39) with MAT, topography and land types, but showed insignificant correlations (< 0.20) (Table 3.32) with other potential driving factors (Table 3.32). BT showed moderate correlations (0.40 – 0.59) with MAP, MAT, topography and land types, while BT showed slight correlations (0.20 – 0.39) with all other potential driving factors (Table 3.32). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.32). BL showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for MAP, which showed an insignificant correlation (< 0.20) with BL (Table 3.32).

For the third time frame (1993-2018), BE showed slight correlations (0.20 – 0.39) with all potential driving factors, except for vegetation units, which showed an insignificant correlation (< 0.20) (Table 3.33). BT showed slight correlations (0.20 – 0.39) with all potential driving factors, except for MAP, which showed an insignificant correlation (< 0.20) (Table 3.33). NC showed insignificant correlations (< 0.20) with all the potential driving factors (Table 3.33). BL showed slight correlations (0.20 – 0.39) with all the potential driving factors, except for MAT and vegetation units, which showed insignificant correlations (< 0.20) (Table 3.33).

Table 3.34 indicates the potential driving factors of BE that showed significant correlations with bush thickening (BT) of the Pilanesberg and Rustenburg areas for time frames, 1993-1998, 1998-2018 and 1993-2018. Only BT was included in Table 3.34 as no other bush spread showed significant correlations with the potential driving factors of BE for all time frames.

**Table 3.34: The potential driving factors of BE that showed significant correlations with bush thickening (BT) of the Pilanesberg and Rustenburg areas for time frames, 1993-1998, 1998-2018 and 1993-2018.**

| | Time frame | | | | | |
|---|---|---|---|---|---|---|
| **BE spread** | **1993-1998** | | **1998-2018** | | **1993-2018** | |
| | **Pilanesberg** | **Rustenburg** | **Pilanesberg** | **Rustenburg** | **Pilanesberg** | **Rustenburg** |
| **Bush thickening (BT)** | None | Topography and geology | None | MAP, MAT, Topography and land types | None | None |

Bush thickening (BT) showed the highest and most significant correlations with topography and geology for the first time frame (1993-1998) and showed the most significant correlations with MAP, MAT, topography and land types for the second time frame (1998-2018) (Table 3.34). From the initially created correlation matrixes (CSV files), topography showed a good correlation (0.66) with geology for the first time frame. All the significant correlations for the second time frame showed good correlations (between 0.6 and 0.8) with each other, with MAT having a great correlation (0.87) with topography.

**Discussion on potential drivers of bush encroachment in the Pilanesberg and Rustenburg areas**

- **Bush thickening (BT)**

Although different potential driving factors had significant correlations with BT for the Pilanesberg and Rustenburg areas, geology had a very significant correlation with the Rustenburg area for the first time frame (1993-1998). The Rustenburg area consisted of ultramafic, mafic and meta-sedimentary rocks (i.e. harzburgite, basalt and amphibolite) and were largely comprised of the Bushveld Complex (McCarthy & Rubidge, 2005). Although, previous studies (Boneschans *et al*., 2015) have shown that certain woody plants have an affinity for certain rock compositions, there were no clear evidence which geological category showed a correlation with severe BT.

From the results, topography, MAP, MAT and land types showed a significant correlation with BT for the second time frame (1998-2018). A study done by Sternberg and Shohany (2001) (in Yang *et al*., 2020) found a significant vegetation difference between opposite slopes in semi-arid regions and observed the strongest slope effects in areas with critical water limitation. The slope aspect, together with slope position can jointly influence vegetation structure. Previous studies indicate that topography is a minor factor influencing bush encroachment, as it can influence vegetation distribution and structure (Nunes *et al*., 2019). As no in-depth research has been done in this study, regarding the influence of topography on BT, it was likely a minor driving factor of BT in the Rustenburg area for the first and second time frames (1993-1998 and 1998-2018). Previous studies have also suggested that temperature influence specific plant species (De Klerk, 2004). Although, no in-depth research has been done in this study, regarding the influence of MAT on specific species, which makes MAT a minor driving factor rather than a main driving factor of BT. The land types of the Rustenburg area are predominantly Ib, which indicates abundant rock outcrops in the area (Table 3.8). As the Ib broad land type generally have shallow soils (Land Type Survey Staff, 1972-2006), this would not have benefited the root growth of woody plants. Although, soil, together with soil likely did influence bush thickening in the Rustenburg area.

As the NWP experienced droughts from 2005 to 2015 (Botai *et al*., 2016), this led to highly variable precipitation during this time. Although, variable precipitation can increase the rate of fire frequency, which reduces the rate of woody vegetation growth (Archibald *et al*., 2009; Turpie *et al*., 2019), it also likely benefitted woody plants. The increased precipitation variability might have greatly increased woody plant and grass competition for water and nutrients (Ward *et al*., 2005; Wiegand *et al*., 2005). As established, woody plants generally have a deeper root system, and have the ability to acquire water in drought periods, whereas grass roots only extent down to 30 cm in the soil (Ward *et al*., 2005). As the soils of the Rustenburg area were very shallow, the competition for water and nutrients in the soil were very high, however, the droughts and precipitation variability likely favoured woody plants and allowed them to outcompete grass and grow thicker in the NWP.

Therefore, the severe BT were likely primarily caused by MAP, but other dynamic factors, such as plant functional type, soil, MAT and topography also likely contributed to the BT in the Rustenburg area.

- **Bush lessening (BL)**

As BL had a slight or insignificant correlation with almost all the potential driving factors (Table 3.31 – 3.33), there were no clear driving factor of BL in the Pilanesberg and Rustenburg areas from 1993 to 2018. Although, land cover did show slightly higher correlations with BL (Table 3.32), there were not enough significant correlations for all three time frames to support that land cover drove BL in these two areas. Although MAP did not show a significant correlation with BL, it might have been the only true driving factor that led to a decrease of bushes in these areas. As mentioned, the droughts decreased in the NWP from 2005 to 2015 (Botai *et al*., 2016), however, the precipitation variability led to a decrease of bush growth. Although fire was not used as potential driving factor, it likely influenced BL in the Pilanesberg and Rustenburg areas. Fire is commonly applied for ecosystem management, especially in the Pilanesberg National Park (Woolley *et al*., 2008), which are used to decrease woody plants (Turpie *et al*., 2019). The Pilanesberg area were also mostly comprised of the Pilanesberg National Park, which meant that browser animals, such as elephants, impala and kudu also likely decreased the bushes, by feeding on the woody plants (Hempson *et al*., 2017). Therefore, browser animals in both these areas fed on the woody plants and the low MAP likely increased frequent fires, which explained the significant increase of bush lessening (BL) distribution from time frame one (1993-1998) to time frame two (1998-2018).

#### 3.3.2.3 Precipitation data

Tables 3.35 – 3.38 indicates the calculated mean MAP (mm), as well as highest and lowest MAP (mm) of the Taung, Mafikeng, Pilanesberg and Rustenburg areas for time frames, 1993 to 1998, 1998 to 2018 and 1993 to 2018.

**Table 3.35: The calculated mean MAP (mm), as well as highest and lowest MAP (mm) of the Taung area for time frames, 1993-1998, 1998-2018 and 1993-2018.**

| Taung | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time frames | | | | | | | | |
| 1993-1998 | | | 1998-2018 | | | 1993-2018 | | |
| Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP |
| 421 | 455 | 373 | 395 | 791 | 81 | 399 | 791 | 81 |

**Table 3.36: The calculated mean MAP (mm), as well as highest and lowest MAP (mm) of the Mafikeng area for time frames, 1993-1998, 1998-2018 and 1993-2018.**

| Mafikeng | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time frames | | | | | | | | |
| 1993-1998 | | | 1998-2018 | | | 1993-2018 | | |
| Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP |
| 622 | 874 | 405 | 503 | 778 | 293 | 524 | 874 | 293 |

**Table 3.37: The calculated mean MAP (mm), as well as highest and lowest MAP (mm) of the Pilanesberg area for time frames, 1993-1998, 1998-2018 and 1993-2018.**

| Pilanesberg | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time frames | | | | | | | | |
| 1993-1998 | | | 1998-2018 | | | 1993-2018 | | |
| Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP |
| 626 | 986 | 397 | 543 | 985 | 57 | 556 | 986 | 57 |

**Table 3.38: The calculated mean MAP (mm), as well as highest and lowest MAP (mm) of the Rustenburg area for time frames, 1993-1998, 1998-2018 and 1993-2018.**

| Rustenburg | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1993-1998 | | | 1998-2018 | | | 1993-2018 | | |
| Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP | Mean MAP | Highest MAP | Lowest MAP |
| 612 | 896 | 275 | 488 | 1032 | 148 | 508 | 1032 | 148 |

From Tables 3.35 – 3.38, the Taung areas showed the lowest mean MAP (421 mm), while the Pilanesberg area showed the highest mean MAP (626 mm) for the first time frame (1993-1998). The Taung area also showed the lowest mean MAP (395 mm) for the second time frame (1998-2018), while the Pilanesberg area also showed the highest mean MAP (543 mm). The Taung area also showed the lowest mean MAP (399 mm) for the third time frame (1998-2018), while both the Pilanesberg and Rustenburg areas showed the highest mean MAP (both 556 mm). The highest MAP for the Taung and Mafikeng areas showed lower values for all time frames, compared with the Pilanesberg and Rustenburg areas.

The decrease of mean MAP could have been attributed to droughts occurring in the NWP (Botai *et al*., 2016). Overall, the mean MAP decreased significantly for all the areas from time frame one (1993-1998) to time frame two (1998-2018), which further substantiated the influence of that MAP had on all four significant areas. As the low MAP likely caused less grass to grow, and overgrazing decreased the grass, which led to the severe BE and BT in the Taung area. The low MAP, together with fire and herbivory likely decreased bushes in the Pilanesberg and Rustenburg areas.

### 3.3.3 Analysis of variance (ANOVA)

The one-way ANOVA and Kruskal-Wallis H-tests both indicated p-values smaller than 0.01 for the % woody cover years of 1993, 1998 and 2018. This indicates that there is a very great statistical significance of the observed difference. However, the great statistical significance was likely due to the amount of data points (114 million). The small p-values were also found for the % woody cover for the years of 1993, 1998 and 2018 for all the significant areas.

## 3.4 Conclusions

For the first time frame (1993-1998), BT was very severe in the north-eastern, western and south-western parts of the province, while bush encroachment (BE) was less severe in the western part of the province. Bush lessening (BL) and no change (NC) were commonly seen in the central and south-eastern parts of the province for the first time frame (1993-1998). For the second time frame (1998-2018), bush thickening (BT) was severe in the northern, south-western and western parts of the province, while BE was severe in the central, southern and south-western parts of the province. BL and NC were severe in the eastern and north-eastern parts of the province for the second time frame (1998-2018). For the third time frame (1993-2018), BT as very severe in the western, northern and north-eastern parts of the province, while BE was very severe in the western, central and southern parts of the province. BL and NC were most severe in the south-eastern and north-western parts of the province for time frame three (1993-2018). The bush spread distribution in the North West Province (NWP) indicated that BT and BL showed the most severe distribution for all time frames, while BE increased with 7% from time frame one (1993-1998) to time frame two (1998-2018).

On provincial scale, the correlation matrixes indicated that BE had no significant correlation with any potential driving factor but showed the highest correlation with land cover for all time frames. The high amount of livestock in the NWP, as well as the low mean annual precipitation (MAP), likely led to overgrazing in many parts of the province, which might have led to the proliferation of woody plant seedlings and explained the slight correlation between BE and land cover in the NWP from 1993 to 2018. The correlation matrixes also indicated that BT had a significant correlation with MAP and bioregions for all time frames. The four largest bioregions have been identified as bush encroachment/thickening zones. The low MAP, together with overgrazing likely decreased the grass cover and density, which benefitted the woody plants as the competition from grass decreased (Walter's two-layer model). The likely absence of fire also caused the woody plants to grow denser without any constraints and explained the significant correlation between MAP, bioregions and BT in the NWP from 1993 to 2018.

For the significant areas, BE and BT were the most severe in the Taung and Mafikeng areas, while BT and BL were most severe in the Pilanesberg and Rustenburg areas for all time frames.

The correlation matrixes showed that BE had significant correlations with land types and vegetation units in the Taung area for the second and third time frames (1998-2018 and 1993-2018). The low MAP and communally management likely made the area very susceptible to overgrazing, and together with deep, well-drained, sandy soils made the soils favourable for woody plant seedlings. This led to the proliferation of woody plant seedlings and encroachment of bushes, and explained the significant correlations of BE with land types from 1993 to 2018. However, the low MAP, overgrazing by livestock were likely the main drivers of BE, while soil was a minor driver of BE in the Taung area. As the vegetation units were characterised by encroacher species, such as S. mellifera and *V. tortilis*, the significant correlation between BE and vegetation units were also likely mainly influenced by MAP. As the Taung area was predominantly communally managed and the vegetation composition of the area is likely dominated by encroacher species, this area was likely very susceptible for overgrazing and the establishment of woody seedlings. This also further substantiates the reason why the bioregions in the NWP is considered as bush encroachment zones and indicating the importance of predominantly communally managed areas.

The correlation matrixes showed that BT had significant correlations with land types in the Taung area for the second time frame (1998-2018). Overgrazing, as well as trampling, likely decreased grass cover and density in both these areas, which increased bush densities and transformed susceptible grazing lands into dense thickets, that resulted in unsuitable rangelands for browsing and grazing animals. This caused the significant correlations between BT and land cover. The low MAP and overgrazing likely caused a decrease in grass and influenced the competition for nutrients and water in the soil, as the woody plants could attain more nutrients and water from the soil, which allowed the plants to grow and become denser with time. Therefore, the significant correlation BT had with land types could be explained by the influence of low MAP, overgrazing and soil depth.

Although different potential driving factors had significant correlations with BT for the Pilanesberg and Rustenburg areas, geology had a very significant correlation with the Rustenburg area for the first time frame (1993-1998). Although, previous studies have shown that certain woody plants have an affinity for certain rock compositions, there were no clear evidence, which geological category showed a correlation with severe BT. From the results, topography, MAP, mean annual temperature (MAT), and land types showed a significant correlation with BT for the second time frame (1998-2018). The severe BT were likely primarily caused by MAP, but other dynamic factors, such as plant functional type, soil, MAT, and topography also likely contributed to the BT in the Rustenburg area.

As BL had a slight or insignificant correlation with almost all the potential driving factors, there were no clear driving factor/s of BL in the Pilanesberg and Rustenburg areas from 1993 to 2018. However, browser animals (such as goats and wildlife) in both these areas likely fed on the woody plants and the low MAP likely increased frequent fires, which explained the significant increase of BL distribution from time frame one (1993-1998) to time frame two (1998-2018).

The precipitation data clearly indicated a decrease of mean MAP regarding all significant areas from time frame one (1993-1998) to time frame two (1998-2018), which could have been attributed to droughts occurring in the NWP. As the low MAP likely caused less grass to grow, as well as overgrazing that led to the severe BE and BT in the Taung area and low MAP, together with fire and herbivory could all have decreased bushes in the Pilanesberg and Rustenburg areas.

In conclusion, this study used GIS to determine the driving factors of BE in the NWP from 1993 to 2018. The results indicated that BE and BT were severe in the NWP. On provincial scale, both BE and BT showed significant correlations with MAP, which indicated that the low MAP of the NWP, likely led to overgrazing in the province, which allowed woody plants to outcompete grass, establish and grow denser. Therefore, on Provincial scale MAP can be considered as the main driving factor of BE and BT in the NWP from 1993 to 2018.

For the significant areas, the Taung area showed significant correlation between land types and BE and BT. Although, the sandy, deep, well-drained soil may have favoured the establishment and growth of woody plants, the low MAP and overgrazing were likely the main drivers of BE and BT in the Taung area. The Rustenburg area showed significant correlations between BT and topography, geology, MAT, MAP and land types. However, considering the droughts and influence of precipitation variability, MAP were likely the main driving factor of BT, with the other factors considered minor driving factors. The low MAP, herbivory and fire were likely responsible for the lessening of bush in the Pilanesberg and Rustenburg areas, though the feeding of browsers and burning management implemented in these areas.

# CHAPTER 4 INVESTIGATING THE EFFECT OF SOIL PHYSICAL PROPERTIES ON BUSH ENCROACHMENT

## 4.1 Introduction

It is difficult to attribute a single factor to the cause of observed bush encroachment (BE), as previous studies have indicated that soil types are not the only factor contributing as an important factor driving BE, but causes such as grazing regimes, climate change and topography may also contribute to BE (Scholes & Archer, 1997; Sankaran *et al*., 2005; Ward, 2005; Abule *et al*., 2005; Gottfried *et al*., 2009; Bowman *et al*., 2011, O'Connor *et al*., 2014; Belayneh & Tessema, 2017; Devine *et al*., 2017; Nunes *et al*., 2019; Turpie *et al*., 2019; Yang *et al*., 2020). In this chapter, a vegetation and soil analysis were carried out to determine the driving factors of bush encroachment (BE) in the North West Province (NWP) of South Africa.

## 4.2 Materials and methods

### 4.2.1 Study area

The study area consists of three study sites that were selected by the Department of Environmental Affairs (DEA) (now part of Department of Forestry, Fisheries and the Environment or DFFE) as they were priority areas regarding the control of BE. These three study sites were selected by the DFFE based on the severity of BE at each location. These three sites are named after the nearest town or region within which each site is located. The three sites are called "Pilanesberg", "Legkraal" and "Kgomo-Kgomo", with their localities seen in Figure 4.1. The Pilanesberg site is situated inside the Pilanesberg National Park, while the Legkraal site is situated within the Legkraal community and Kgomo-Kgomo site situated within the Kgomo-Kgomo community, near Makapanstad (Figure 4.1).

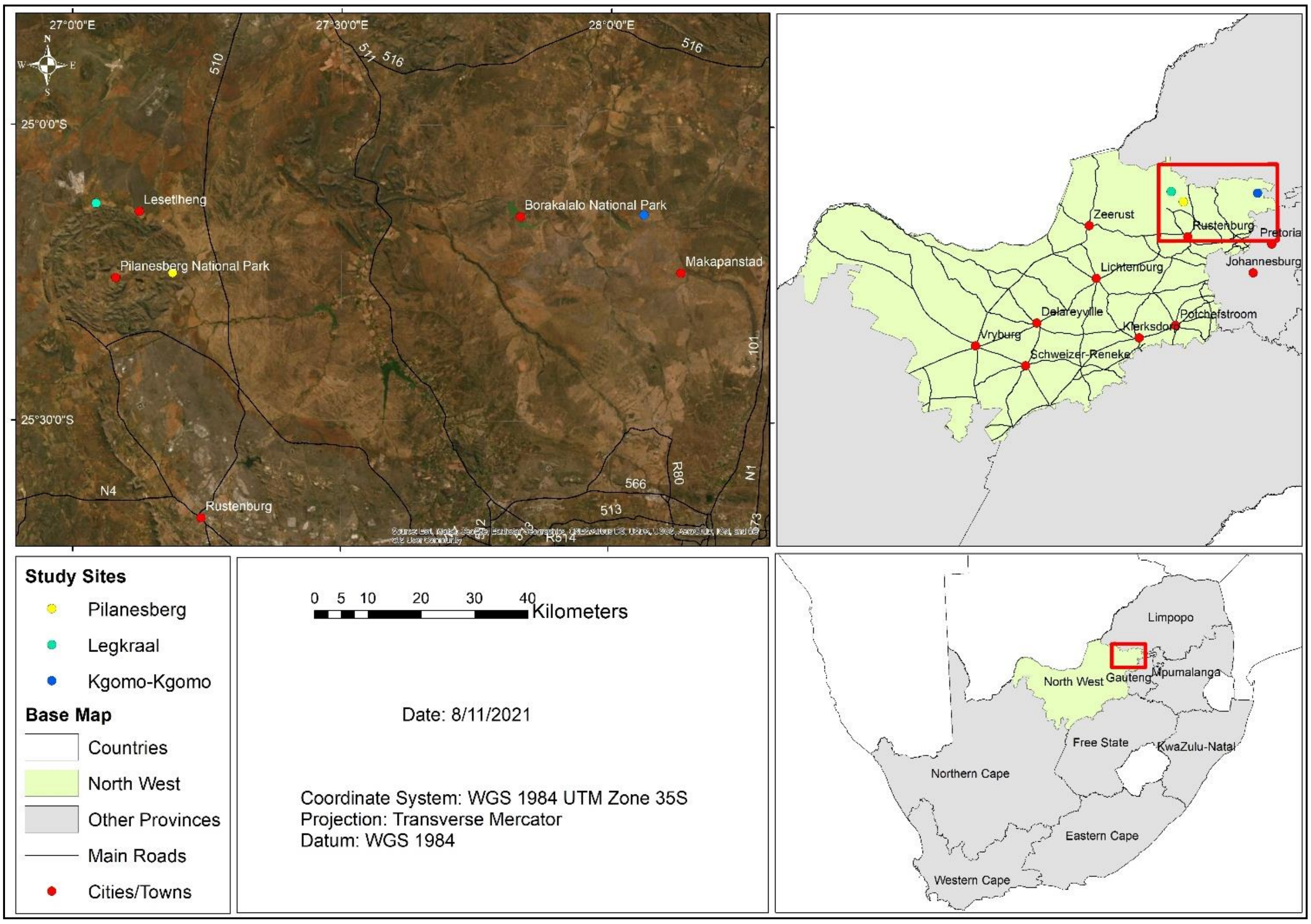



**Figure 4.1: A map indicating the location of the North West Province, as well as the localities of the three study sites, i.e Pilanesberg (yellow dot), Legkraal (green dot), and Kgomo-Kgomo (blue dot).**

- **Pilanesberg site**

The Pilanesberg site is situated at 25°15'4.93" S and 27°11'8.726" E, which is within the Pilanesberg National Park, approximately 5 km from the Bosele Gate (Figure 4.2). Pilanesberg is found on the Pilanesberg Mountain Bushveld, which is part of the Central Bushveld Bioregion (Mucina and Rutherford, 2006). The geology of the Pilanesberg site consists of the Pilanesberg Complex, which contains igneous rocks such as syenite, nepheline syenite and tuff (Council of Geosciences, 2019). The mean annual precipitation (MAP) of the Pilanesberg site is approximately 650 mm, while the mean annual temperature (MAT) is approimately 19 °C (Schulze, 2007). The Pilanesberg site is situated on a Ib broad land type, where rock outcrops comprise more than 60% of the land type (Land Type Survey Staff, 1972-2006). Wildlife herbivores, such as impala, kudu, white rhinoceros and elephants are found inside the Pilanesberg National Park (Pilanesberg National Park, 2021) and at the Pilanesberg site.

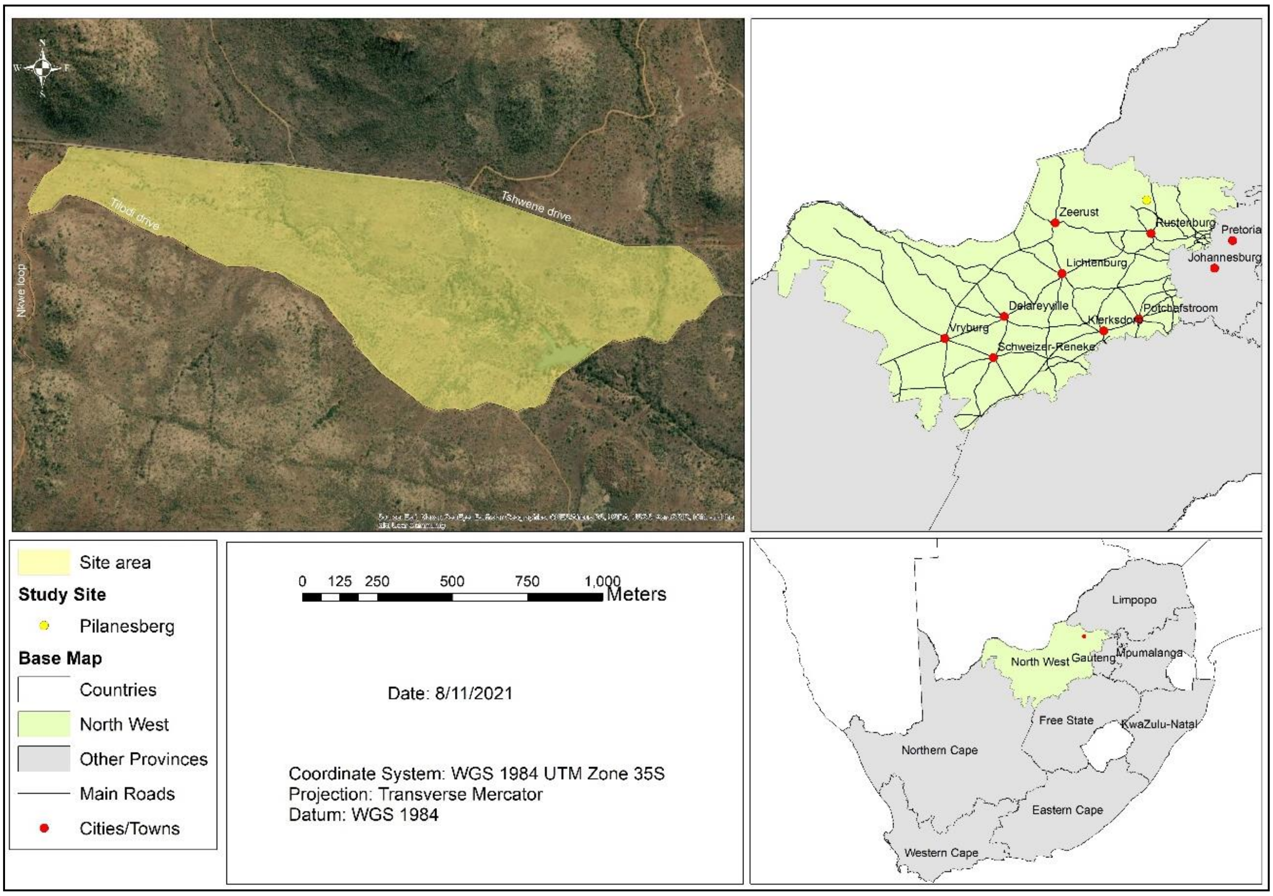



**Figure 4.2: A map indicating the location of the North West Province, as well as the Pilanesberg site (yellow dot) and study area (yellow square), as selected by the DEA.**

- **Legkraal site**

The Legkraal site is surrounded by a communal area situated within the communally managed area of Legkraal at 25°8'2.574" S and 27°2'36.417" E (Figure 4.3). Legkraal is found on the Dwaalboom Thornveld, which is part of the Central Bushveld Bioregion (Mucina and Rutherford, 2006). The geology of Legkraal indicated that it is characterized by alluvium, colluvium, sand and gravel stratigraphy (Council of Geosciences, 2019). The MAP of the Legkraal site is around 650 mm, while the MAT is approximately 19 °C (Schulze, 2007). The Legkraal site is situated on a Ea broad land type, where black or red clays comprise more than 50% of the land type (Land Type Survey Staff, 1972-2006). With the help of Kwevho's Business Enterprise[1], managed by Emmanuel Mukwevho, the community has started implementing chemical and mechanical (bush cutting) methods to control BE. Livestock, such as cattle and goats, are found at the study site. Livestock utilise the rangeland at the study site for fodder, especially after BE was addressed.

[1] Contact number: 072 896 0786
Address: 192 Hillary Drive, Bendor, Limpopo, 0699

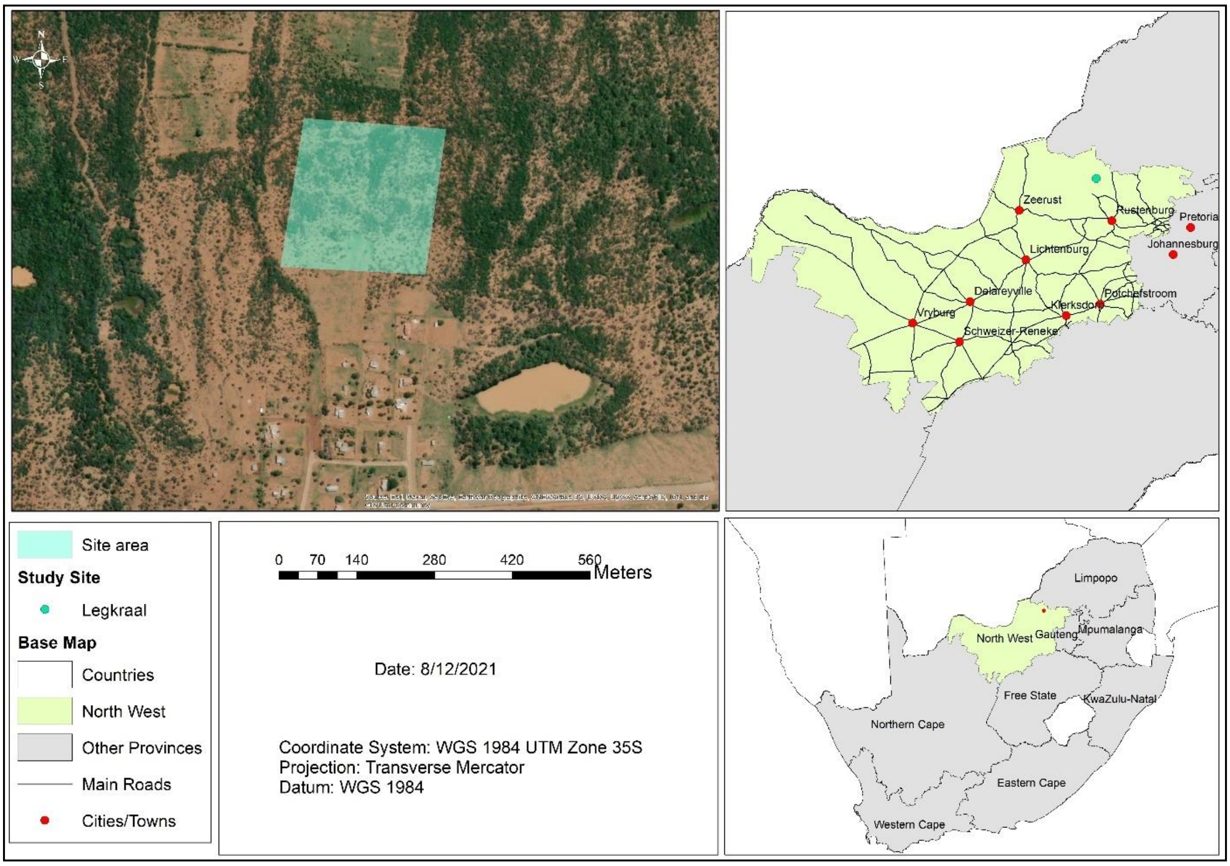



**Figure 4.3: A map indicating the location of the North West Province, as well as the Legkraal site (light blue dot) and study area (light blue square), as selected by the DEA.**

- **Kgomo-Kgomo site**

The Kgomo-Kgomo site is found near the communally managed area of Kgomo-Kgomo and situated at 25°8'53.878" S and 28°3'34.749" E, which is approximately 12 km from Makapanstad (Figure 4.4). This study site is found on the Springbokvlakte Thornveld, which is part of the Central Bushveld Bioregion (Mucina and Rutherford, 2006). The geology of the site is characterized by the Molteno Formation, which includes sedimentary rocks, such as sandstone, mudstone and shale (Council of Geosciences, 2019). The MAP of the Kgomo-Kgomo site is approximately 600 mm, while the MAT is approximately 20 °C (Schulze, 2007). The Kgomo-Kgomo site is situated on a Ae broad land type, which consists of freely-drained, red, apedal soils comprising more than 40% of the land type (Land Type Survey Staff, 1972-2006). Livestock, such as cattle and goats, are found at the study site. Livestock utilise the rangeland at the study site for fodder, especially after BE was addressed.

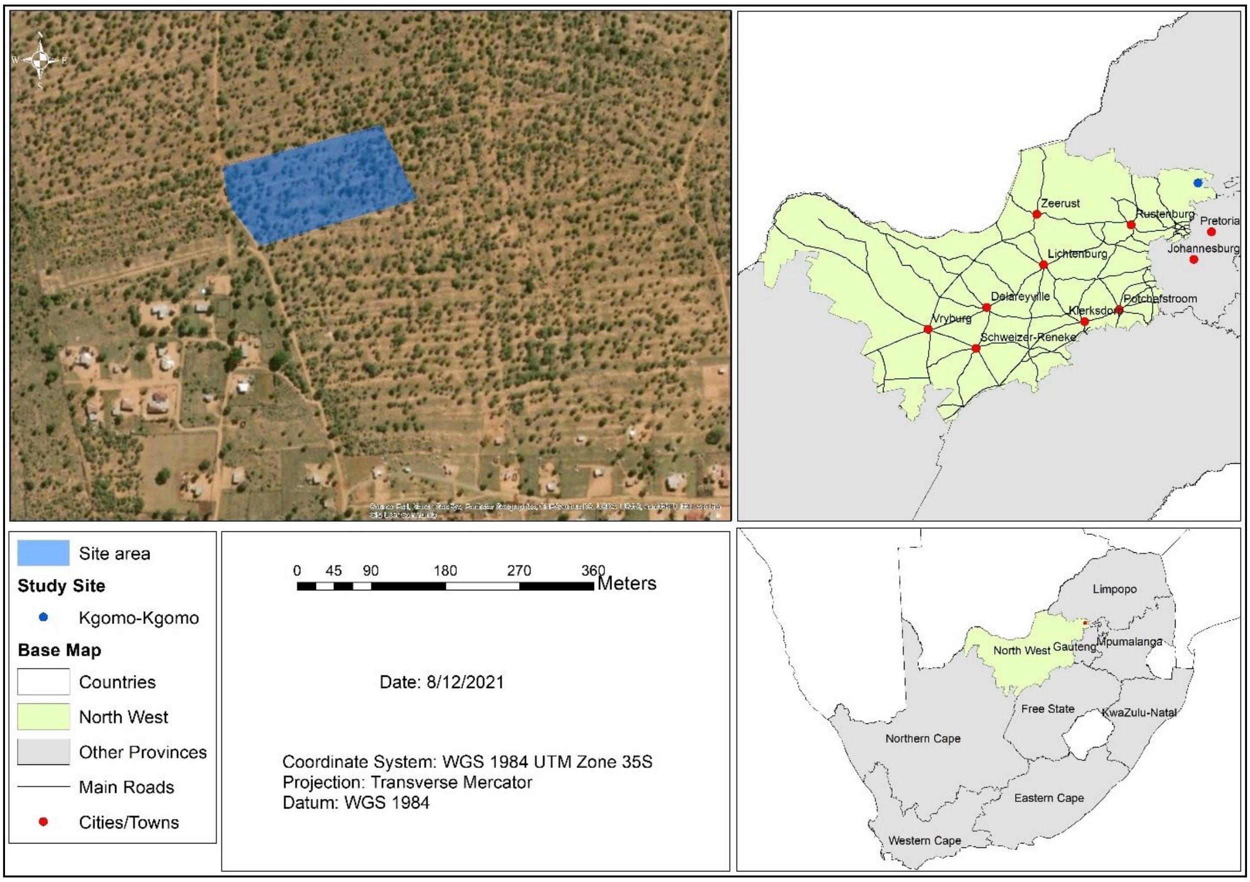



**Figure 4.4: A map indicating the location of the North West Province, as well as the Kgomo-Kgomo site (dark blue dot) and study area (dark blue square), as selected by the DEA.**

### 4.2.2 Transect layout

Before the on-site visit, the three study areas within the selected sites were reviewed, using available GIS data including: Google Maps, land cover- (Thompson, 2018), land type- (Land Type Survey Staff, 2006), and geology (Council of Geosciences, 2007) maps. With these data sources, the suitability of the area for vegetation and soil analysis could be identified and it also indicated if there were any environmental obstructions that had to be overcome, such as rock outcrops and waterbodies. The SW Maps - GIS and Data Collector (Softwel (P) Limited, 2016) was used to record the start and end coordinates of each transect, as well as the coordinates of the undisturbed core samples taken within each transect.

Three, 100 m long × 2 m wide transects were laid out at each site that makes up the continuous belt transect sampling method (Copenheaver *et al*., 2004; Yamamoto *et al*., 2011; Parker *et al*., 2011; Abate *et al*., 2012; Mokgosi, 2018). A 100 m tape was placed on the ground, while a 2 m pole was set down on the ground perpendicular to the tape to complete the sampling area of 200 $m^2$. Figures 4.6 and 4.7 indicates the layout of the continuous belt transect, with the 2 m pole set down on the ground perpendicular to the tape to complete the area of the transect. The vegetation surveys and soil observations were done inside the area of each transect.

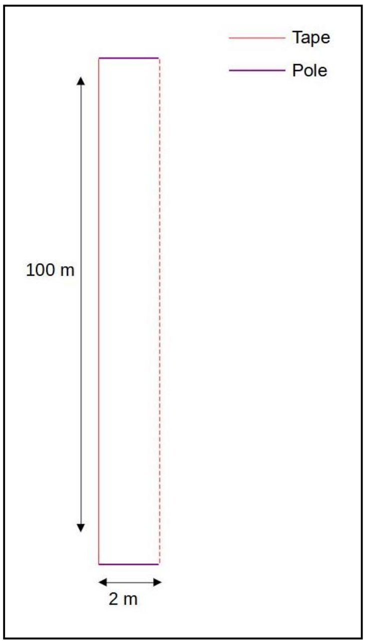



**Figure 4.5: Layout of the continuous belt transects used during the study for each site, created in LibreOffice 7.0.**

**Figure 4.6: A photograph of the tape and pole set on the ground to complete the continuous belt transect. Photograph taken by Willie Cloete.**

The transects at the Pilanesberg site were laid out between the Tshwene drive and Tilodi drive of the Pilanesberg National Park (Figure 4.8). The transects had to be laid out on the midslope or upper midslope as the Seshabele stream flows between these two roads and prohibited effective augering and soil classification. The transects were not laid out on the footslope area as fewer woody plants were found and not considered as "encroached", such as the midslope area. The transects at the Legkraal site were laid out in the centre of the Legkraal site area (Figure 4.9). The transects were also laid out in the most encroached area possible, which was not yet being chemically and mechanically cleared by employees of Kwevho's Business Enterprise. This area was also the easiest accessible by vehicle. The transects of the Kgomo-Kgomo site were also laid out in the centre of the site area (Figure 4.10). The selected area was also next to an area that was chemically and mechanically cleared of BE.

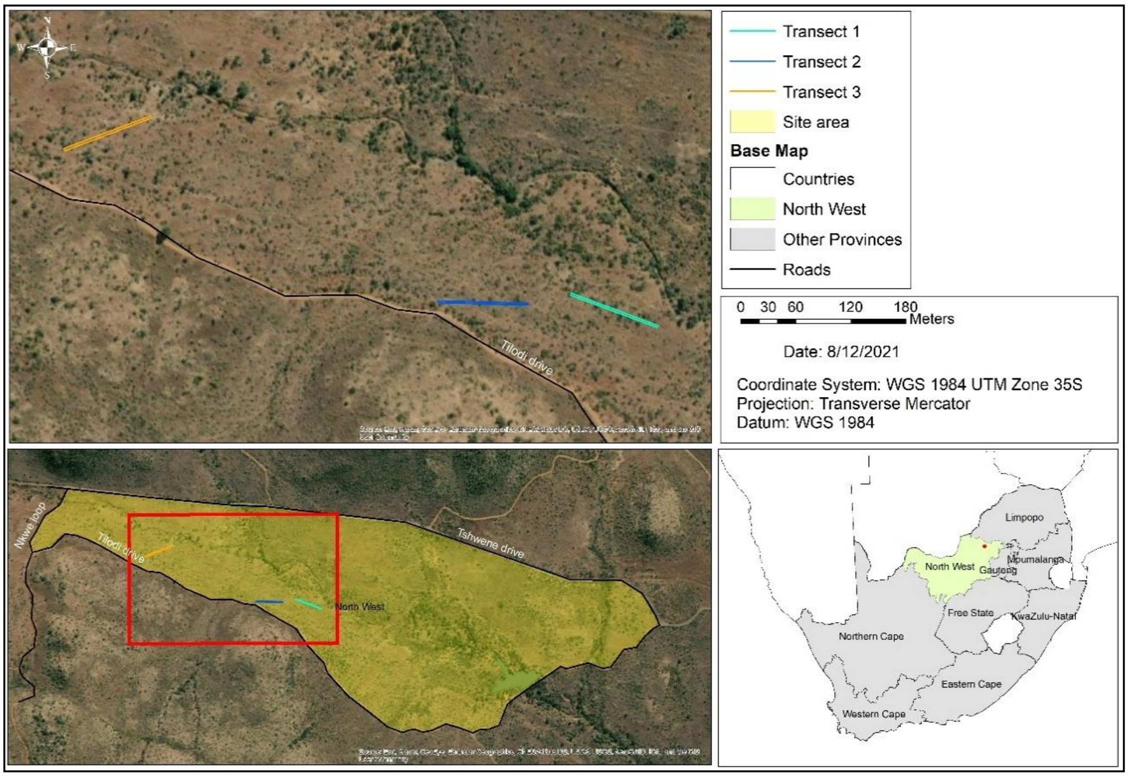



**Figure 4.7: A map indicating the transect layout of the Pilanesberg site, situated between the Tshwene drive and Tilodi drive, laid out on the midslope or upper midslope.**

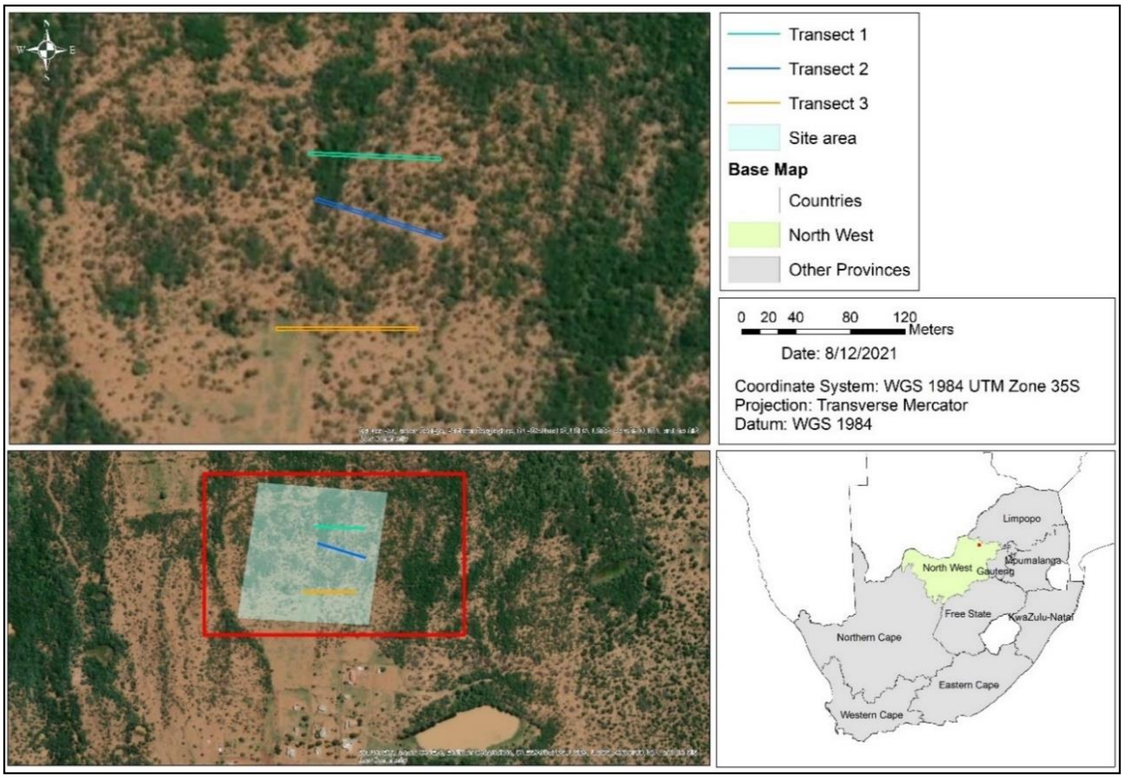



**Figure 4.8: A map indicating the transect layout of the Legkraal site, laid out in the centre of the Legkraal site area.**

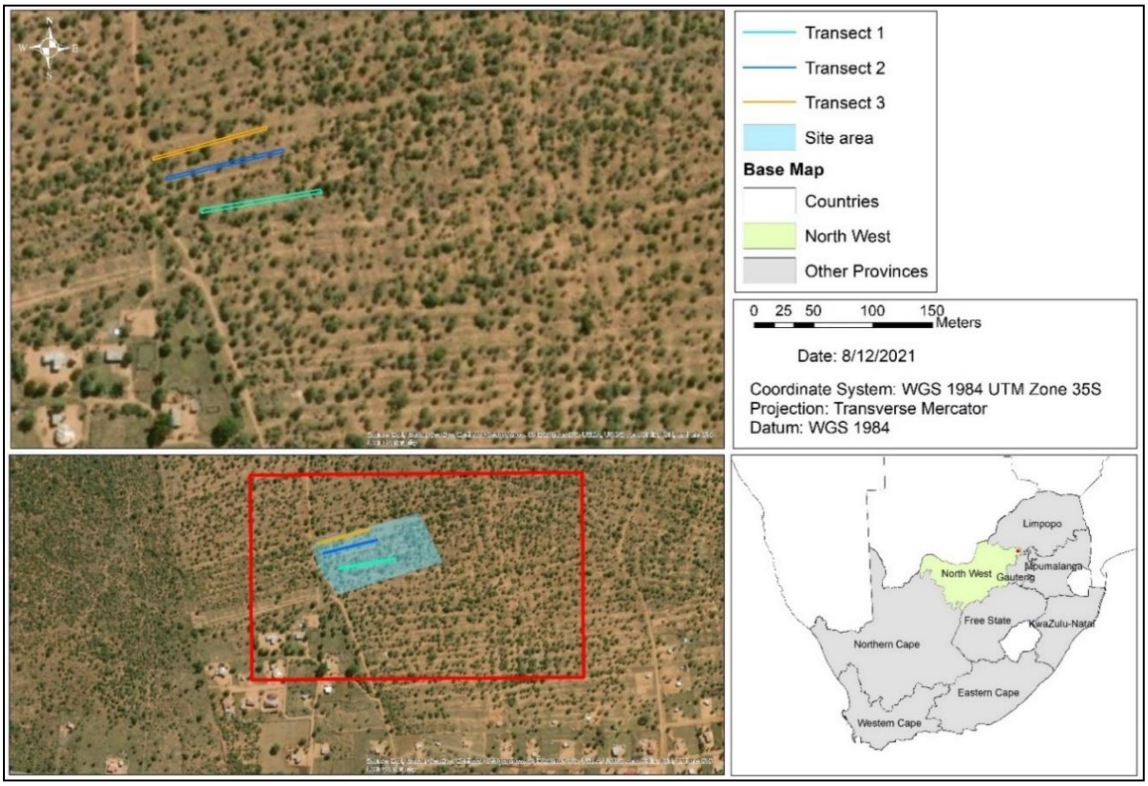



**Figure 4.9: A map indicating the transect layout of the Kgomo-Kgomo site, laid out in the centre of the site area.**

### 4.2.3 Vegetation survey

Within the belt transects the composition, density and structure (height classes) of the woody tree- and shrub species at each site was recorded (United Stated Department of Agriculture, 1996; Abate *et al*., 2012) (Figure 4.10 and Table 4.1). The density of the woody component was determined by counting each tree or shrub (individual single/multi-stemmed) within each belt transect. The structure was determined by dividing the woody species into height classes using a 1.8 m pole. The 1.8 m pole was placed vertically next to the woody species, measuring at 30 cm intervals (Figure 4.10 and Table 4.1).

**Figure 4.10: A photograph of the 1.8 m pole placed next to the woody trees and shrubs for measuring the structure. The green tape presents the 30 cm intervals. Photograph taken by Willie Cloete.**

**Table 4.1: Height classes identified for measuring tree- and shrub species.**

| Height class | Length (cm) |
|---|---|
| **1** | < 30 |
| **2** | 30 – 60 |
| **3** | 60 – 90 |
| **4** | 90 – 120 |
| **5** | 120 – 150 |
| **6** | 150 – 180 |
| **7** | > 180 |

### 4.2.4 Soil analysis

Soil observations were made by soil auger to a depth of 120 cm or refusal. Profiles were described per soil horizon, with hand-feel texture, structure, stone content, lime presence, colour and mottling noted (Brady & Weil, 2017 and Munsell, 2000). The augured soil profiles were classified according to the Soil Classification Working Group (2018) to soil family level. Soil samples from the A and B horizons (if applicable), were taken and placed into zip-locked bags to determine soil pH (in KCl), electrical conductivity (EC) with the saturated paste method and particle size distribution with the Hydrometer method (Bouyoucos, 1962) in the laboratory. Although two soil observations were made (at 30 m and 70 m), samples were only taken from the first observation, as there were not enough zip-licked bags (Figure 4.12). Each soil sample that were observed were also used to calculate averages for indicating the soil parameters of each transect of each study site. The gravel (> 2 mm) distribution was calculated and afterwards the sand, silt and clay fraction was calculated. The pH (KCl) and EC were determined using a calibrated pH/EC multi-meter. The pH was determined using a ratio of 1:2.5 substrate samples to de-ionized water/KCl suspension on a mass basis. Undisturbed core samples were taken from the A horizon to determine hydraulic soil parameters in the laboratory with a pressure plate extractor (Brady & Weil, 2017; Environmental Monitoring Branch, 2018). Although field capacity was not measured in this study, the samples were measured at 1 Bar suction pressure and 15 Bar suction pressure (wilting point), which were used to calculate the plant available water (PAW) (difference in soil moisture between field capacity and wilting point) and total plant available water (TPAW) (maximum amount of water stored in the soil profile that can be used by plants) of each study site (Gerakis & Ritchie, 2002; Burk & Dalgliesh, 2013; Brady & Weil, 2017). Field capacity refers to "*the highest, field-measured volumetric water content of a soil after thorough wetting and draining and until drainage becomes practically negligible*", whereas wilting point refers to "*the lowest, field-measured, volumetric water content of a soil after plants stop extracting water due to premature death*" (Gerakis & Ritchie, 2002). Figure 4.11 indicates an example of an undisturbed core sample that was taken from the Pilanesberg site. Figure 4.12 indicates the layout of the soil sampling and taking of undisturbed core samples within each transect.

**Figure 4.11: A photograph of an undisturbed core sample about to be taken from the Pilanesberg site. Photograph taken by Willie Cloete.**

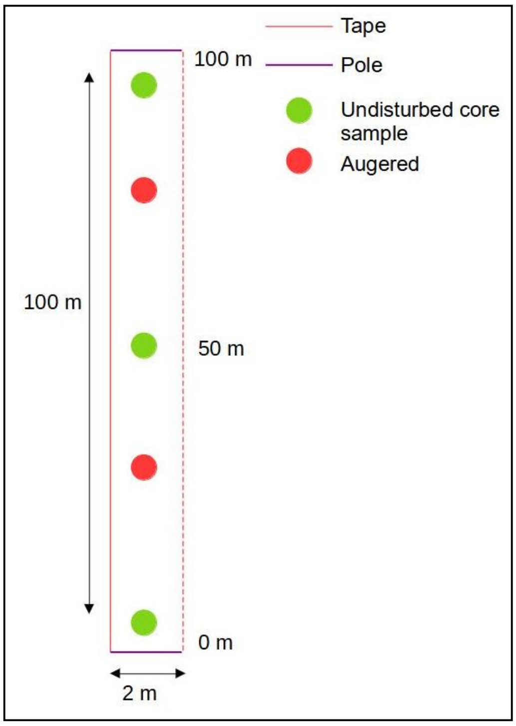



**Figure 4.12: Layout of the continuous belt transects and the layout of the soil sampling at every 30 m and 70 m, as well as the undisturbed core samples taken at the beginning (0 m), middle (50 m) and end (100 m) within each transect. This layout was created in LibreOffice 7.0.**

#### 4.2.5 Determining the relationship between the woody species and soil variables

A redundancy ordination analysis (RDA) was carried out to determine the variables influencing the density of individual woody plants within each transect. Paleontological Statistics Software for Education and Data Analysis version 4.03 (PAST) (Hammer *et al*., 2001) was used to first normalise the data using the "Evaluate expression" tool (under "transform" tool) and with the expression, indicated by equation 4-1. Thereafter, the RDA was created using the "multivariate" tool.

**Equation 4.1:** **(x-mean)/stdev**

Where x is the data that needs to be normalised and stdev is the standard deviation.

### 4.3 Results and discussion

#### 4.3.1 Vegetation survey

##### 4.3.1.1 Species composition and abundance

The woody species composition and abundance showed that *Dichrostachys cinerea* (Sicklebush) was the dominant species at the Pilanesberg and Legkraal sites, while *Diosphyros lycioides* (Blue Bush) was the dominant species at the Kgomo-Kgomo site (Figure 4.13). Figure 4.13 indicates the total species abundance (TSA) of the major woody plant species identified within all transects (600 $m^2$) from all three study sites.

The other encroaching species in the study sites included: *Grewia flava* (Brandybush), *Grewia flavescens* (Rough-leaved raisinbush), *Senegalia mellifera* (Blackthorn), *Vachellia karroo* (Sweet thorn), *Vachellia tortillis* (Umbrella thorn) and *Ziziphus mucronata* (Buffalo thorn). *D*. *cinerea* and *D*. *lycioides* can be regarded as the main encroacher species as *D*. *cinerea* occurred at all study sites and *D*. *lycioides* encroaching significantly at the Kgomo-Kgomo site. However, as woody species differed from each transect at the three study sites, the extent of BE was characterised differently at each site on different levels. The total species abundance (TSA) and specifically the different species identified, gave an indication of the extent of BE at each study site.

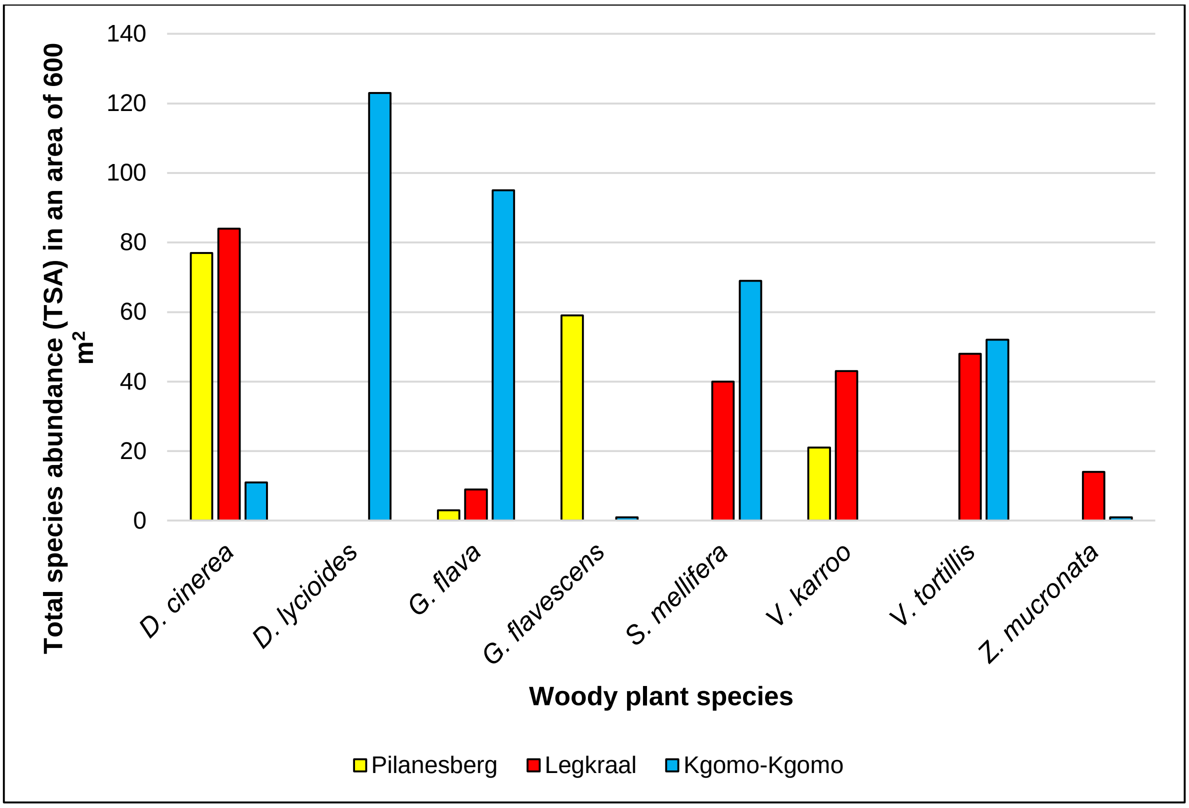



**Figure 4.13: A graph indicating the total species abundance (TSA) of the major woody plant species identified within all transects (area of 600 m$^2$) from all three study sites.**

- **Bush encroachment at the Pilanesberg study site**

The total species abundance (TSA) of the woody component at the Pilanesberg study site was the highest, with 25 different species identified within the three transects (area of 600 m$^2$) (Figure 4.14).

Overall, *D*. *cinerea* had the highest TSA (77) within all transects of 600 m$^2$, while *G*. *flavescens* and *Chascanum spp.* the second and third highest TSAs (59 and 26, respectively) (Figure 4.14). The TSA for *E*. *crispa*, *M*. *feniospinum* and *V*. *karroo* was also high, with 12, 11 and 21, compared to other woody species (Figure 4.15). From Figure 4.15, the Pilanesberg study site were clearly dominated by *D*. *cinerea* (28% of all woody species) and *G*. *flavescens* (22% of all woody species), while *Chascanum spp*. And *V*. *karroo* were also very abundant. Although *D*. *cinerea* dominated the Pilanesberg study site, this site had the lowest BE extent, as it was the least dense of all the sites and there were a clear herbaceous layer (grass) that could compete with woody plant seedlings for soil moisture and nutrients.

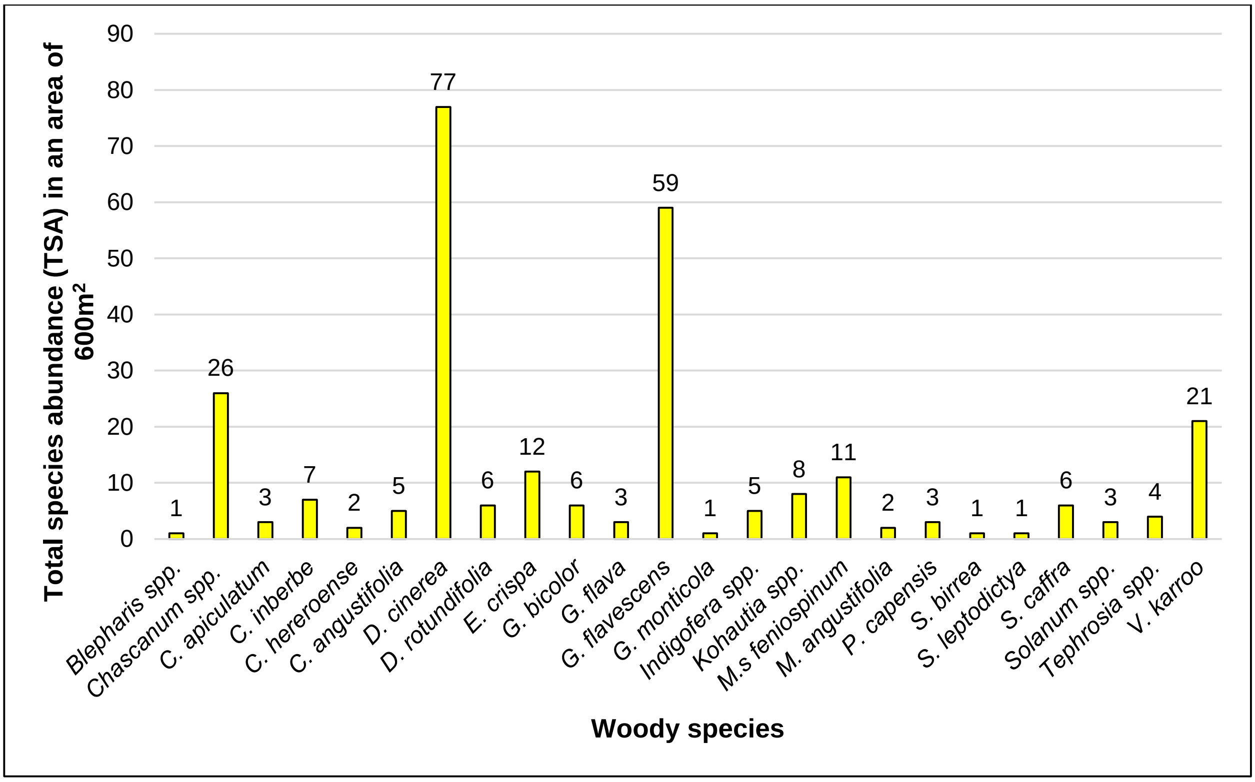



**Figure 4.14: The total species abundance (TSA) of all the woody species identified within all transects (area of 600 m$^2$) at the Pilanesberg study site.**

- **Bush encroachment at the Legkraal study site**

The Legkraal study site found that *D. cinerea* had the highest TSA, with 84 individuals (29% of all woody species) identified within the three transects (area of 600 m$^2$) (Figure 4.15).

Other dominant woody species included *V. tortillis*, *V. karroo* and *S. mellifera*, which had second, third and fourth highest TSAs (48, 43 and 40, respectively) (Figure 4.15). The TSA of *A. procumbens*, *Asparagus spp*., and *Z. mucronata* were also high (20, 21 and 14, respectively) compared to other woody species of the Legkraal study site (Figure 4.15). The Legkraal study site was deemed as the highest BE extent, as the most species of *D. cinerea* were found at this site, there was an herbaceous layer (grass) absent, and this site was also the densest.

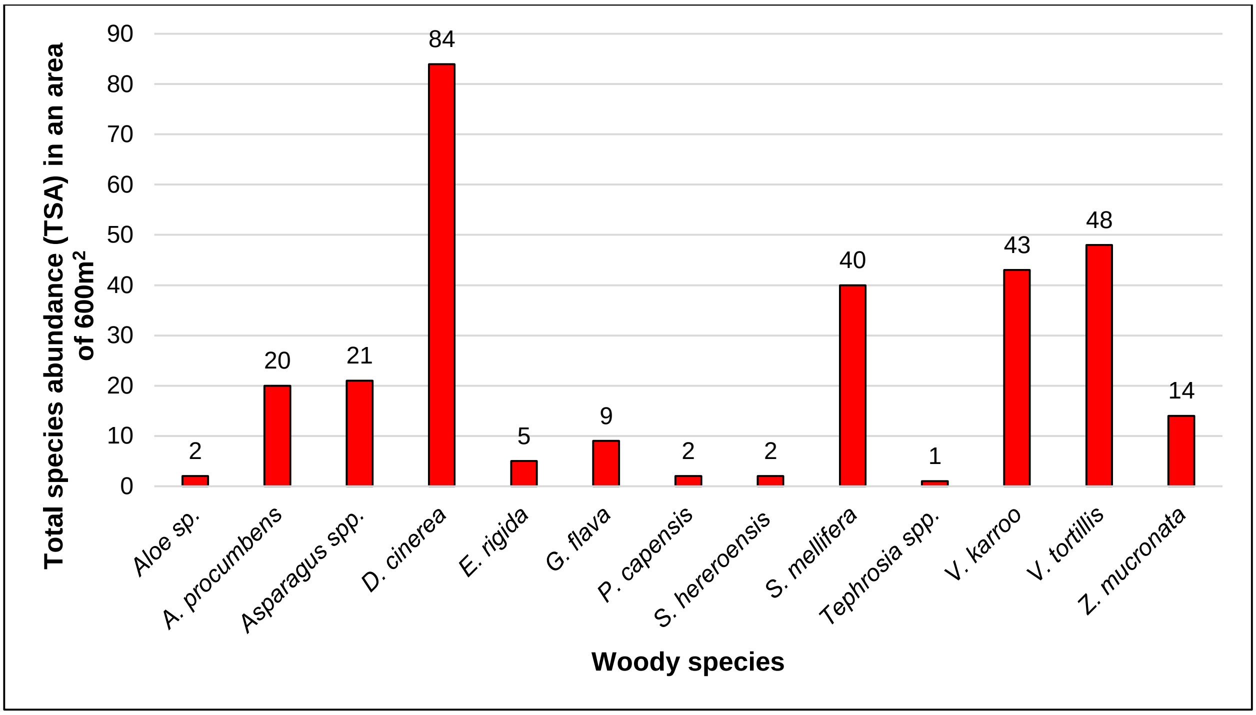



**Figure 4.15: The total species abundance (TSA) of all the woody species identified within all transects (area of 600 m²) at the Legkraal study site.**

- **Bush encroachment at the Kgomo-Kgomo study site**

The TSA of *D. lycioides* showed the highest TSA (123) of all woody species (31%) within the three transects (area of 600 m²) (Figure 4.16).

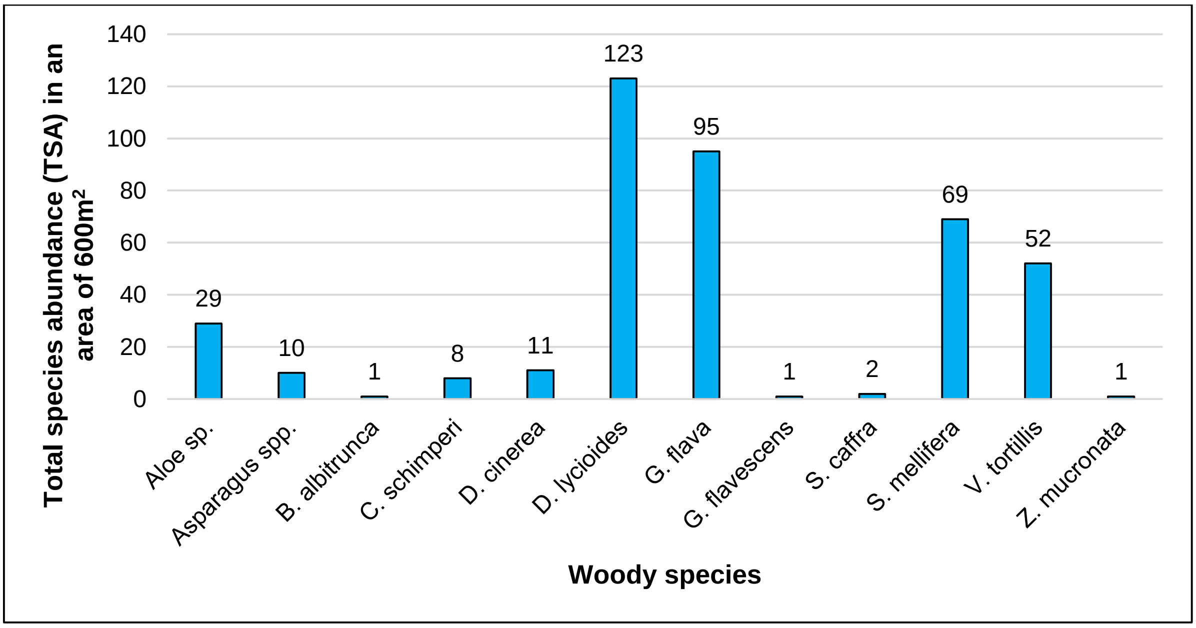



**Figure 4.16: The total species abundance (TSA) of all the woody species identified within all transects (area of 600 m²) at the Kgomo-Kgomo study site.**

Other dominant woody species included *G. flava*, *S. mellifera* and *V. tortillis*, which had the second, third and fourth highest TSAs (95, 69 and 52, respectively) at the Kgomo-Kgomo study site (Figure 4.16). This site also had a very high BE extent, as almost all the woody species found at this site was classed as encroacher species and there was an herbaceous layer (grass) absent that could compete with woody plant seedlings.

#### 4.3.1.2 Vegetation structure at the three study sites

The number of woody plants per height class may give another indication of the extent of BE (Van Rooyen, 2016, in Naudé, 2018). The height classes of all the woody species were abundant in the lower height classes (1-4) (< 120 cm), but less abundant in the higher height classes (5-7) (> 120 cm) (Table 4.1). Figure 4.17 indicates the total species abundance (TSA) of woody plants identified within all transects (area of 600 $m^2$) from all three study sites in the seven height classes.

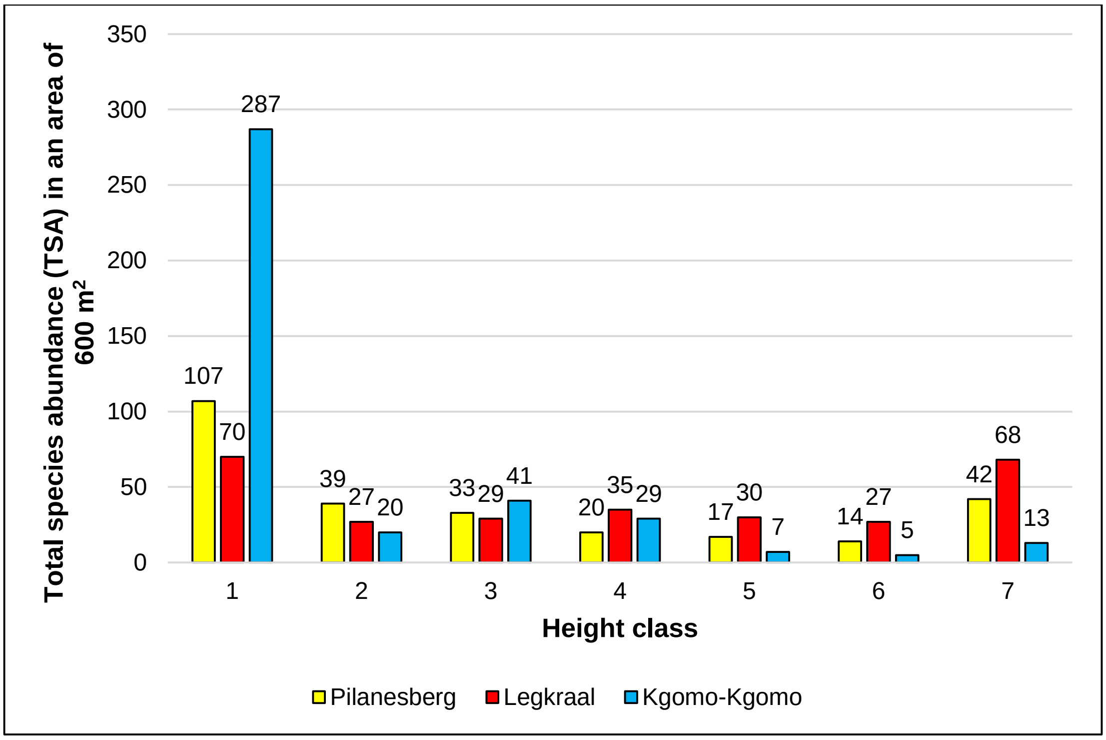



**Figure 4.17: A graph indicating the total species abundance (TSA) of woody plants per height class identified within all transects (area of 600 $m^2$) at all three study sites. Height class 1 = < 30 cm, height class 2 = 30-60 cm, height class 3 = 60-90 cm, height class 4 = 90-120 cm, height class 5 = 120-150cm, height class 6 = 150-180 cm and height class 7 = > 180 cm.**

From Figure 4.17, it is clear that the total species abundance (TSA) of height class one to three for the three study sites were very similar, except for height class one with a very high TSA for the Kgomo-Kgomo study site. However, the TSA for height classes four to seven, were higher at the Legkraal study site compared to the Pilanesberg- and Kgomo-Kgomo study sites. As the majority of woody species were abundant in the lower classes (1-4) compared to the higher classes (5-7), it might be an indication that BE may be in an early stage within all three study sites.

#### 4.3.1.3 Single or multi-stem of woody species

Most woody species found in all the transects at all the sites were multiple stemmed (Figure 4.18). Figure 4.18 indicates the total species abundance (TSA) of woody plants identified within all the transects (area of 600 m$^2$) from all three study sites divided into single- and multi-stemmed.

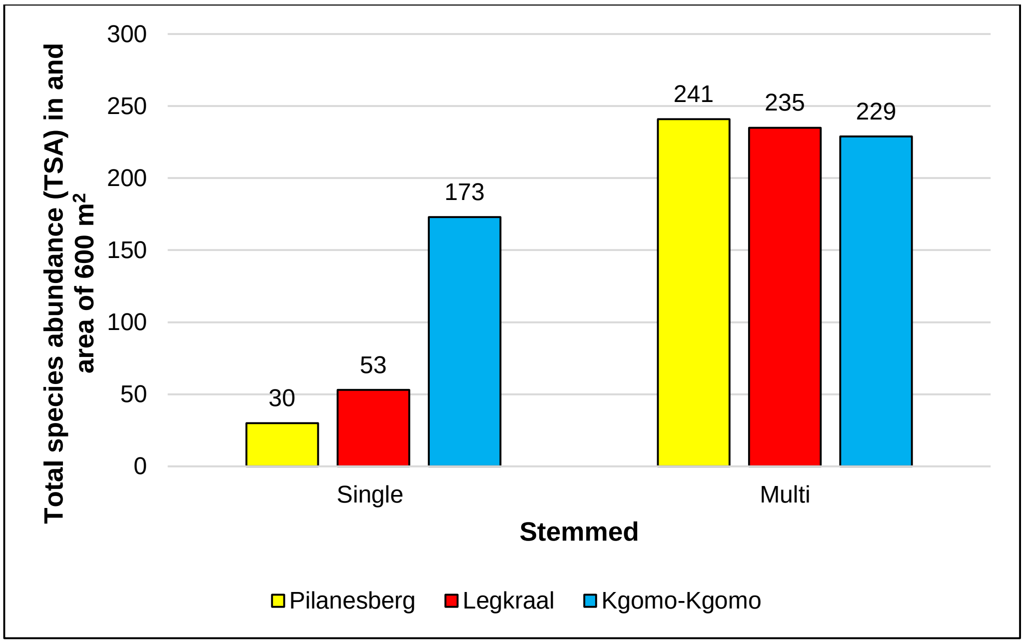



**Figure 4.18: A graph indicating the single- and multi-stemmed total species abundance (TSA) of woody plants identified within all transects (area of 600 m$^2$) from all three study sites.**

Overall, it is clear that the Pilanesberg study site had the lowest TSA of single-stemmed woody plants (30) and also the highest TSA of multi-stemmed woody plants (241) (Figure 4.18). The Kgomo-Kgomo study site on the other hand, had the highest TSA of single-stemmed woody plants (173) and also the lowest TSA of multi-stemmed woody plants (229) (Figure 4.18). The Legkraal study site had a TSA of 53 single-stemmed woody plants and a TSA of 235 multi-stemmed woody plants (Figure 4.18).

The higher abundance of multi-stemmed species compared to single-stemmed species of all three sites, is likely because of the herbivores (wildlife and goats) browsing on the woody plants at each site (Peterson & Jones, 1997, in Bellingham & Sparrow, 2009). As disturbances can promote a multi-stemmed structure by stimulating growth of existing or new sprouts after damage to existing stems (Peterson & Jones, 1997, in Bellingham & Sparrow, 2009), the browser animals (i.e. impala and goats) promote multi-stemmed growth of woody plants as occurred at each site for the three study sites. The higher TSA ratio of multi-stemmed plants in the Pilanesberg study site could also be attributed to the variety of different browser animals in the Pilanesberg National Park, promoting the multi-stemmed architecture for survival. However, the higher ratio of multi-stemmed species to single-stemmed species at the Pilanesberg study site could also likely be caused by frequent fires that occur in the Pilanesberg National Park (Fujii & Kikuzawa, 2006, in Bellingham & Sparrow, 2009). Therefore, disturbances (i.e. fire and/or browsers) can benefit tree fitness through enhanced carbon gain or sexual reproductive output and enables more persistence at a site compared to single-stemmed species (Fujii & Kikuzawa, 2006, in Bellingham & Sparrow, 2009).

### 4.3.2 Soil analysis

#### 4.3.2.1 Soil classification

The Glenrosa and Clovelly soil forms occurred at the Pilanesberg study site, while only the Clovelly soil form occurred at the Legkraal study site (Table 4.2). The Hutton and Tongwane soil forms occurred at the Kgomo-Kgomo study site (Table 4.2).

**Table 4.2: The soil classification of all transects of the three study sites.**

| | Pilanesberg | | Legkraal | | Kgomo-Kgomo | |
|---|---|---|---|---|---|---|
| **Transect** | **Soil form** | **Soil family** | **Soil form** | **Soil family** | **Soil form** | **Soil family** |
| **1** | Glenrosa | 2220 | Clovelly | 2221 | Hutton | 2210 |
| **2** | Glenrosa | 2220 | Clovelly | 2221 | Hutton | 2210 |
| **3** | Clovelly | 2221 | Clovelly | 2221 | Tongwane | 2210 |

The soils at the Pilanesberg study site were shallow (less than 700 mm deep), while the soils at both the Legkraal and Kgomo-Kgomo study sites were deep (more than 1 200 mm deep). The soils for the three transects differed slightly, with soil at the Pilanesberg study site classed as an orthic topsoil horizon (300 mm) on top of a lithic subsoil horizon for the first and second transect. An orthic topsoil horizon (300 mm) was identified on top of a yellow-brown subsoil horizon (700 mm deep) for the third transect at the Pilanesberg study site.

For first and second transects of the Legkraal study site, two orthic topsoil horizons (200 mm and 400 mm deep) were identified on top of a yellow-brown subsoil horizon (1 500 mm deep). For the third transect, only one orthic topsoil horizon (200 mm deep) were identified on top of a yellow-brown subsoil horizon (1 500 mm deep).

The soils of the three Kgomo-Kgomo study site transects had orthic topsoil horizons (300 mm deep) above red apedal subsoil horizons, which were 1 200 mm deep, except for Transect 3 where the red apedal horizon extended to only 600 mm, above a neocutanic subsoil horizon (1 500 mm deep).

#### 4.3.2.2 Soil texture and soil particle size distribution

The soil texture at the Pilanesberg study sites were predominantly sandy loam and the texture of the Legkraal study site were predominantly sandy loam and silt loam, while it was predominantly sandy loam at the Kgomo-Kgomo study site. As for the soil forms, the texture differed slightly for the three transects at the three study sites. A sandy loam topsoil was found at the first transect of the Pilanesberg study site, while a loamy sand topsoil and a silt loam subsoil was found at the third transect of the Pilanesberg study site.

A loamy sand and silt loam topsoils (A1 and A2) were found above a silt loam subsoil at the first transect, while a sandy loam topsoil and a clayey subsoil was found at the third transect of the Legkraal study site. The second transect had two sandy loam topsoils and a silt loam subsoil. All the horizons of the Kgomo-Kgomo study site had a sandy clay loam texture, except for the topsoil of the second transect that showed a loamy sand texture.

- **Soil particle size distribution of the Pilanesberg study site**

Table 4.3 indicates the soil particle size distribution (%) of all three transects of the Pilanesberg study site.

**Table 4.3: The soil particle size distribution of all three transects of the Pilanesberg study site.**

| | Soil particle size distribution (%) | | | | |
|---|---|---|---|---|---|
| **Soil sample** | **Gravel (> 2 mm)** | **Sand (2 – 0.05 mm)** | **Silt (0.05 – 0.002 mm)** | **Clay (< 0.002 mm)** | **Texture class** |
| **Transect 1 topsoil** | 22 | 57 | 36 | 7 | Sandy loam |
| **Transect 2 topsoil** | 28 | 70 | 23 | 7 | Sandy loam |
| **Transect 3 topsoil** | 21 | 78 | 15 | 7 | Loamy sand |
| **Transect 3 subsoil** | 62 | 70 | 23 | 7 | Sandy loam |

Sandy loam textures were found for Transect 1 topsoil, Transect 2 topsoil and Transect 3 subsoil, while a loamy sand texture was found for Transect 2 topsoil.

Overall, the sand fraction (2–0.05 mm) for all three transects had the highest distribution, while the clay fraction (< 0.002 mm) had the lowest distribution (7% for all transects) (Table 4.3). Transect 3 subsoil had the highest gravel (> 2 mm particles) distribution (62%), while Transect 3 topsoil had the highest sand distribution (78%) and lowest silt fraction (0.05–0.002 mm) distribution (15%) compared with the top- and subsoils of the other transects. Transect 1 topsoil had the highest silt distribution (36%) compared with the top- and subsoils of the other transects.

- **Soil particle size distribution of the Legkraal study site**

Table 4.4 indicates the soil particle size distribution (%) of all three transects of the Legkraal study site.

**Table 4.4: The soil particle size distribution of all three transects of the Legkraal study site.**

| | Soil particle size distribution (%) | | | | |
|---|---|---|---|---|---|
| **Soil sample** | **Gravel (> 2 mm)** | **Sand (2 – 0.05 mm)** | **Silt (0.05 – 0.002 mm)** | **Clay (< 0.002 mm)** | **Texture class** |
| **Transect 1 topsoil (A1)** | 5 | 78 | 15 | 7 | Sandy loam |
| **Transect 1 topsoil (A2)** | 28 | 42 | 51 | 7 | Silt loam |
| **Transect 1 subsoil** | 36 | 40 | 53 | 7 | Silt loam |
| **Transect 2 topsoil (A1)** | 6 | 62 | 33 | 5 | Sandy loam |
| **Transect 2 topsoil (A2)** | 14 | 52 | 43 | 5 | Sandy loam |
| **Transect 2 subsoil** | 28 | 42 | 53 | 5 | Silt loam |
| **Transect 3 topsoil** | 13 | 54 | 41 | 5 | Sandy loam |
| **Transect 3 subsoil** | 26 | 36 | 9 | 55 | Clay |

Sandy loam textures were found for Transect 1 topsoil (A1), Transect 2 topsoil (A2) and Transect 2 topsoil (A2) and Transect 3 topsoil. Silt loam textures were found for Transect 1 topsoil (A2), Transect 1 subsoil and Transect 2 subsoil, while a clay texture was found for Transect 3 subsoil.

Overall, the sand fraction (2–0.05 mm) and silt fraction (0.05–0.002 mm) showed the highest distribution, while the clay fraction (< 0.002 mm) had the lowest distribution (< 8% for all transects), except for Transect 3 subsoil, which showed a very high clay distribution (55%) (Table 4.4). Transect 1 subsoil had the highest gravel (> 2 mm particles) distribution (36%), while Transect 1 topsoil (A1) had the highest sand distribution (78%) and Transect 3 subsoil had the lowest silt fraction (0.05–0.002 mm) distribution (9%) compared with the top- and subsoils of the other transects. Transect 1 subsoil had the highest silt distribution (53%) compared with the top- and subsoils of the other transects (Table 4.4).

- **Soil particle size distribution of the Kgomo-Kgomo study site**

Table 4.5 indicates the soil particle size distribution (%) of all three transects of the Kgomo-Kgomo study site.

**Table 4.5: The soil particle size distribution of all three transects of the Kgomo-Kgomo study site.**

| | Soil particle size distribution (%) | | | | |
|---|---|---|---|---|---|
| **Soil sample** | **Gravel (> 2 mm)** | **Sand (2 – 0.05 mm)** | **Silt (0.05 – 0.002 mm)** | **Clay (< 0.002 mm)** | **Texture class** |
| **Transect 1 topsoil** | 4 | 80 | 1 | 20 | Sandy loam |
| **Transect 1 subsoil** | 10 | 70 | 3 | 27 | Sandy clay loam |
| **Transect 2 topsoil** | 2 | 86 | 1 | 13 | Loamy sand |
| **Transect 2 subsoil** | 10 | 76 | 5 | 17 | Sandy loam |
| **Transect 3 topsoil** | 3 | 80 | 3 | 17 | Sandy loam |
| **Transect 3 subsoil (B1)** | 20 | 69 | 7 | 25 | Sandy clay loam |
| **Transect 3 subsoil (B2)** | 12 | 71 | 15 | 15 | Sandy loam |

Sandy loam textures were found for Transect 1 topsoil, Transect 2 subsoil, Transect 3 topsoil and Transect 3 subsoil (B2). Sandy clay loam textures were found for Transect 1 subsoil and Transect 3 subsoil (B1), while a loamy sand texture was found for Transect 2 topsoil.

Overall, the sand fraction (2–0.05 mm) showed the highest distribution, while the silt fraction (0.05–0.002 mm) had the lowest distribution (< 15% for all transects) (Table 4.5). Transect 3 subsoil had the highest gravel (> 2 mm particles) distribution (20%), while Transect 2 topsoil had the highest sand distribution (86%) and lowest silt distribution (1%) and lowest clay fraction (< 0.002 mm) distribution (13%) compared with the top- and subsoils of the other transects. Transect 3 subsoil (B2) had the highest silt distribution (15%), while Transect 1 subsoil had the highest clay distribution (27%) compared with the top- and subsoils of the other transects.

- **Relationship between soil particle size distribution and woody species of all three study sites**

There was no clear relationship between the distribution of clay (%) and the TSA of all the woody species of the three study sites, with $R^2$ values lower than 0.2 found for top- and subsoil (Figure 4.19 and Figure 4.20). A TSA between 60 and 110 were found within all the study site transects with 5 to 20% clay distribution of the topsoil and with 5 and 30% clay of the subsoil. The dominant encroacher species of the Kgomo-Kgomo study site, *D. lycioides*, were also found at all three transects where the clay content was higher than the other study sites, however, only one individual were found at the first transect and 122 individuals at the third transect. Therefore, there was no clear relationship between soil particle distribution and *D. lycioides*.

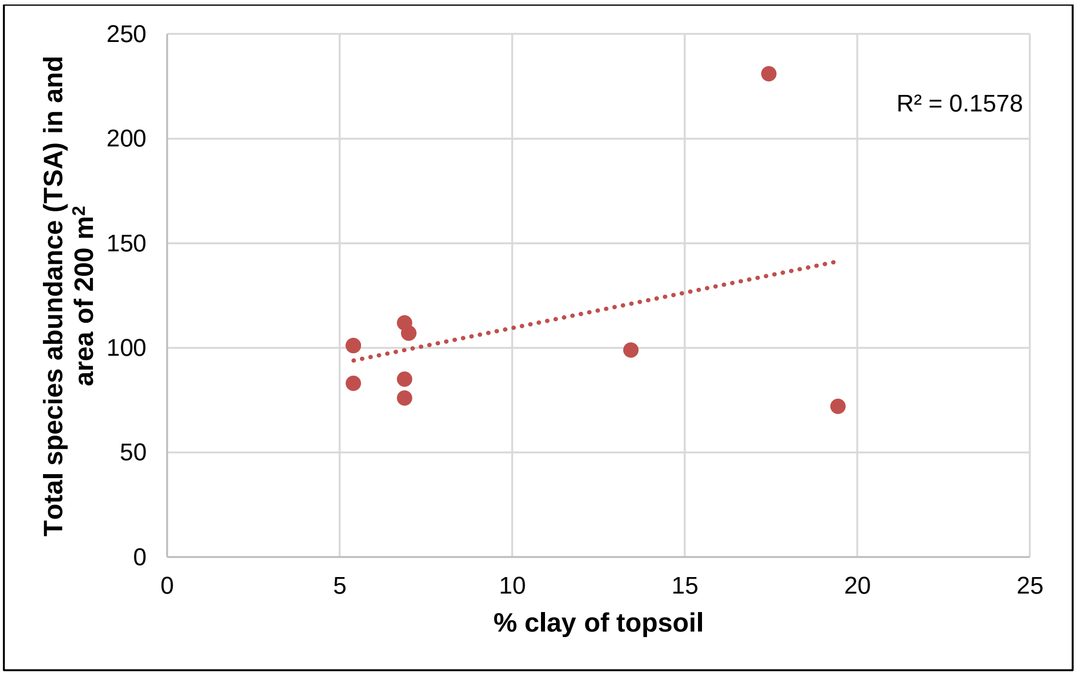



**Figure 4.19: The relationship between the total species abundance (TSA) of all woody species identified and the percentage (%) clay distribution of the topsoil at the three transects (200 m$^2$) of each study site.**

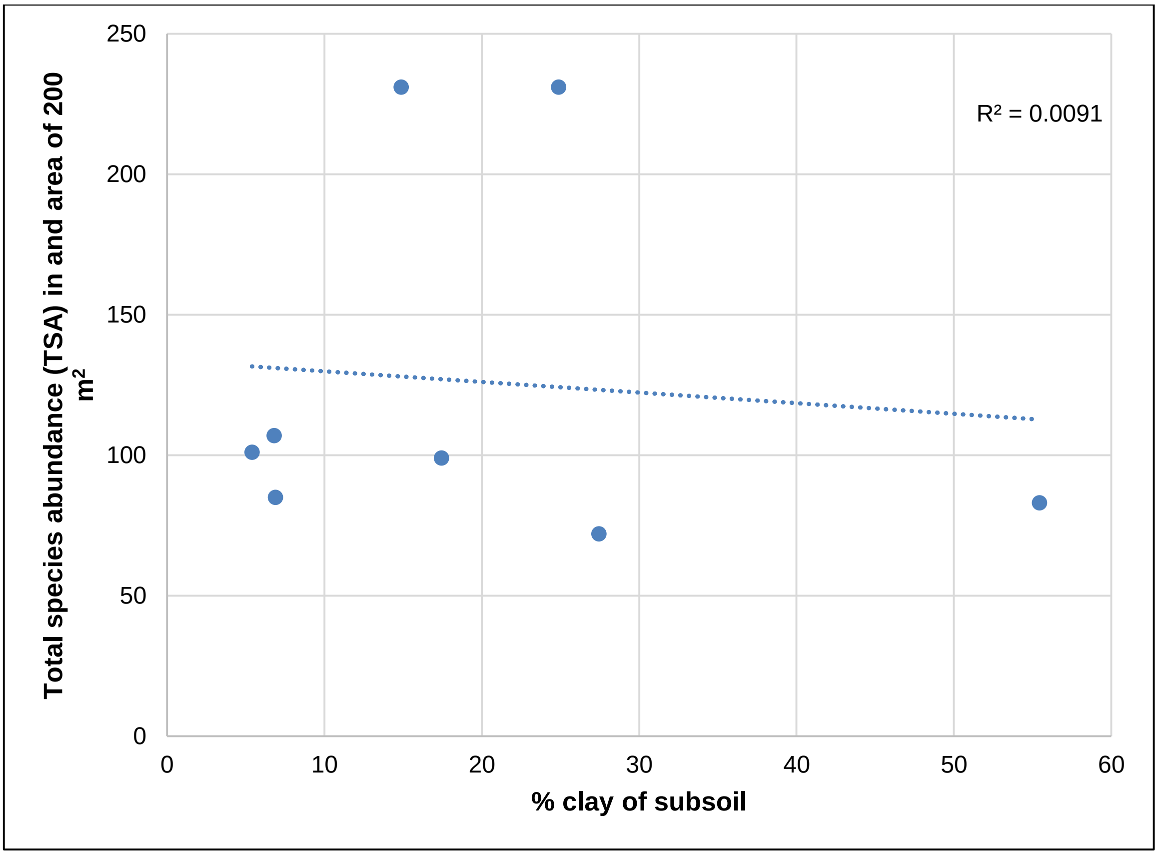



**Figure 4.20: The relationship between the total species abundance (TSA) of all woody species identified and the percentage (%) clay distribution of the subsoil at the three transects (200 m²) of each study site.**

Two encroacher species that occurred at all three study sites, namely *D. cinerea* and *G. flava*, had a definite relationship with the soil particle size distribution.

The TSA of *D. cinerea* were very high at the Pilanesberg and Legkraal study sites, but very low at all transects of the Kgomo-Kgomo study site. The encroacher species, *D. cinerea* had a good relationship with the % clay of the topsoil ($R^2$ = 0.5674) and a great relationship with the % clay of the subsoil ($R^2$ = 0.9479) (Figure 4.21 and Figure 4.22). The third transect of the Legkraal study site was considered to be an outlier. The low TSA of *D. cinerea* were found where the topsoil had between 10 and 20% clay and the subsoil between 10 and 30% clay (Figure 4.21 and Figure 4.22). The highest TSA of *D. cinerea* were found where the topsoil had between 5 and 8% clay and the subsoil between 2 and 10% clay (Figure 4.21 and Figure 4.22). The subsoil of the third transect of the Legkraal study site had the highest clay (55%), but not the highest TSA of *D. cinerea* regarding all transects (Figure 4.22).

The TSA of *G. flava* were very low at the transects of the Pilanesberg- and Legkraal study sites, but were very high at the transects of the Kgomo-Kgomo study site. The encroacher species, *G.*

*flava* had a great relationship with the % clay of the topsoil ($R^2$ = 0.8911) and a good relationship with the % clay of the subsoil ($R^2$ = 0.6592) (Figure 4.23 and Figure 4.24). The third transect of the Kgomo-Kgomo study site was considered as an outlier. The low TSA of *G. flava* were found where the topsoil had between 5 and 7% clay and the subsoil between 5 and 10% clay (Figure 4.23 and Figure 4.24). The highest TSA of *G. flava* were found where the topsoil had between 13 and 20% clay and the subsoil between 12 and 30% clay (Figure 4.21 and Figure 4.22). The subsoil of the third transect of the Legkraal study site had the highest clay (55%), but the lowest TSA of *G. flava* regarding all transects (Figure 4.24).

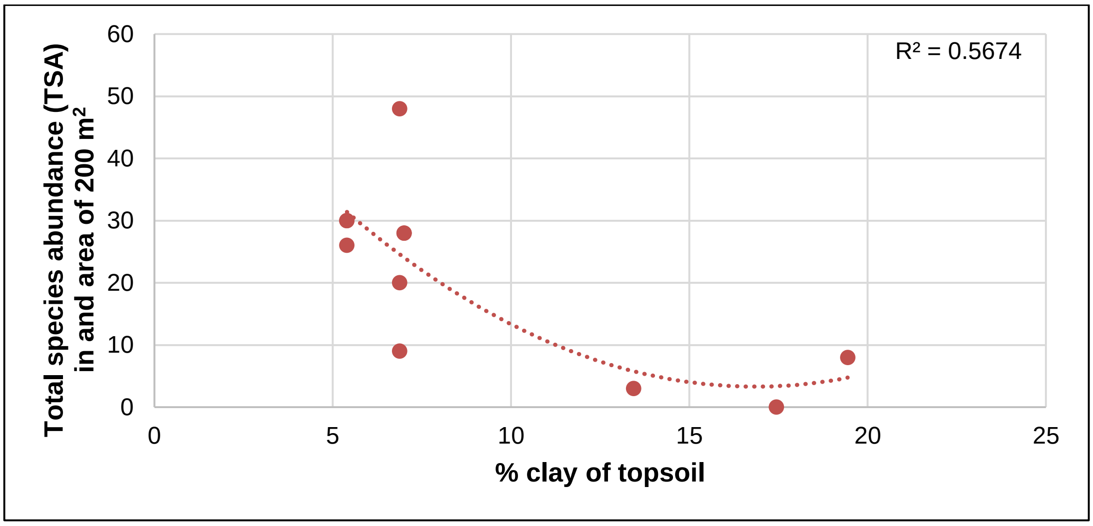



**Figure 4.21: The relationship between the total species abundance (TSA) of *D. cinerea* identified and the percentage (%) clay distribution of the topsoil at the three transects (200 m²) of each study site.**

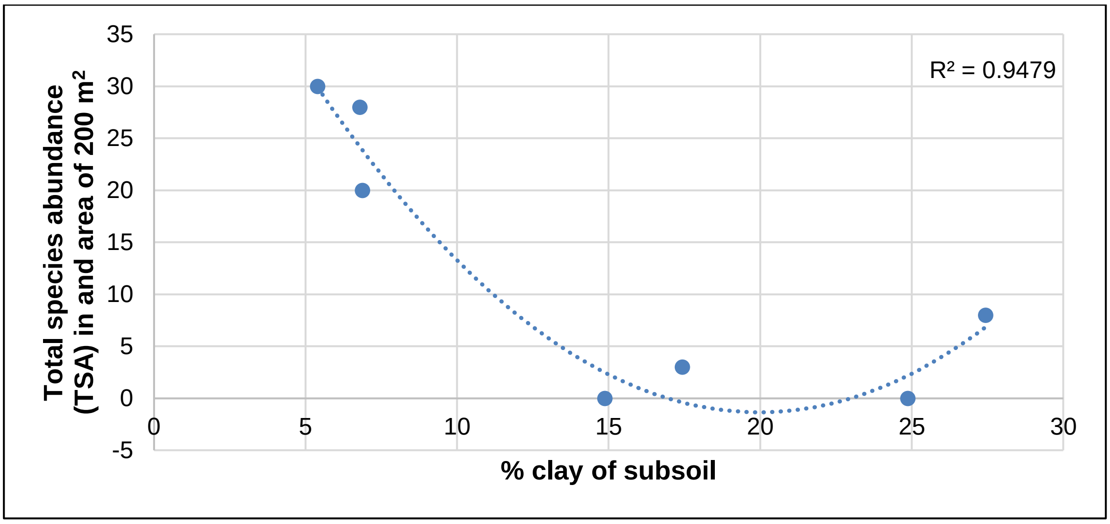



**Figure 4.22: The relationship between the total species abundance (TSA) of *D. cinerea* identified and the percentage (%) clay distribution of the subsoil at the three transects (200 m²) of each study site.**

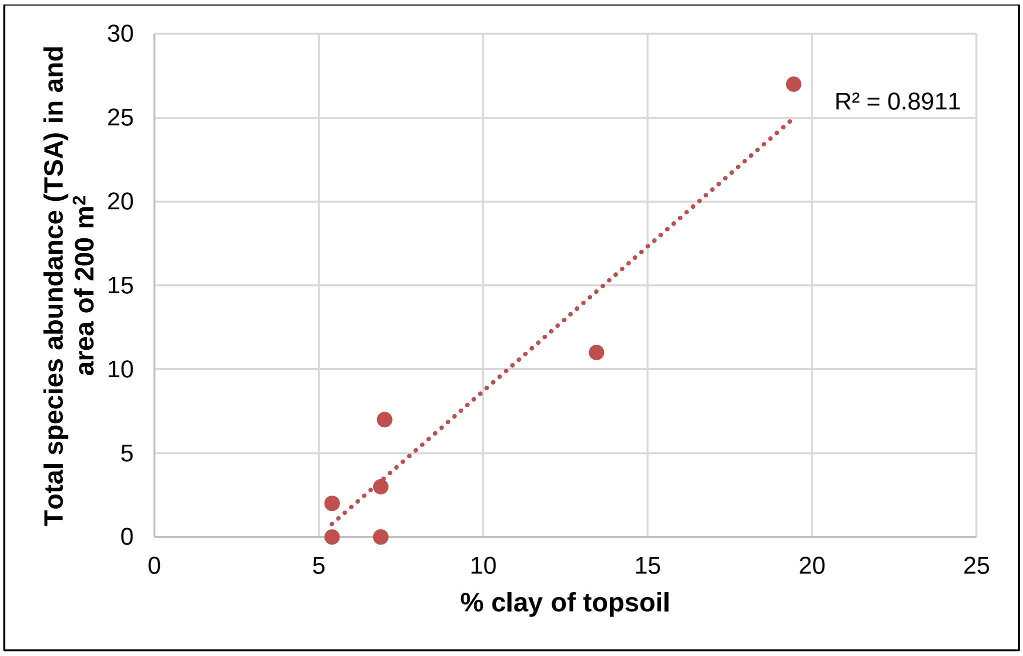



**Figure 4.23: The relationship between the total species abundance (TSA) of *G. flava* identified and the percentage (%) clay distribution of the topsoil at the three transects (200 m$^2$) of each study site.**

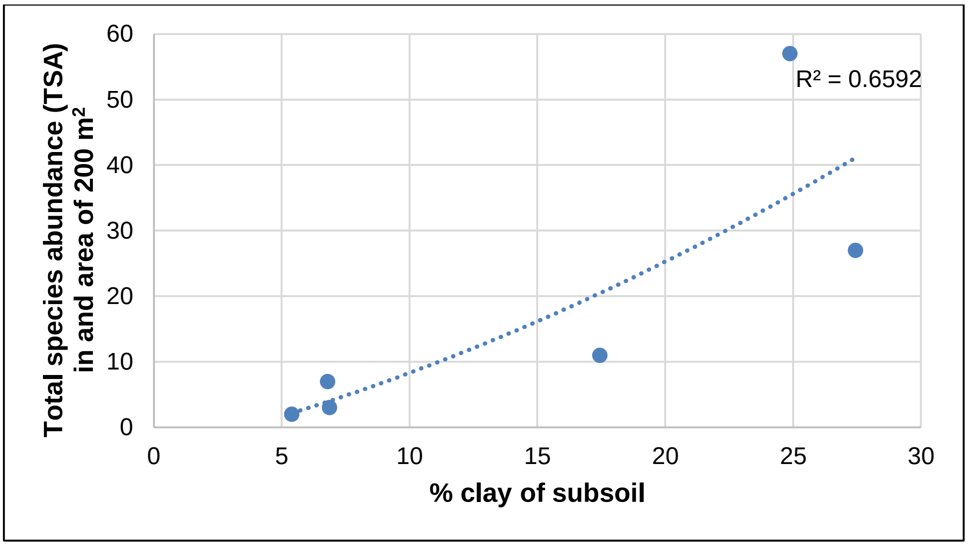



**Figure 4.24: The relationship between the total species abundance (TSA) of *G. flava* identified and the percentage (%) clay distribution of the subsoil at the three transects (200 m$^2$) of each study site.**

- **Relationship between soil depth and woody species of all three study sites**

There was no clear relationship between the soil depth and the TSA of all the woody species at the three study sites, with a $R^2$ value lower than 0.1 (Figure 4.25). A TSA between 60 and 110 were found, where the depth was between 200 and 1 500 mm. The third transect of Kgomo-

Kgomo had a very high TSA, as 122 of *D. lycioides* were found within the transect (Figure 4.16), but there was no relationship with the number of individuals found of this species and soil depth.

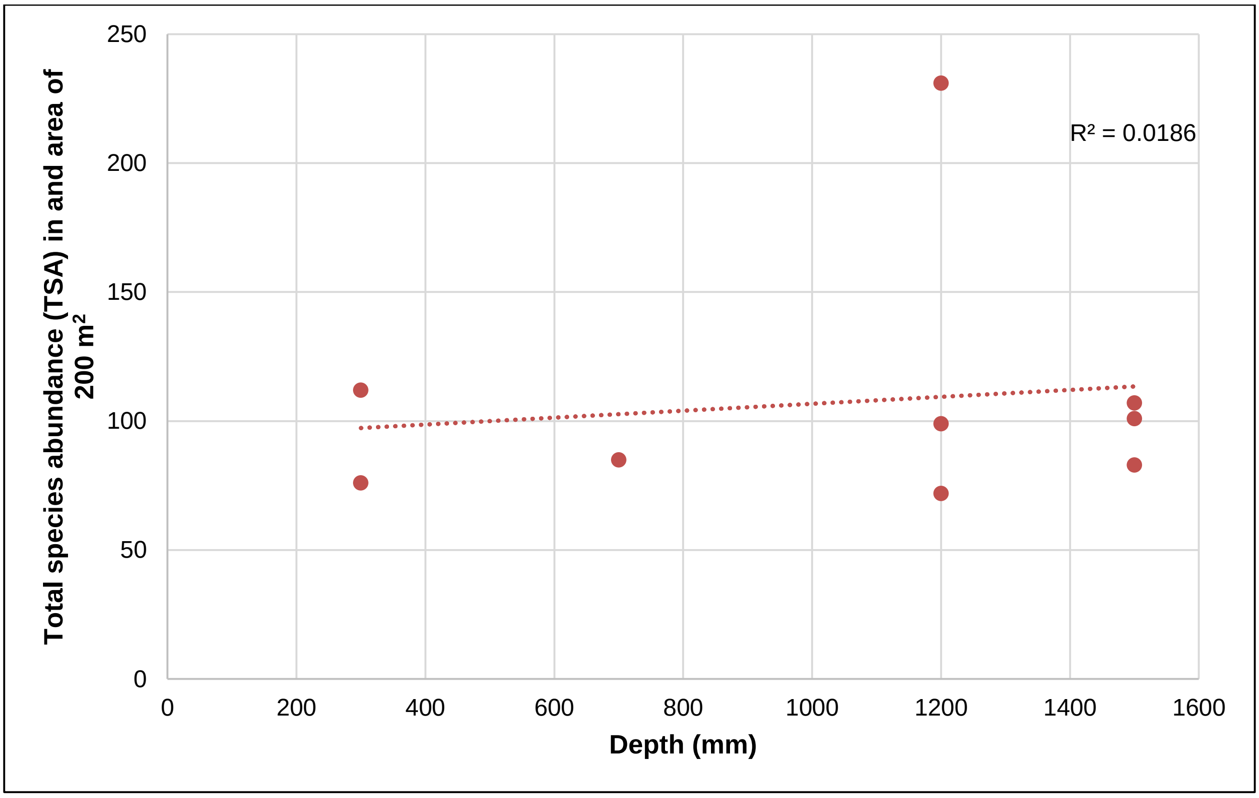



**Figure 4.25: The relationship between the total species abundance (TSA) of the woody species identified and the soil depth (mm) at the three transects (200 m$^2$) of each study site.**

The encroacher species, namely *V. tortillis*, *C. apiculatum*, *C. inberbe* and *C. hereroense* had a definite relationship with soil depth.

The TSA of *V. tortillis* were reasonably high at the Legkraal and Kgomo-Kgomo study sites, but very low at all transects of the Pilanesberg study site, this indicated a relationship good relationship ($R^2$ = 0.7657) between soil profile depth and *V. tortillis* (Figure 4.26). The low TSA of *V. tortillis* were found where the soil profile depth was shallower than 1 200 mm (Figure 4.26). The highest TSA of *V. tortillis* were found where soil depth was between 1 200 and 1 500 mm (Figure 4.26).

All the species of the genus *Combretum*, including *C. apiculatum*, *C. inberbe* and *C. hereroense*, were found at the Pilanesberg study site, while not one individual of this genus was found at the Legkraal or Kgomo-Kgomo study sites.

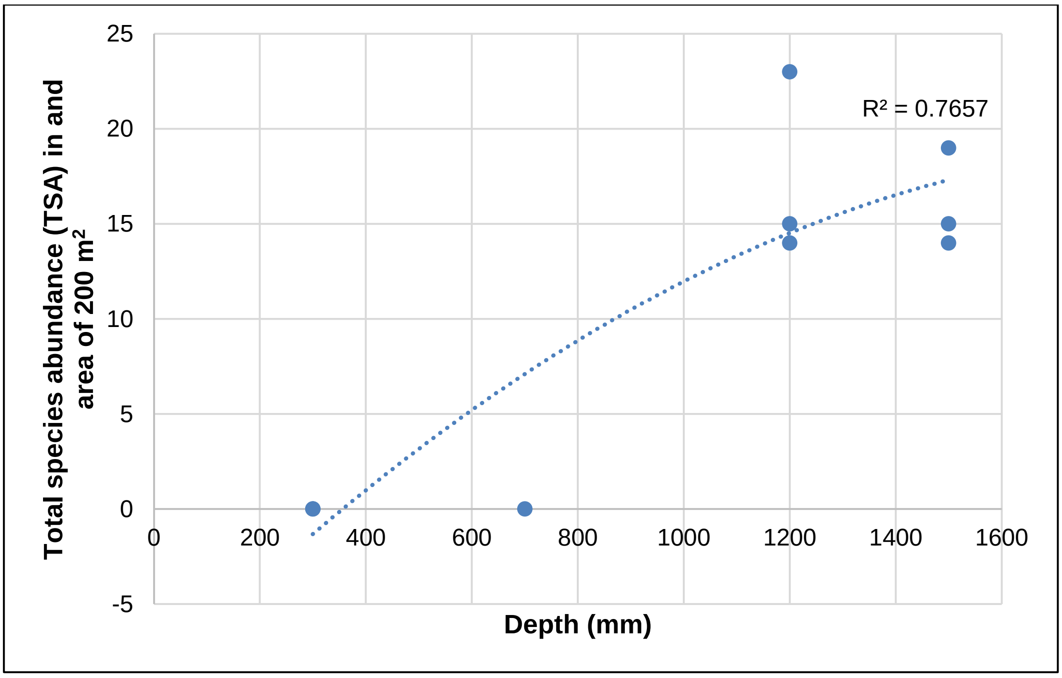



**Figure 4.26: The relationship between the total species abundance (TSA) of *V. tortillis* and the soil profile depth (mm) at the three transects (200 m$^2$) of each study site.**

- **Influence of soil texture, soil particle size distribution and soil depth on bush encroachment at all three study sites**

There were clear differences in soil texture, particle size distribution and soil depth regarding all three study sites. The Pilanesberg study site had predominantly a sandy loam texture, a low clay fraction and very shallow soils, while the Legkraal study site had predominantly a sandy loam and silt loam texture, a very high silt fraction and very deep soil profile (1 500 mm). The high silt fraction was likely caused by the weathering of the rocks of the Molteno Formation, on which the Legkraal study site was situated (Bordy *et al*., 2005). The Kgomo-Kgomo study site had had sandy loam, sandy clay loam and loamy sand texture, the highest clay fraction of all study sites and also deep soil profile (1 200 mm). This difference in soil texture, particle size distribution and depth had a definite influence on BE at each study site.

There was no clear relationship found between the particle size distribution of clay (%) and the TSA of the woody species found at the three study sites, however, *D. cinerea* and *G. flava*, had a definite relationship with the soil particle size distribution. The TSA of *D. cinerea* were low, where the clay fraction was higher in the top- and subsoil at the Kgomo-Kgomo study site. The TSA of *G. flava* were high, where the clay fraction was higher in the top- and subsoil at the Kgomo-Kgomo study site. This indicates that some woody species are more adapted to certain soil conditions, specifically the distribution of soil particles (Mucina & Rutherford, 2006). Although *D. cinerea* can be found on all soil types, it does prefer deep, sandy soils and occasionally clayey soils (Pedroso & Martin, 2012). As previous studies have shown that *D. cinerea* can be found on clayey soils, the low TSA could have been the result of competition between *D. cinerea* and *D*. *lycioides* for nutrients and water in the soil, that resulted in *D*. *lycioides* being the dominant species at the Kgomo-Kgomo study site. Previous studies have also found that *D*. *lycioides* mainly occurred on deep, clayey soils (Bezuidenhout, 2009), but there was no conclusive evidence found that *D*. *lycioides* preferred these types of soils. Although *G. flava* can also be found on different soil types, especially shallow, sandy soil (Mainah, 2001; Ravhuhali *et al*., 2020), a higher TSA were found for this species at the Kgomo-Kgomo study site. As *G. flava* is known to be most abundant on nutrient-rich soils (Ravhuhali *et al*., 2020), it is plausible that the Kgomo-Kgomo study had higher nutrients in the soil, even though no chemical analysis of the soils were done.

There was no clear relationship between the soil depth and the TSA of all the woody species at the three study sites, however, *V. tortillis*, *C. apiculatum*, *C. inberbe* and *C. hereroense* had a definite relationship with soil depth. Van Rooyen (1971) (in Mucina & Rutherford, 2006) reported strong relation between soil and vegetation, with *S*. *mellifera* and *V*. *tortillis* associated with red, sandy, deep soils (Hutton soil form). The results indicated that *V. tortillis* had a good relationship with soil profile depth, further substantiating that *V. tortillis* prefers deep soils. Verster (1974) (in Mucina & Rutherford, 2006) reported that shallow soils (Glenrosa soil form) are associated with *C*. *zeyheri*, *C*. *apiculatum* and *S*. *caffra*. This relationship can be seen in this study, as the soil at the Pilanesberg study site were predominantly the Glenrosa soil form (Table 4.2) and *C. apiculatum*, *C. inberbe* and *C. hereroense* were found at this study site.

Therefore, soil particle distribution and soil depth had a clear influence on the density and extent of certain encroacher species that influence BE at the three study sites.

#### 4.3.2.3 pH and electrical conductivity (EC)

The soil pH for all three study sites was relatively the same, with pH levels between 5.4 and 7, except for the subsoil of the Kgomo-Kgomo third transect (Transect 3 subsoil (B2)) that had a pH of 7.64 (Table 4.8). The soil EC for all three study sites was relatively the same, with EC levels between 6 and 27 mS/m, except for the topsoil of the Pilanesberg first transect (Transect 1 topsoil) that had an EC of 41 mS/m (Table 4.6).

- **pH and EC of the Pilanesberg study site**

Table 4.6 indicates the soil pH and EC of all three transects of the Pilanesberg study site.

**Table 4.6: The soil pH and EC (mS/m) of the samples from the Pilanesberg study site.**

| Soil sample | pH | EC (mS/m) |
| --- | --- | --- |
| **Transect 1 topsoil** | 5.9 | 41 |
| **Transect 2 topsoil** | 6 | 10 |
| **Transect 3 topsoil** | 5.8 | 8 |
| **Transect 3 subsoil** | 6 | 8 |

The soil pH of the Pilanesberg study site was between 5.7 and 6.1, while the soil EC of the Pilanesberg study site was between 7 and 41 mS/m (Table 4.6). Transect 2 topsoil had the highest pH (6), while Transect 3 topsoil had the lowest pH (5.8). Transect 1 topsoil had the highest EC (41 mS/m), while Transect 3 subsoil had the lowest EC (8 mS/m).

- **pH and EC of the Legkraal study site**

Table 4.7 indicates the soil pH and EC of all three transects of the Legkraal study site.

**Table 4.7: The soil pH and EC (mS/m) of the samples from the Legkraal study site.**

| Soil sample | pH | EC (mS/m) |
| --- | --- | --- |
| **Transect 1 topsoil (A1)** | 5.5 | 10 |
| **Transect 1 topsoil (A2)** | 6.3 | 14 |
| **Transect 1 subsoil** | 6.9 | 14 |
| **Transect 2 topsoil (A1)** | 5.5 | 11 |
| **Transect 2 topsoil (A2)** | 5.8 | 22 |
| **Transect 2 subsoil** | 6.8 | 13 |
| **Transect 3 topsoil** | 5.5 | 15 |
| **Transect 3 subsoil** | 6.7 | 15 |

The soil pH of the Legkraal study site was between 5.4 and 6.9, while the soil EC of the Legkraal study site was between 9 and 23 mS/m (Table 4.7). Transect 1 subsoil had the highest pH (6.9), while Transect 2 topsoil (A1) and Transect 3 topsoil had the lowest pH (5.5). Transect 2 topsoil (A2) had the highest EC (22 mS/m), while Transect 1 topsoil (A1) had the lowest EC (10 mS/m).

- **pH and EC of the Kgomo-Kgomo study site**

Table 4.8 indicates the soil pH and EC of all three transects of the Kgomo-Kgomo study site.

**Table 4.8: The soil pH and EC (mS/m) of the samples from the Kgomo-Kgomo study site.**

| Soil sample | pH | EC (mS/m) |
|---|---|---|
| **Transect 1 topsoil** | 5.9 | 9 |
| **Transect 1 subsoil** | 6.4 | 8 |
| **Transect 2 topsoil** | 6.0 | 6 |
| **Transect 2 subsoil** | 6.7 | 6 |
| **Transect 3 topsoil** | 5.6 | 6 |
| **Transect 3 subsoil (B1)** | 6.6 | 10 |
| **Transect 3 subsoil (B2)** | 7.6 | 26 |

The soil pH of the Kgomo-Kgomo study site was between 5.5 and 7.7, while the soil EC of the Legkraal study site was between 6 and 27 mS/m (Table 4.8). Transect 3 subsoil (B2) had the highest pH (7.6), while Transect 3 topsoil had the lowest pH (5.6). Transect 3 subsoil (B2) had the highest EC (26.1 mS/m), while Transect 2 topsoil, Transect 2 subsoil and Transect 3 topsoil had the lowest EC (all 6 mS/m).

- **Relationship between soil pH and EC and woody species of all three study sites**

There was no clear relationship between the pH of the topsoil and the TSA of all the woody species of the three study sites, with a $R^2$ value lower than 0.1 (Figure 4.27). There was however, a slightly better relationship between the pH of the subsoil and the TSA of the three study sites, with a $R^2$ value of 0.338 (Figure 4.28). A TSA between 80 and 110 were found, where the topsoil pH was between 5.4 and 6.4, while the TSA between 60 and 110 were found where the subsoil pH was between 5.8 and 7.

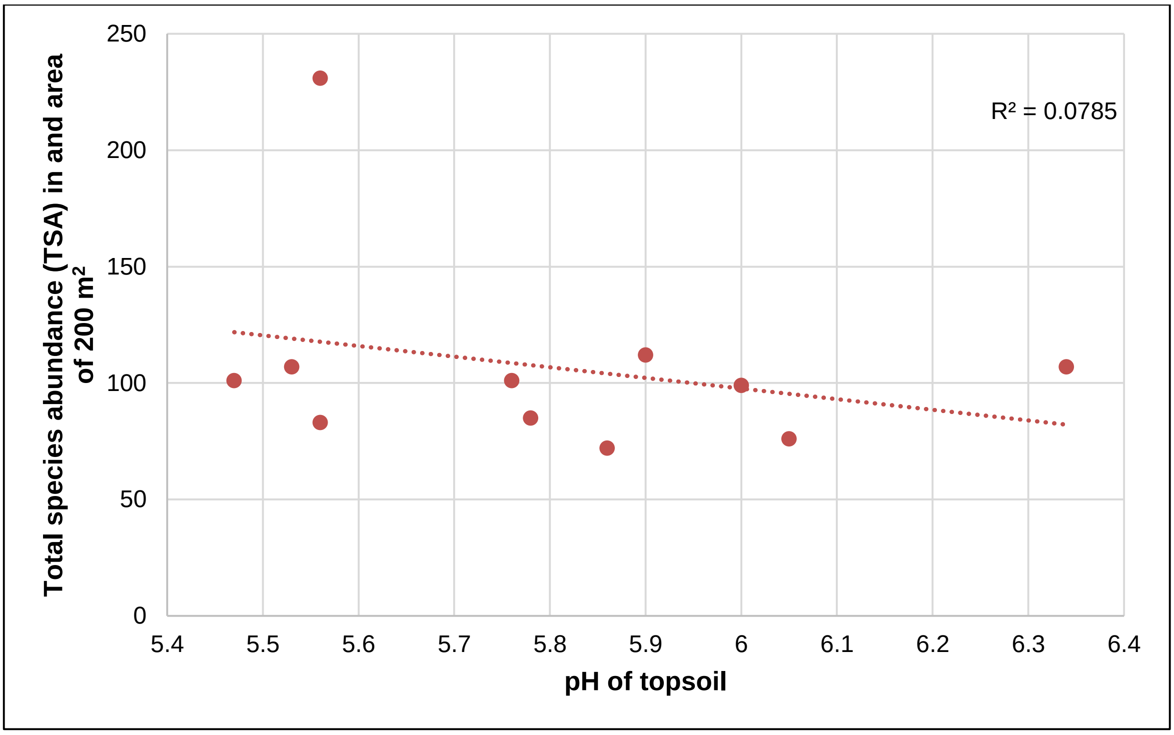



**Figure 4.27: The relationship between the total species abundance (TSA) of all the woody species and the pH of the topsoil at the three transects (200 $m^2$) of each study site.**

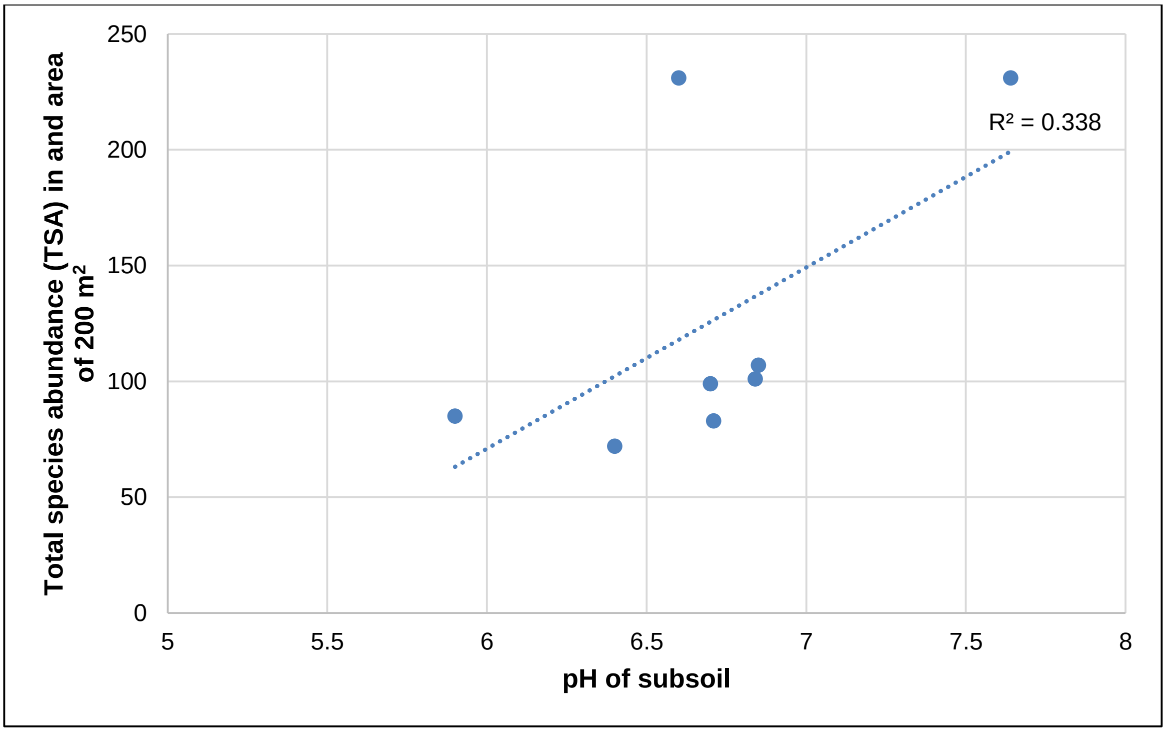



**Figure 4.28: The relationship between the total species abundance (TSA) of all the woody species and the pH of the subsoil at the three transects (200 $m^2$) of each study site.**

The encroacher species, namely *D. lycioides*, had a great relationship with soil pH ($R^2$ = 0.9762) as 122 individuals of this species were found at the third transect of the Kgomo-Kgomo study site, which also had the highest subsoil (B2) pH (7.6) (Figure 4.29). It might have been incidental as at all other study sites there were less than 50 individuals of a species found. However, the fact that there was such a large increase in number of *D. lycioides* individuals found on the only site with an alkaline pH could be a significant finding and should be investigated further.

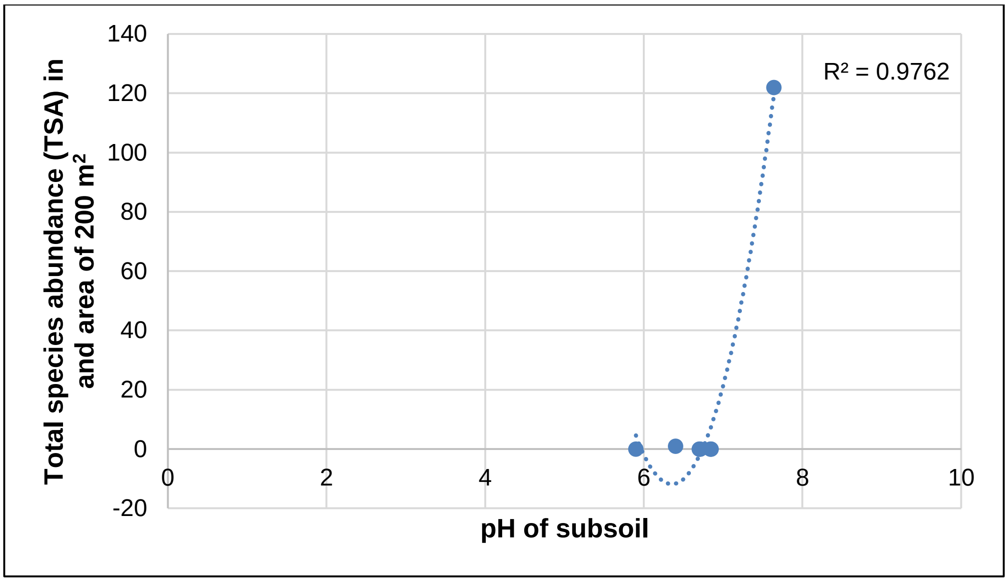



**Figure 4.29: The relationship between the total species abundance (TSA) of *D. lycioides* and the pH of the subsoil at the three transects (200 $m^2$) of each study site.**

There was no clear relationship between the EC of the topsoil and the TSA of all the woody species of the three study sites, with a $R^2$ value lower than 0.1 (Figure 4.30). There was however, a slightly better relationship between the EC of the subsoil and the TSA of the three study sites, with a $R^2$ value of 0.3216 (Figure 4.31).

The TSA of all the woody species were found, where the topsoil EC was between 5 and 25 mS/m, while the TSA between 60 and 110 were found where the subsoil EC was between 5 and 15 mS/m. The TSA of 112 (second highest) were found on the topsoil with the highest EC (41 mS/m).

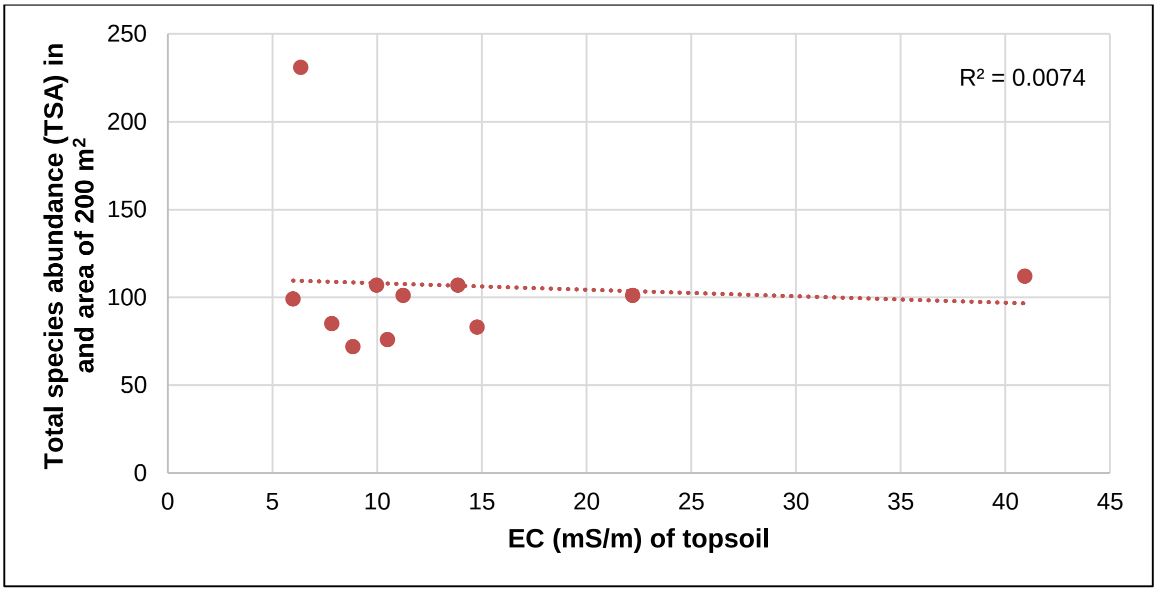



**Figure 4.30: The relationship between the total species abundance (TSA) of all the woody species and the EC (mS/m) of the topsoil at the three transects (200 m²) of each study site.**

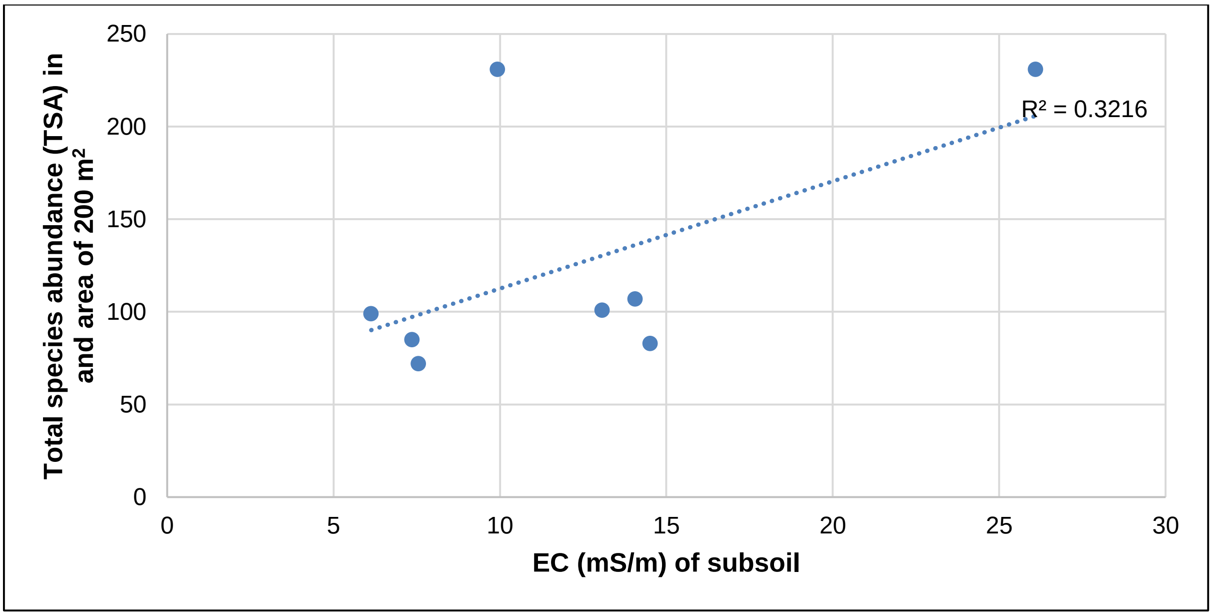



**Figure 4.31: The relationship between the total species abundance (TSA) of all the woody species and the EC (mS/m) of the subsoil at the three transects (200 m²) of each study site.**

Two encroacher species, namely *D. cinerea* and *D. lycioides*, had a definite relationship with soil EC. The encroacher species *D. cinerea* had a good relationship ($R^2$ = 0.7235) with topsoil EC (Figure 4.32), while *D. cinerea* had an excellent relationship ($R^2$ = 0.9972) with subsoil EC (Figure 4.33). Forty-eight individuals (highest of species) of *D. cinerea* were found at the first transect of the Pilanesberg study site, which had the highest topsoil EC of all transects (41 mS/m) and 122 individuals of *D. lycioides* were found at the third transect of the Kgomo-Kgomo study site, which had the highest subsoil (B2) EC (26 mS/m). As the most number of individuals were found at the transect which had the highest EC, it could be seen as a significant finding and should be investigated further.

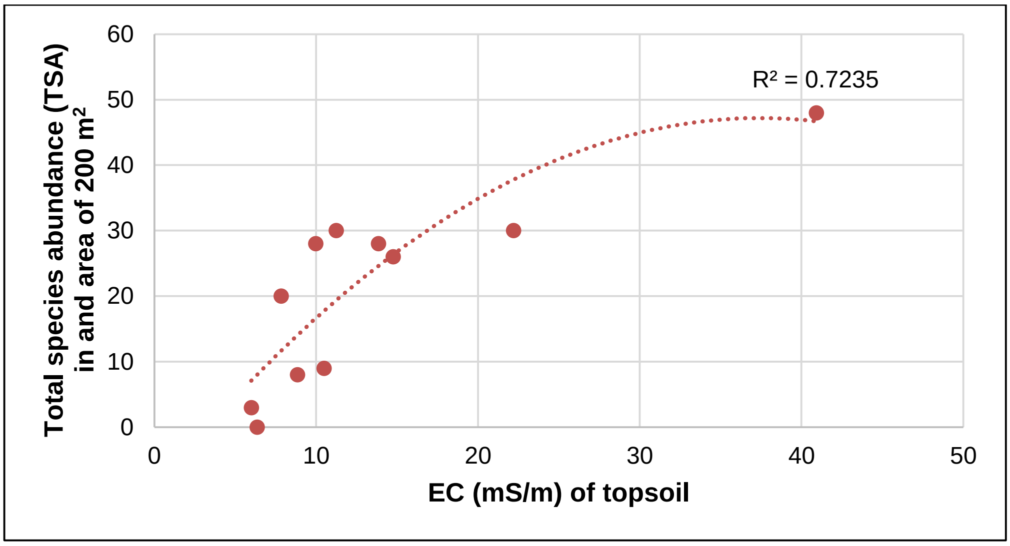



**Figure 4.32: The relationship between the total species abundance (TSA) of *D. cinerea* and the EC (mS/m) of the topsoil at the three transects (200 m²) of each study site.**

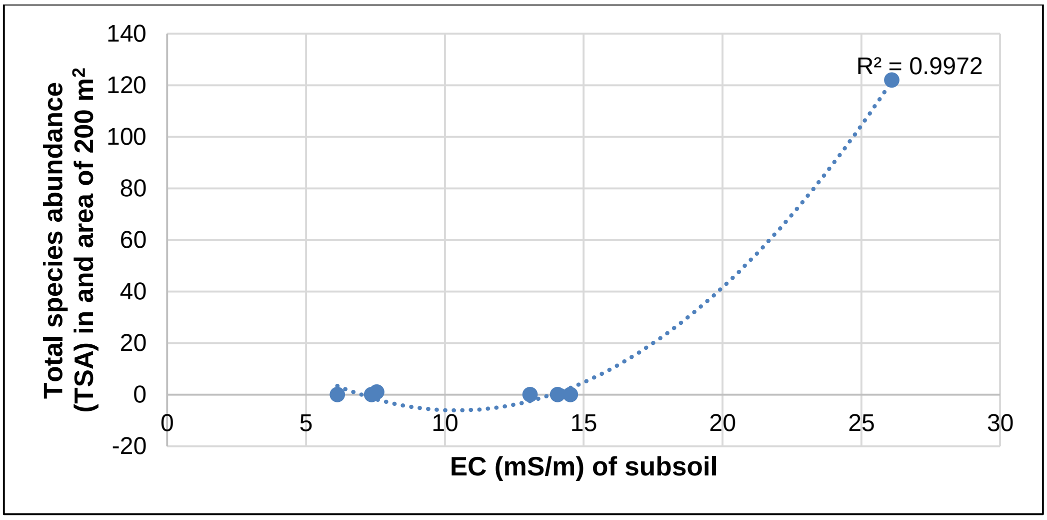



**Figure 4.33: The relationship between the total species abundance (TSA) of *D. lycioides* and the EC (mS/m) of the subsoil at the three transects (200 m²) of each study site.**

- **Influence of soil pH and EC on bush encroachment**

Soil pH is an important characteristic as it influences soil bacteria, soil structure, nutrient availability (Perry, 2003, in Naudé, 2018) that, in turn, influences the survival and growth of woody encroacher species causing BE. An example is *Rhizobium* bacteria (bacteria that release N from soil organic matter), that operates best at pH levels between 5.5 and 7, while this range will also keep nutrients from leaching out (Perry, 2003, in Naudé, 2018). Woody encroacher species, specifically, usually possess a broader tolerance to environmental conditions, including pH (Hao *et al*., 2017, in Gentili *et al*., 2018). Woody encroacher species have an optimum for pH mostly ranging from 5.5 to 6.5 (Köpp *et al*., 2011, in Gentili *et al*., 2018). Electrical conductivity (EC) refers to the ability of a material to transmit or conduct an electrical current between the elements and is used as a measure of soil salinity. The higher the EC, the more soluble salts are present in the soil (Grisso *et al*., 2009, in Naudé, 2018). The overall EC level for all three study sites was relatively the same and had typical standard values (USDA, 2014) (Table 4.6, 4.7 and 4.8).

There was no clear relationship between the soil pH and EC and the TSA of all the woody species of the three study sites, however, *D*. *lycioides*, had a definite relationship with subsoil pH (Figure 4.29), while *D*. *lycioides* and *D*. *cinerea* had a definite relationship with soil EC (Figure 4.32 and Figure 4.33). The slightly alkaline subsoil pH seems to favour the growth of *D*. *lycioides*, which could be attributed to the free carbonates present in the soils, increased availability of the most macro-nutrients and the slightly less availability of potentially toxic elements (PTEs), including phosphorous (P), iron (Fe), manganese (Mn), boron (B), copper (Cu) and zinc (Zn) (Brady & Weil, 2017). This, along with no competition from grass for soil water and nutrients (Ward *et al*., 2013), further increased the establishment and growth of *D*. *lycioides* at the Kgomo-Kgomo study site. The encroacher species, *D*. *cinerea*, is more commonly found on nutrient-rich soils and is less tolerant on nutrient-poor soils (Pedroso & Martin, 2012), which indicate that *D*. *cinerea* prefer soils with higher nutrient availability, however, no chemical analysis was done to substantiate this finding. The highest EC that were found for the first transect of the Pilanesberg study site indicated that the amount of nutrients in that transect likely led to the most individuals of *D*. *cinerea* found regarding all transects, as the soil of that transect had the highest nutrients, even though it found to be a shallow soil (300 mm).

Therefore, soil pH and EC did not have a definite influence on all the woody species, but had a clear influence on the density and extent of certain encroacher species that influence BE at the three study sites.

#### 4.3.2.4 Hydraulic soil parameters

The hydraulic soil parameters for each study site includes soil moisture retention (Volumetric water content % at specific pressures), dry bulk density (Pb) (g/cm$^3$) and porosity (cm$^3$/cm$^3$).

- **Soil moisture retention of all three study sites**

Table 4.9 indicates the relationship between the soil moisture retention, volumetric water content at 1 and 15 Bar (wilting point), plant available water (PAW) (%) and total plant available water (TPAW) (mm) for the entire soil profile of the three transects (200 $m^2$) of each study site.

**Table 4.9: The relationship between the soil moisture retention, volumetric water content at 1 and 15 Bar (wilting point), plant available water (PAW) (%) and total plant available water (TPAW) (mm) and the total species abundance (TSA) of all woody species identified at the three transects (200 $m^2$) of each study site.**

| Soil sample | Volumetric water content (%) at 1 Bar | Volumetric water content (%) at 15 Bar | Plant available water (PAW) (%) | Total plant available water (TPAW) (mm) |
|---|---|---|---|---|
| **Pilanesberg Transect 1** | 29.79 | 25.81 | 3.98 | 11.94 |
| **Pilanesberg Transect 2** | 25.61 | 20.21 | 5.4 | 16.2 |
| **Pilanesberg Transect 3** | 26.2 | 24.2 | 2.0 | 14.0 |
| **Legkraal Transect 1** | 27.64 | 23.59 | 4.05 | 60.75 |
| **Legkraal Transect 2** | 28.45 | 21.46 | 6.99 | 104.85 |
| **Legkraal Transect 3** | 24.19 | 20.63 | 3.56 | 53.4 |
| **Kgomo-Kgomo Transect 1** | 23.87 | 19.49 | 4.38 | 52.56 |
| **Kgomo-Kgomo Transect 2** | 20.03 | 14.06 | 5.97 | 71.64 |
| **Kgomo-Kgomo Transect 3** | 24.7 | 18.16 | 6.54 | 78.48 |

The second transect of the Pilanesberg study site had the lowest PAW (3.98%) and TPAW (11.94 mm), while the second transect of the Legkraal study site had the highest PAW (6.99%) and TPAW (104.85 mm) (Table 4.15). The first transect of the Pilanesberg study site had the highest VWC at 1 Bar (29.79%) and 15 Bar (wilting point) (25.81%). Although the second transect of the Kgomo-Kgomo study site had the lowest VWC at 1 Bar (20.03%) and 15 Bar (wilting point) (14.06%), the soil had a very high PAW (5.97%) and TPAW (71.64 mm) (Table 4.15). Overall, the Kgomo-Kgomo study site had the highest PAW and PTAW compared with the other study sites.

- **Hydraulic soil parameters of the Pilanesberg study site**

Figure 4.34 shows the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bar) of all samples of the Pilanesberg study site.

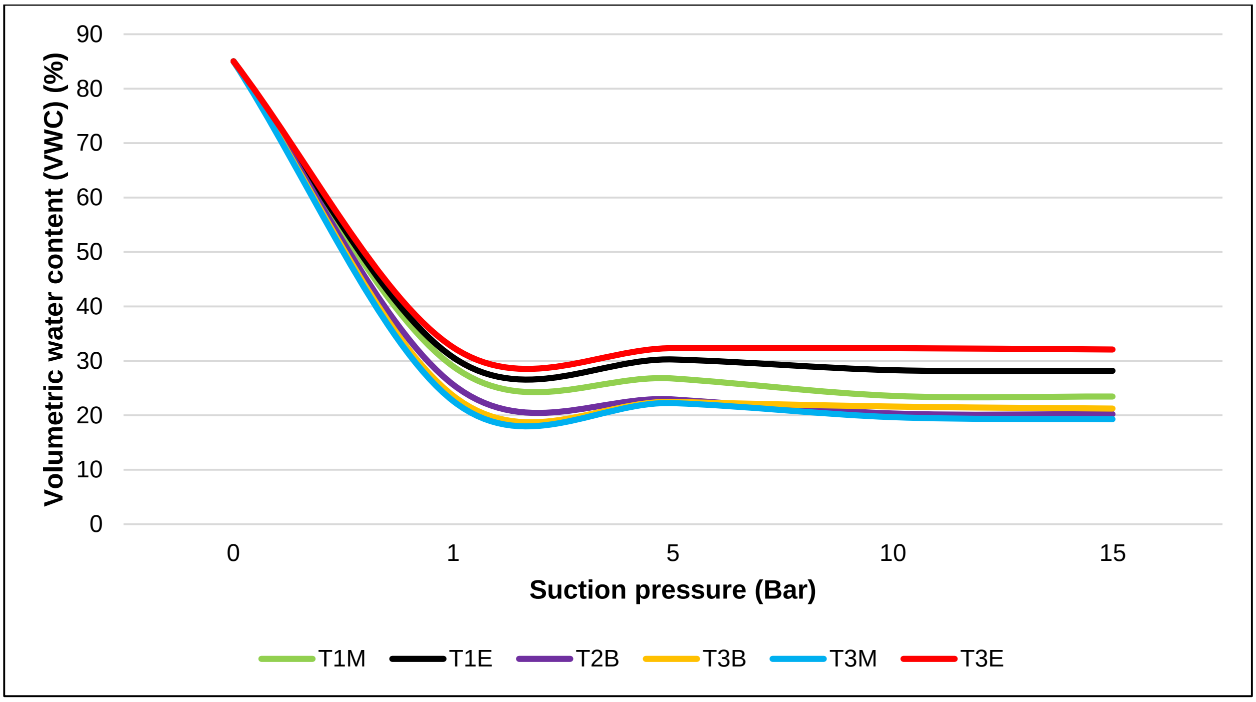



**Figure 4.34: A graph presenting the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bars) of all samples of the Pilanesberg study site. T1M (green line) stands for transect 1 middle, T1E (black line) stands for transect 1 end, T2B (purple line) stands for transect 2 beginning, T3B (orange line) stands for transect 3 beginning, T3M (blue line) stands for transect 3 middle and T3E (red line) stands for transect 3 end.**

All the samples had between 45 and 15% volumetric water content for pressures between 5 and 15 Bar (Figure 4.34). The sample, T3E (red line) had the highest soil moisture retention and 32% volumetric water content at wilting point (15 Bar). Samples, T3M (blue line) and T2B (purple line) had the lowest soil water retention, with 19.2% and 20.2% volumetric water content at wilting point (15 Bar), respectively (Figure 4.34).

Figure 4.35 shows the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bar) of the three transects of the Pilanesberg study site.

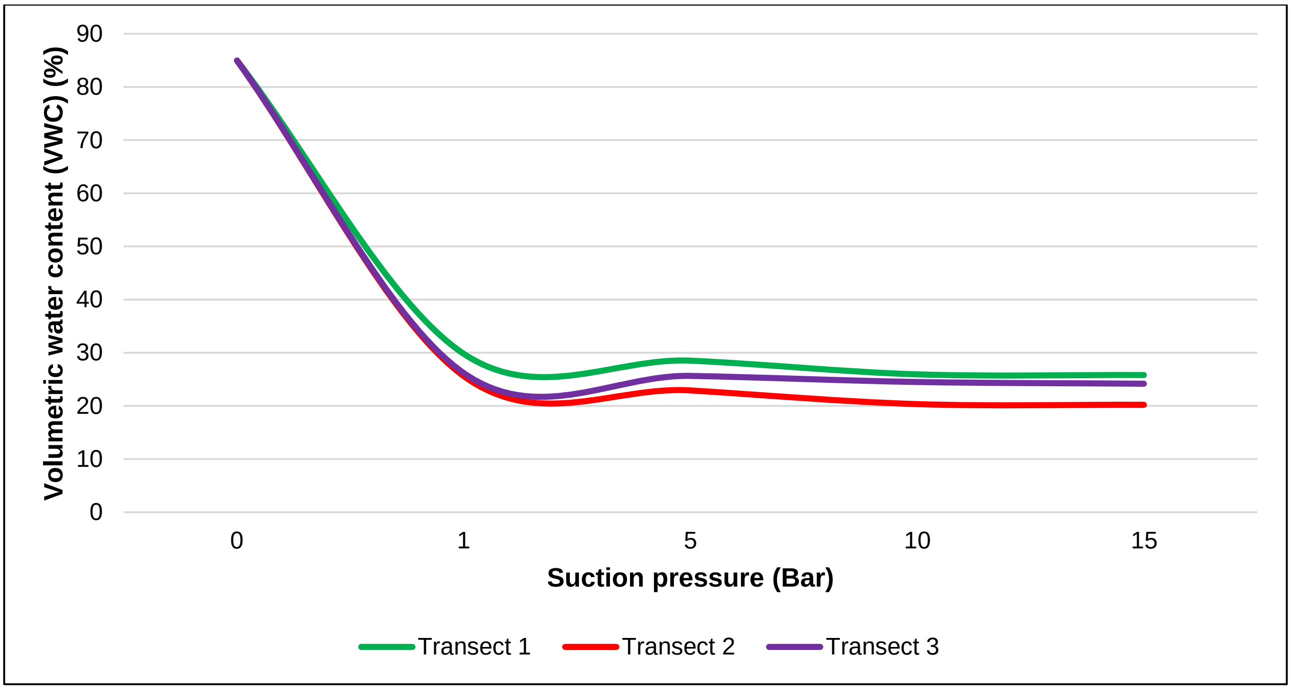



**Figure 4.35: A graph presenting the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bars) of the three transects of the Pilanesberg study site. Transect 1 (green line), transect 2 (red line) and transect 3 (purple line).**

All three transects had a volumetric water content between 30 and 20% for pressures 1 to 15 Bar (Figure 4.35). The first transect (green line) had the highest soil moisture retention and 25.8% volumetric water content at wilting point (15 Bar), while the second transect (red line) had the lowest soil moisture retention (20.2% volumetric water content) at wilting point (15 Bar) (Figure 4.35).

Table 4.10 indicates the average textures, dry bulk density (Pb) (g/cm$^3$) and porosity (cm$^3$/cm$^3$) of the three transects of the Pilanesberg study site.

**Table 4.10: The average textures, dry bulk density (Pb) (g/cm$^3$) and porosity (cm$^3$/cm$^3$) of the three transects of the Pilanesberg study site.**

| Soil sample | Texture | Dry bulk density (Pb) (g/cm$^3$) | Porosity (cm$^3$/cm$^3$) |
|---|---|---|---|
| **Transect 1** | Sandy loam | 1.50 | 0.44 |
| **Transect 2** | Sandy loam | 1.14 | 0.57 |
| **Transect 3** | Loamy sand | 1.33 | 0.50 |

The three transects of the Pilanesberg study site had a sandy loam texture, with Pbs between 1.1 and 1.50 g/cm$^3$ and porosities between 0.4 and 0.6 cm$^3$/cm$^3$. The first transect had the highest Pbs (1.50 g/cm$^3$) and lowest porosity (0.44 cm$^3$/cm$^3$), while the second transect had the lowest Pbs (1.14 g/cm$^3$) and highest porosity (0.57 cm$^3$/cm$^3$) of the Pilanesberg study site (Table 4.10).

- **Hydraulic soil parameters of the Legkraal study site**

Figure 4.36 shows the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bar) of all samples of the Legkraal study site.

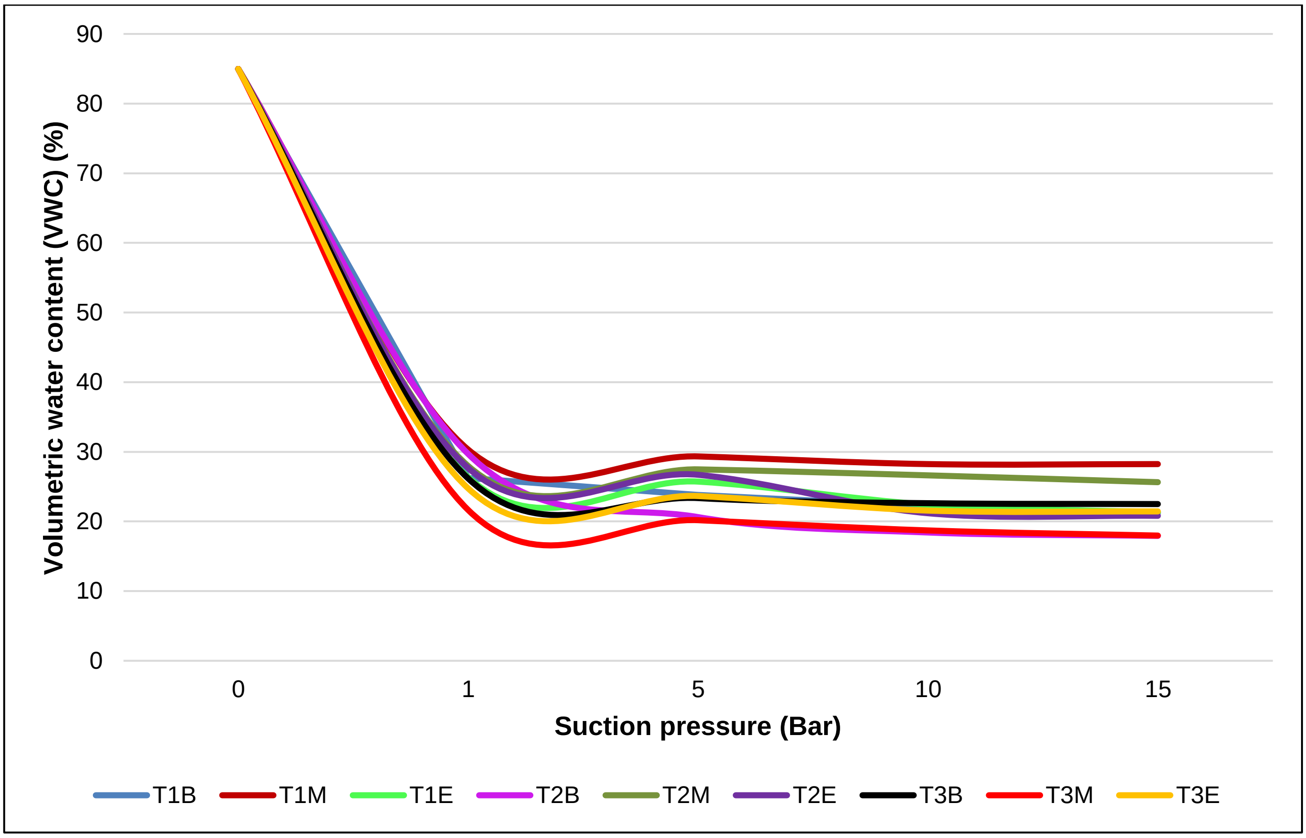



**Figure 4.36: A graph presenting the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bars) of all samples of the Legkraal study site. T1B (blue line) stands for transect 1 middle, T1M (dark red line) stands for transect 1 middle, T1E (light green line) stands for transect 1 end, T2B (pink line) stands for transect 2 beginning, T2M (dark green) stands for transect 2 middle, T2E (purple line) stands for transect 2 end, T3B (black line) stands for transect 3 beginning, T3M (light red line) stands for transect 3 middle and T3E (orange line) stands for transect 3 end.**

All the samples had between 45 and 15% volumetric water content for pressures between 5 and 15 Bar (Figure 4.36). The sample, T1M (dark red line) had the highest soil moisture retention (28.2% volumetric water content) at wilting point (15 Bar). Samples, T3M (light red line) and T2B (pink line) had the lowest soil water retention, with 17.98% and 17.93% volumetric water content at wilting point (15 Bar), respectively (Figure 4.33).

Figure 4.37 shows the soil moisture retention (volumetric water content % at different pressures) of the three transects of the Legkraal study site.

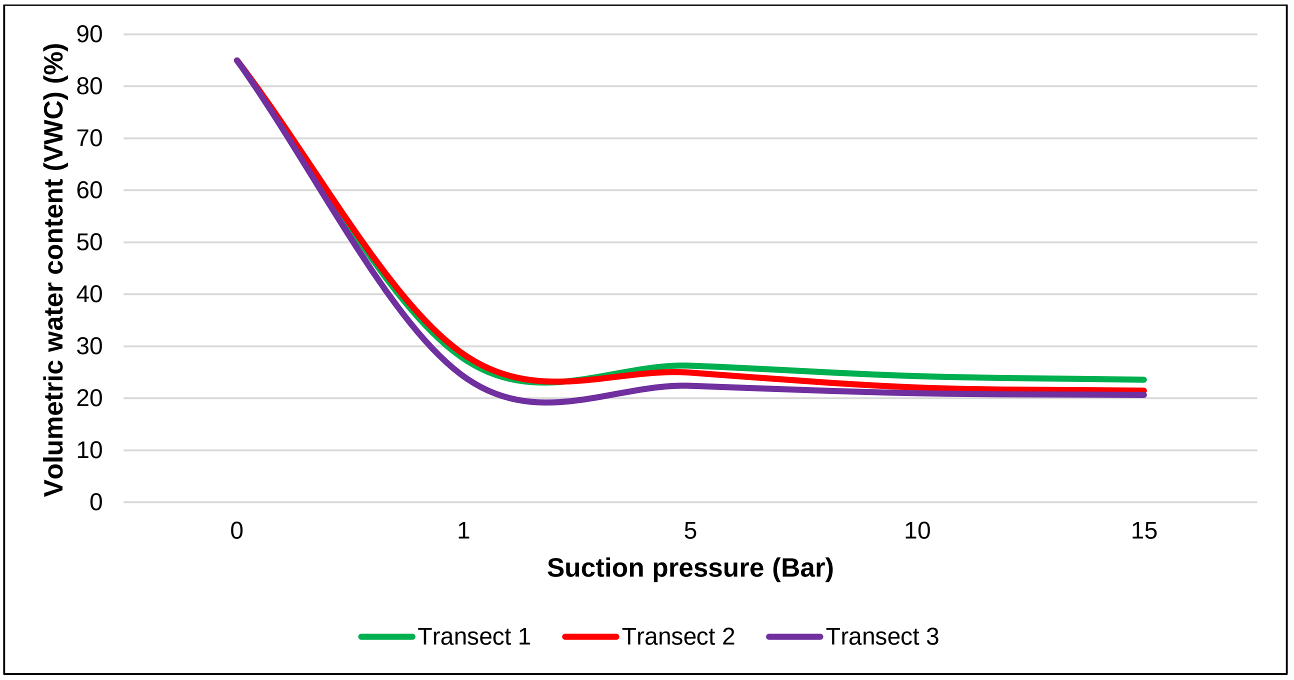



**Figure 4.37: A graph presenting the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bars) of the three transects of the Legkraal study site. Transect 1 (green line), transect 2 (red line) and transect 3 (purple line).**

All three transects had a volumetric water content between 25 and 20% for pressures 1 to 15 Bar (Figure 4.37). The first transect (green line) had the highest soil moisture retention (23.87% volumetric water content) at wilting point (15 Bar), while the third transect (purple line) had the lowest soil moisture retention (20.63% volumetric water content) at wilting point (15 Bar) (Figure 4.37).

Table 4.11 indicates the average textures, dry bulk density (g/cm$^3$) and porosity (cm$^3$/cm$^3$) of the three transects of the Legkraal study site.

**Table 4.11: The average textures, dry bulk density ($g/cm^3$) and porosity ($cm^3/cm^3$) of the three transects of the Legkraal study site.**

| Soil sample | Texture | Dry bulk density (Pb) ($g/cm^3$) | Porosity ($cm^3/cm^3$) |
|---|---|---|---|
| **Transect 1** | Loamy sand | 1.31 | 0.51 |
| **Transect 2** | Sandy loam | 1.19 | 0.55 |
| **Transect 3** | Sandy loam | 1.39 | 0.48 |

As mentioned, the first transect of the Legkraal study site had a loamy sand texture, while the second and third transect had sandy loam textures (Table 4.11). The three transects had dry bulk densities between 1.18 and 1.40 $g/cm^3$ and porosities between 0.45 and 0.56 $cm^3/cm^3$. The third transect had the highest dry bulk density (1.39 $g/cm^3$) and lowest porosity (0.48 $cm^3/cm^3$), while the second transect had the lowest dry bulk density (1.19 $g/cm^3$) and highest porosity (0.55 $cm^3/cm^3$) of the Legkraal study site (Table 4.11).

- **Hydraulic soil parameters of the Kgomo-Kgomo study site**

Figure 4.38 shows the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bar) of all samples of the Kgomo-Kgomo study site.

All the samples had between 30 and 10% volumetric water content for pressures between 5 and 15 Bar (Figure 4.38). The sample, T3E (orange red line) had the highest soil moisture retention (21.64% volumetric water content) at wilting point (15 Bar). Samples, T2M (dark green line) and T2E (purple line) had the lowest soil water retention, with 12.73% and 13.05% volumetric water content at wilting point (15 Bar), respectively (Figure 4.38).

Figure 4.39 shows the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bar) of the three transects of the Kgomo-Kgomo study site.

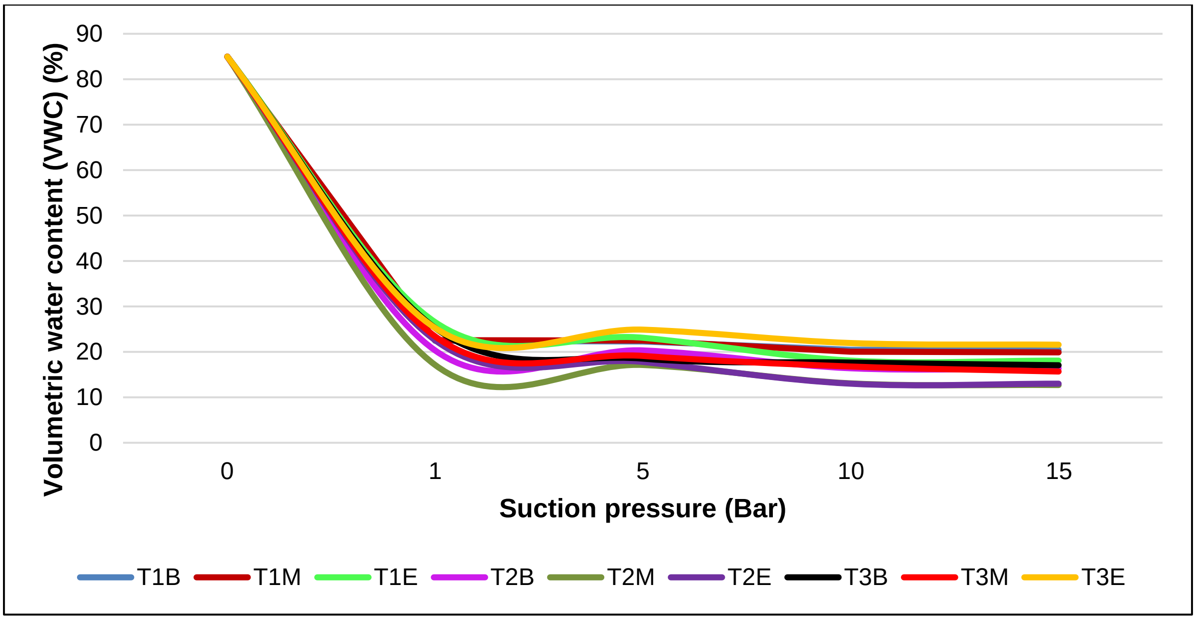



**Figure 4.38: A graph presenting the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bars) of all samples of the Kgomo-Kgomo study site. T1B (blue line) stands for transect 1 middle, T1M (dark red line) stands for transect 1 middle, T1E (light green line) stands for transect 1 end, T2B (pink line) stands for transect 2 beginning, T2M (dark green line) stands for transect 2 middle, T2E (purple line) stands for transect 2 end, T3B (black line) stands for transect 3 beginning, T3M (light red line) stands for transect 3 middle and T3E (orange line) stands for transect 3 end.**

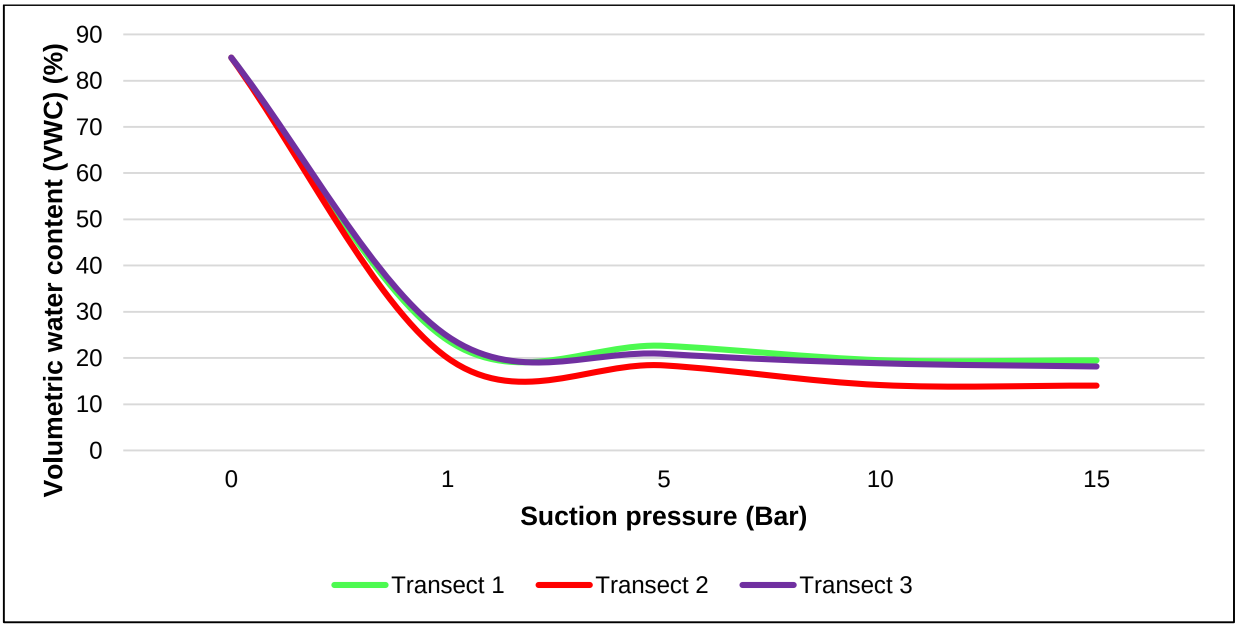



**Figure 4.39: A graph presenting the soil moisture retention (volumetric water content %) at different pressures (1 to 15 Bars) of the three transects of the Kgomo-Kgomo study site. Transect 1 (green line), transect 2 (red line) and transect 3 (purple line).**

All three transects had a volumetric water content between 30 and 10% for pressures 1 to 15 Bar (Figure 4.39). The first transect (green line) had the highest soil moisture retention (19.49% volumetric water content) at wilting point (15 Bar), while the second transect (red line) had the lowest soil moisture retention (14.06% volumetric water content) at wilting point (15 Bar) (Figure 4.39).

Table 4.12 indicates the average textures, dry bulk density (Pb) (g/cm$^3$) and porosity (cm$^3$/cm$^3$) of the three transects of the Kgomo-Kgomo study site. The bulk densities that affect root growth is shown in orange and the bulk densities that restrict root growth (USDA, 2018) is shown in red.

**Table 4.12: The average textures, dry bulk density (Pb) (g/cm$^3$) and porosity (cm$^3$/cm$^3$) of the three transects of the Kgomo-Kgomo study site. The Pb that affect root growth is shown in orange and the bulk densities that restrict root growth (USDA, 2018) is shown in red.**

| Soil sample | Texture | Dry bulk density (Pb) (g/cm$^3$) | Porosity (cm$^3$/cm$^3$) |
|---|---|---|---|
| **Transect 1** | Sandy loam | 1.80 | 0.32 |
| **Transect 2** | Loamy sand | 1.71 | 0.35 |
| **Transect 3** | Sandy loam | 1.71 | 0.36 |

As mentioned, the first and third transects of the Kgomo-Kgomo study site had a sandy clay loam texture, while the first transect had loamy sand texture. The three transects had dry bulk densities between 1.7 and 1.81 g/cm$^3$ and porosities between 0.31 and 0.37 cm$^3$/cm$^3$ (table 4.12). The first transect had the highest dry bulk density (1.80 g/cm$^3$) and lowest porosity (0.32 cm$^3$/cm$^3$), while the third transect had the lowest dry bulk density (1.71 g/cm$^3$) and highest porosity (0.36 cm$^3$/cm$^3$) of the Kgomo-Kgomo study site. The bulk density of Transect 1 restrict root growth, while Transect 2 and transect 3 affect root growth (Table 4.12).

- **Relationship between soil moisture retention and woody species of all three study sites**

There was no clear relationship between the soil water retention and the TSA of all the woody species of the three study sites. Both, PAW and TPAW had a poor relationship with the TSA of all woody species, with $R^2$ values lower than 0.21 (Figure 4.40 and Figure 4.41). A TSA between 60 and 110 were found within all the study site transects with 5 to 20% clay distribution of the topsoil and with 5 and 30% clay of the subsoil. The third transect of Kgomo-Kgomo had a very high TSA, as 122 of *D. lycioides* were found within the transect (Figure 4.16), and had the second highest PAW (6.54 %) and TPAW (78.48 mm) compared with the other transects, however PAW and TPAW did not influence *D. lycioides*.

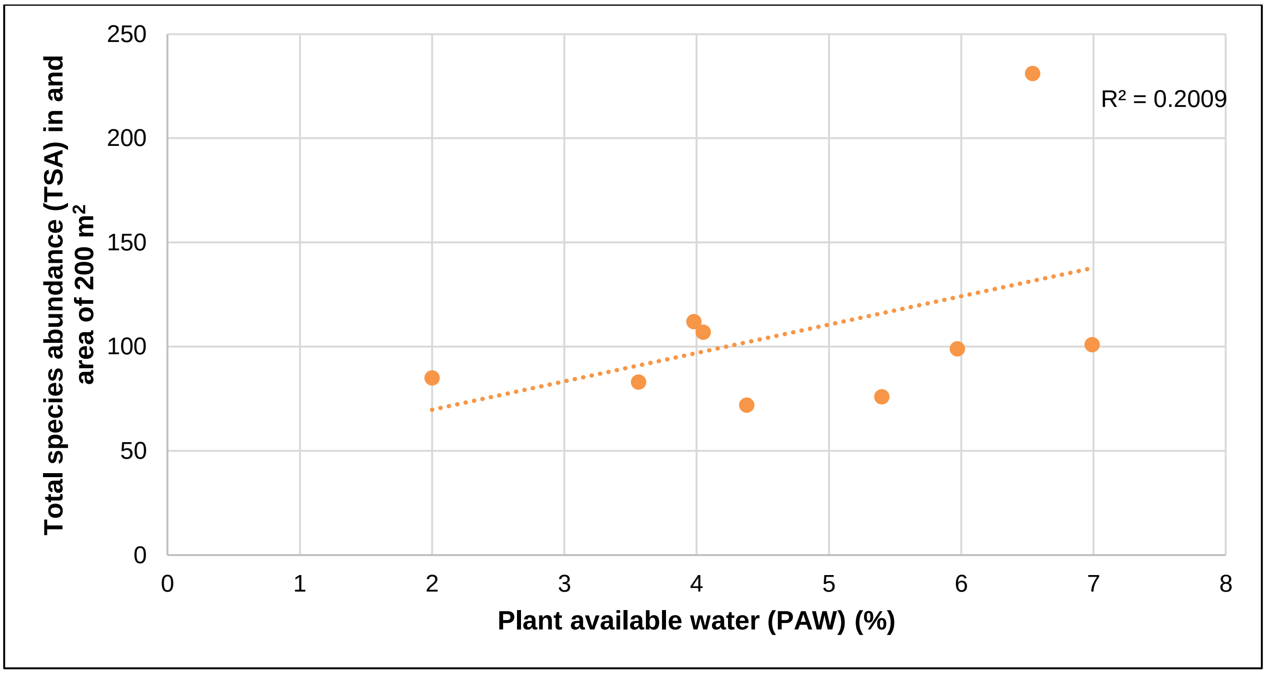



**Figure 4.40: The relationship between the total species abundance (TSA) of all the woody species and the plant available water (PAW) (%) at the three transects (200 $m^2$) of each study site.**

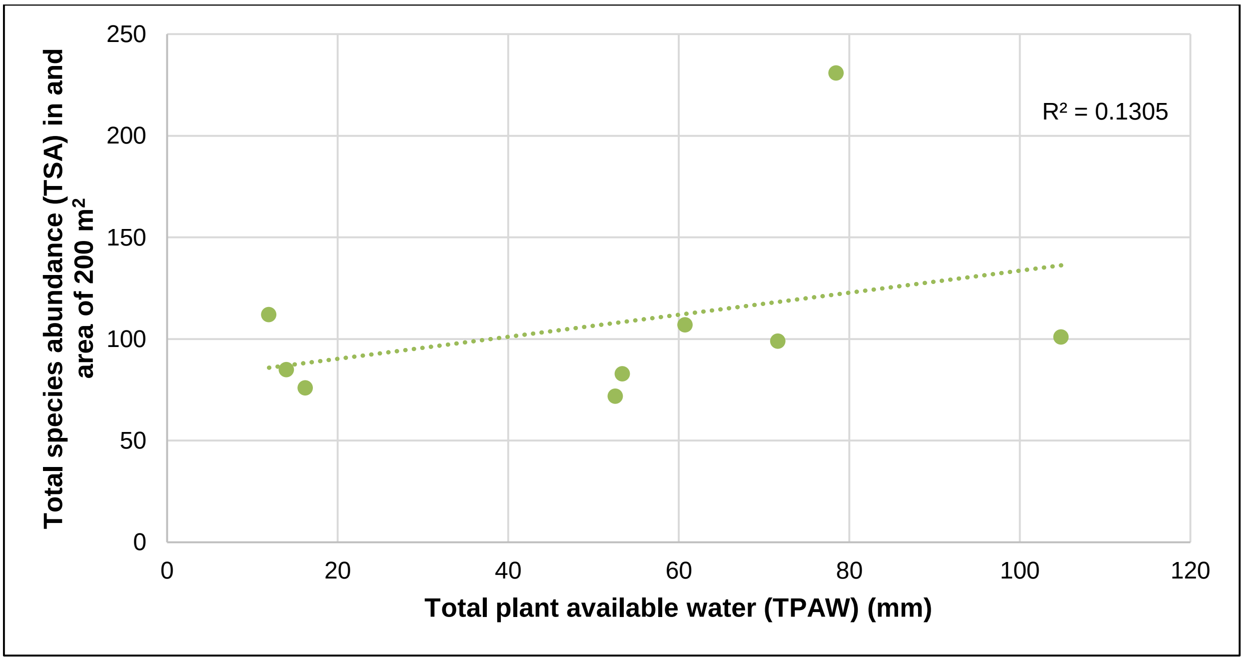



**Figure 4.41: The relationship between the total species abundance (TSA) of all the woody species and the total plant available water (TPAW) (mm) at the three transects (200 $m^2$) of each study site.**

- **Relationship between bulk density (Pb) and porosity and woody species of all three study sites**

There was no clear relationship between the Pb and the TSA of all the woody species of the three study sites, with a $R^2$ value lower than 0.15 (Figure 4.42). A TSA between 60 and 110 were found within all the study site transects where Pb was between 1.1 and 1.8. There was however, a relationship between two encroacher species, namely *D*. *lycioides* and *G*. *flava*, which were the most individuals were found at the Kgomo-Kgomo study site, where the Pb was the highest regarding all study sites (Figure 4.43 and Figure 4.44). The encroacher species, *G*. *flava*, had a moderate relationship with Pb ($R^2$ =0.5116) and the highest TSA of this species occurred where Pb was above 1.7 g/cm$^3$ (Figure 4.43). The encroacher species, *D*. *lycioides*, only had a slight relationship with Pb (R2 =0.5116), with the highest TSA of this species (122 individuals) occurring where Pb was 1.7 g/cm$^3$, however, this indicates that these species lived in soils with a high Pb.

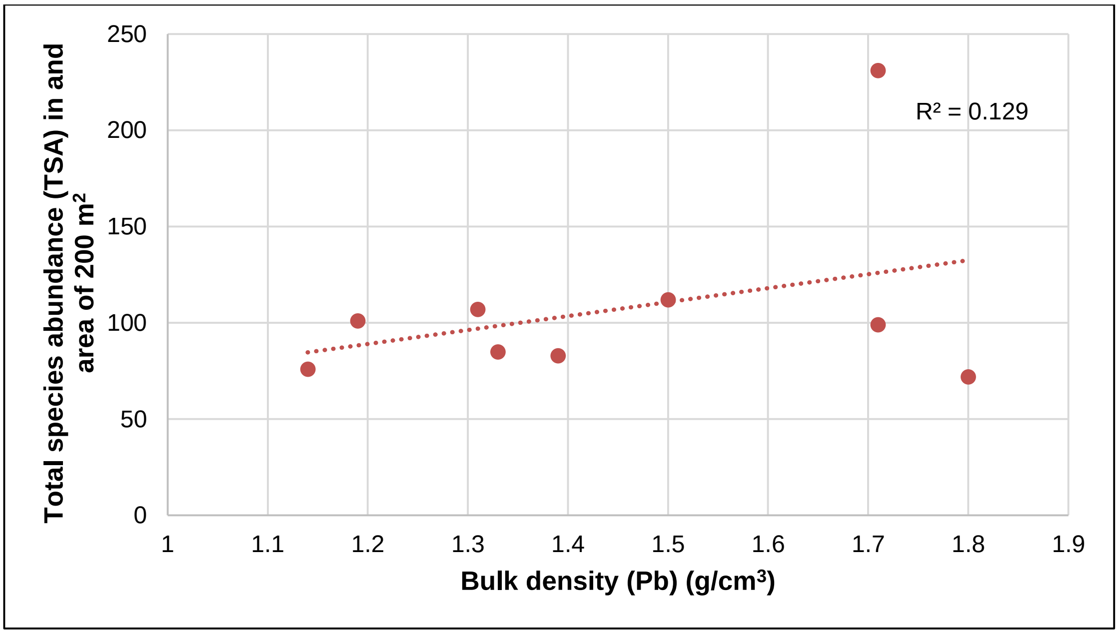



**Figure 4.42: The relationship between the total species abundance (TSA) of all the woody species and the bulk density (Pb) (g/cm$^3$) at the three transects (200 m$^2$) of each study site.**

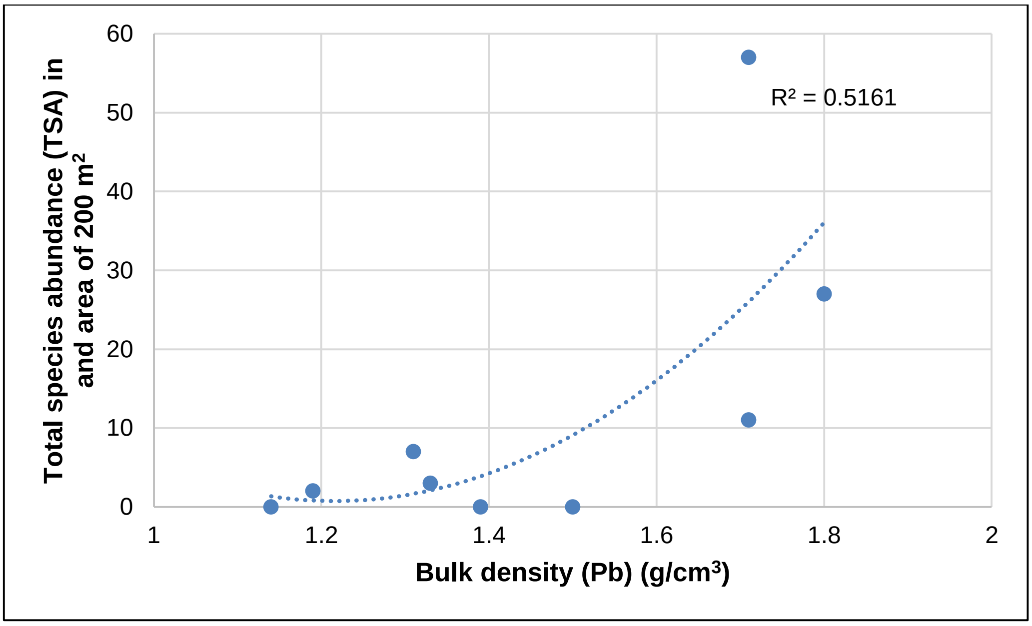



**Figure 4.43: The relationship between the total species abundance (TSA) of *G. flava* and the bulk density (Pb) (g/cm³) at the three transects (200 m²) of each study site.**

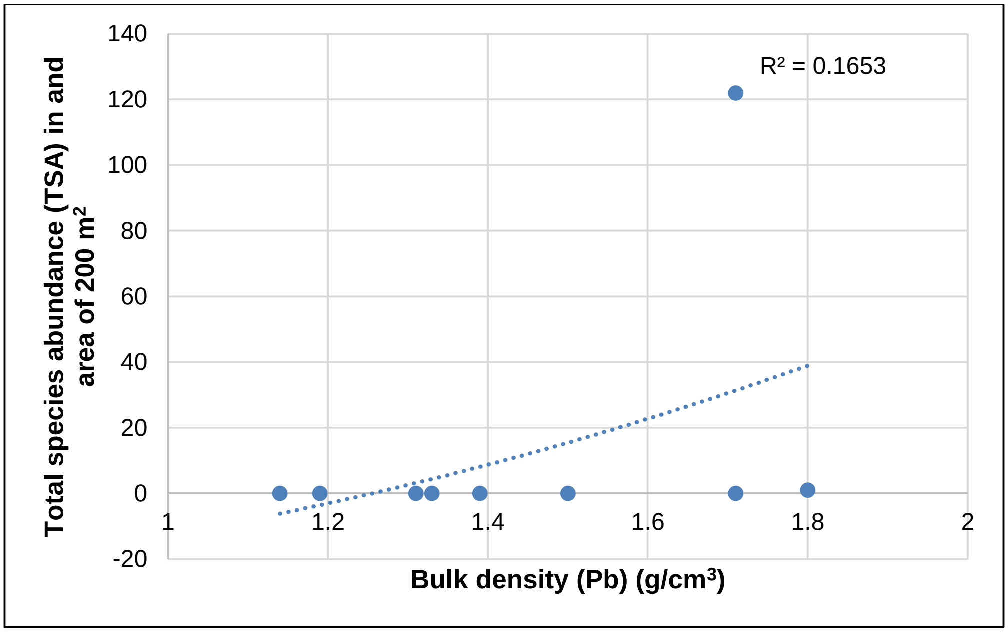



**Figure 4.44: The relationship between the total species abundance (TSA) of *D. lycioides* and the bulk density (Pb) (g/cm³) at the three transects (200 m²) of each study site.**

- **Influence of hydraulic soil parameters on bush encroachment at the three study sites**

Soil moisture content has a dominant influence on root growth, through the direct effects of water availability on root growth, effects of water on photosynthesis and therefore carbohydrate availability effects of water on oxygen availability and effects of soil impedance (dryness) on root growth (Lynch *et al*., 2011). As soils dry out, water usually remains in the deep soil layers, leading to decreased shoot growth and increasing root growth of herbaceous plants (grass). Much of the water held at field capacity (0.33 Bar) is available to plant uptake through roots (Brady & Weil, 2017). From the results, there was no clear relationship between the soil moisture retention and the TSA of all the woody species of the three study sites. The soil of the second transect of the Legkraal study site did have the highest PAW (6.99%) and TPAW (104.85 mm) compared with the other transects (Table 4.9), but did not show any relationship with any of the dominant encroacher species at the study sites. As there was no clear relationship between the soil water retention and the TSA of all the woody species or dominant encroacher species of the three study sites, indicating soil moisture retention did not influence BE at the three study sites.

The soil of all three transects of the Pilanesberg and Legkraal study sites had ideal Pbs for plant growth (USDA, 2018), however, the soil of the Kgomo-Kgomo study site had Pb that either affected or restricted root growth. As soil compaction is described by soil Pb (Soil Science Society of America (SSSA), 2005, in Tokunaga, 2006), the Kgomo-Kgomo study site had the most compacted soil (Pb > 1.7 g/cm$^3$). As there was almost no grass found within the three transects of the Kgomo-Kgomo study site, trampling and overgrazing might also have contributed to the high Pb, as grazing and trampling increases compaction and, in turn, increasing Pb by rearranging soil grains and decreasing void space (Chanasyk & Naeth, 1995, Donkor *et al*., 2002, in Tokunaga, 2006; Luong *et al*., 2015). The high Pb of the Kgomo-Kgomo study site resulted in restricted root growth, which influenced encroacher species (Turpie *et al*., 2019), such as *G*. *Flava* and *D*. *lycioides* that were found at this site, with *D*. *lycioides* the most dominant species at the third transect of the Kgomo-Kgomo study site. These encroacher species were likely more adapted to survive in these soils compared to other woody species, as these woody encroacher species were likely able to extract water in compacted soils, they likely had a competitive advantage over other woody species and grass, which led to the proliferation of their woody seedlings (Fravolini *et al*., 2005).

Therefore, bulk density (Pb) was an important soil characteristic that influenced BE, with adapted species able to thrive in compacted soils and outcompete other woody species potentially causing BE.

## 4.4 Relationships between woody species and soil variables

Figure 4.45 indicates the variance between the total species abundance (TSA) of the different transects, as well as other soil characteristics collected during the soil analysis. The main difference in variation of the TSA can be noted that on the right-hand side, between 1.5 and 3.0

on the x-axis, the transects of the Kgomo-Kgomo site occur, while the rest of the transects of the Pilanesberg and Legkraal sites occur on the left-hand side of the x-axis, between -0.5 and -1.5.

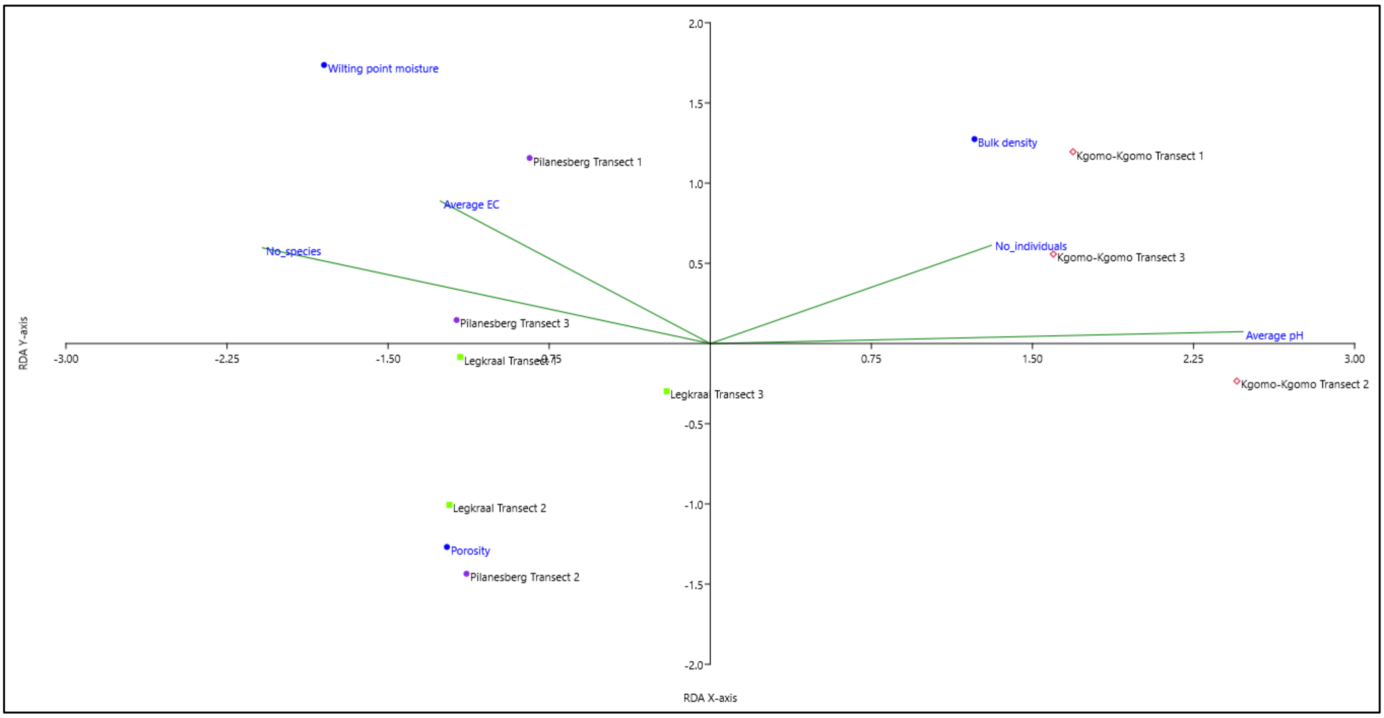



**Figure 4.45: Redundancy ordination analysis (RDA) for the transects of the three study sites in relation with number of individual woody plants (No_individuals), number of woody species (No_species), soil moisture at 15 Bar (Wilting point moisture), EC (average EC), pH (Average pH), dry bulk density (Bulk density) and total porosity (Porosity) of soil.**

The RDA ordination indicates that a positive correlation exists between the TSA of the three transects of the Kgomo-Kgomo study site (Kgomo-Kgomo Transect 1, Kgomo-Kgomo Transect 2 and Kgomo-Kgomo Transect 3) with the number of individual woody plants, Pb and average pH. Although average pH had a positive correlation, Pb likely had the most significant effect on the high amount of individuals woody plants found at the Kgomo-Kgomo study site. There is also a positive correlation between the TSA of Pilanesberg Transect 1 and Pilanesberg Transect 3 with the number of woody species, average EC and wilting point moisture. However, from the previous results there is no clear relationship between the number of species and the average EC. A positive correlation also existed between the TSA of all the transects of the Legkraal study site and Pilanesberg Transect 2 and porosity. However, from the previous results there is no clear relationship between the number of individual woody plants and number of species and porosity.

## 4.5 Conclusion

From the vegetation survey, *D. cinerea* and *D. lycioides* can be regarded as the main woody encroacher species as *D. cinerea* occurred at all study sites and *D. lycioides* that encroached significantly at the Kgomo-Kgomo study site. The other recognized woody encroaching species in the study sites include: *G*. *flava*, *G*. *flavescens*, *S*. *mellifera*, *V*. *karroo*, *V*. *tortillis* and *Ziziphus mucronata*. The Pilanesberg site presented the highest diversity of woody species, with 25 different species identified within the three transects (area of 600 $m^2$), however, this site had the lowest BE extent as there was an herbaceous layer present that could compete with woody seedlings for soil water and nutrients. The Legkraal site had the highest BE extent with the absence of an herbaceous layer and the thickest bushes found from all three sites. The majority of woody species found in all the transects of all the sites presented multiple stems. The high occurrence of multiple-stemmed species at the Legkraal and Kgomo-Kgomo sites could be attributed to the livestock (goats) promoting multi-stemmed structure by stimulating growth of existing or new sprouts after damage to existing stems. The high occurrence of multiple-stemmed species at the Pilanesberg study site could be attributed to the wildlife and fires in the Pilanesberg National Park, that promoted multi-stemmed structure by stimulating growth of existing or new sprouts after damage to existing stems. As the majority of woody species were abundant in the lower classes (1-4) compared to the higher classes (5-7), it might be an indication that BE may have been in an early stage within all three sites.

There were clear differences in soil texture, particle size distribution and soil depth regarding all three study sites. The Pilanesberg study site had predominantly a sandy loam texture, a low clay fraction and very shallow soils, while the Legkraal study site had predominantly a sandy loam and silt loam texture, a very high silt fraction and very deep soil profile (1 500 mm). The Kgomo-Kgomo study site had had sandy loam, sandy clay loam and loamy sand texture, the highest clay fraction of all study sites and also deep soil profile (1 200 mm). This difference in soil texture, particle size distribution and depth had a definite influence on BE at each study site. The Legkraal study site had a very high silt fraction, which was likely due to the weathering of the rocks from the Molteno Formation, where the Legkraal study site was situated on.

There was no clear relationship found between the particle size distribution of clay (%) and the TSA of the woody species found at the three study sites, however, *D. cinerea* and *G. flava*, had a definite relationship with the soil particle size distribution. The TSA of *D. cinerea* were low, where the clay fraction was higher in the top- and subsoil at the Kgomo-Kgomo study site and the TSA of *G. flava* were high, where the clay fraction was higher in the top- and subsoil at the Kgomo-Kgomo study site. Although *G. flava* can also be found on different soil types, especially shallow, sandy soil, a higher TSA were found for this species at the Kgomo-Kgomo study site. Although no chemical analysis of the soils was done, it is plausible that the Kgomo-Kgomo study had higher nutrients in the soil, making the soil more favourable for certain encroacher species, such as *G. flava* compared to species such as *D. cinerea*. There was no clear relationship between the soil depth and the TSA of all the woody species at the three study sites, however, *V. tortillis*, *C. apiculatum*, *C. inberbe* and *C. hereroense* had a definite relationship with soil depth. The results indicated that *V. tortillis* had a good relationship with soil profile depth, further substantiating that *V. tortillis* prefers deep soils. Previous studies have reported that *C. zeyheri*, *C. apiculatum* and *S. caffra* are associated with shallow soils (Glenrosa soil form), which were substantiated by this study as *C. apiculatum*, *C. inberbe* and *C. hereroense* were found at the Pilanesberg study site, which had the shallowest soils.

Therefore, soil particle distribution and soil depth had a clear influence on the density and extent of certain encroacher species that influence BE at the three study sites.

The subsoil of the third transect of the Kgomo-Kgomo study site had the highest pH (7.64), while the topsoil of the first transect of the Pilanesberg study site had the highest EC (40.93 mS/m). There was no clear relationship between the soil pH and EC and the TSA of all the woody species of the three study sites, however, *D. lycioides*, had a definite relationship with subsoil pH, while *D. lycioides* and *D. cinerea* had a definite relationship with soil EC. The high subsoil pH indicated that the soil was fertile and that most macronutrients were likely available for root uptake. This, along with no competition from grass for soil water and nutrients, further increased the establishment and growth of *D. lycioides* at the Kgomo-Kgomo study site. Previous studies indicate that *D. cinerea* prefer soils with higher fertility. The first transect of the Pilanesberg study site indicated that the high EC (41 mS/m) indicated a high amount of nutrients in that transect, which likely led to the most individuals of *D. cinerea* being found.

Therefore, soil pH and EC did not have a definite influence on all the woody species, but had a clear influence on the density and extent of certain encroacher species that influence BE at the three study sites.

Soil moisture content has a dominant influence on root growth, through the direct effects of water availability on root growth, effects of water on photosynthesis and therefore carbohydrate availability effects of water on oxygen availability and effects of soil impedance (dryness) on root growth. The second transect of the Pilanesberg study site had the lowest PAW (3.98%) and TPAW (11.94 mm), while the second transect of the Legkraal study site had the highest PAW (6.99%) and TPAW (104.85 mm). Overall, the Kgomo-Kgomo study site had the highest PAW and TPAW compared with the other study sites. There was no clear relationship between the soil water retention and the TSA of all the woody species or dominant encroacher species of the three study sites, indicating soil moisture retention did not influence BE at the three study sites.

The soil of all three transects of the Pilanesberg and Legkraal study sites had ideal Pbs for plant growth. The Kgomo-Kgomo study site had the highest Pb compared to the Pilanesberg and Legkraal study sites. The three transects of the Kgomo-Kgomo had the highest Pb of all transects, with Pb of 1.80, 1.71 and 1.71 $g/cm^3$, respectively. The Kgomo-Kgomo study site had the highest compacted soil, with Pb that effected and restricted root growth. There was no clear relationship between the Pb and the TSA of all the woody species of the three study sites. There was however, a relationship between *D*. *lycioides* and *G*. *flava* and high Pb ($< 1.7$ $g/cm^3$). As there was almost no grass found within the three transects of the Kgomo-Kgomo study site, trampling and overgrazing might also have contributed to the high Pb, which resulted in restricted root growth. This influenced encroacher species, such as *G*. *Flava* and *D*. *lycioides*, which were likely more adapted to survive in these compacted soils compared to other woody species. As these woody encroacher species were likely able to extract water in compacted soils, they likely had a competitive advantage over other woody species and grass, which led to the proliferation of their woody seedlings.

Therefore, bulk density (Pb) was an important soil characteristic that influenced BE, with adapted species able to thrive in compacted soils.

The RDA ordination indicates that a positive correlation existed between the TSA of all the woody species of the three transects of the Kgomo-Kgomo study site (Kgomo-Kgomo Transect 1, Kgomo-Kgomo Transect 2 and Kgomo-Kgomo Transect 3) with the number of individual woody plants, bulk density and average pH. The RDA further also substantiated the influence of soil characteristics (specifically dry bulk density) on BE, with specific soil variables influencing the total number of individual woody plants and species found at each study site.

In conclusion, the Kgomo-Kgomo and Legkraal study sites had a higher extent of BE because of the absence of an herbaceous layer and high occurrence of recognized woody encroacher species, compared to the Pilanesberg study site, even though the Pilanesberg study site had the highest diversity of woody species. Soil characteristics, such as soil particle distribution, pH, EC and bulk density influenced the occurrence certain woody species at each site. However, as the MAP of the NWP is generally very low, the low MAP, as well as overgrazing contributed greatly in the absence of grass at the Legkraal and Kgomo-Kgomo study sites and abundance of the woody encroacher species at each site. Therefore, soil together with precipitation and grazing management, likely influenced BE at the study sites.

# CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

Bush encroachment (BE) is a serious form of land degradation and South Africa alone has lost an estimated 8 million hectares (ha) of grazing or cultivation land due to BE. This consequently leads to decreased food security. To prevent BE, one needs to understand the drivers and mechanisms that control the process and to advise when and where certain management actions should be implemented. Unfortunately, the proposed drivers for bush encroachment in African savannas are still widely debated given that this process is poorly understood. Only a few previous studies in certain areas included soil as a possible cause for BE. The focus of this study was on the gap that exists regarding the effect of soil type on BE in the North West Province (NWP) between 1993 and 2018. This study aimed to determine whether soil is a driving factor of BE in the NWP between 1993 and 2018, and whether different soil types and properties can be associated with the growth characteristics of the woody species causing BE.

For this study, the main driving factors of BE extent and spread were identified in the study area for the specified period by taking a GIS approach on provincial (NWP) and regional scales (four significant areas). Maps indicating the percentage (%) of woody cover for the years 1993, 1998 and 2018 were sourced from Symeonakis *et al*. (2020) and used for calculating the spread of bush and create bush spread maps for time frames, 1993-1998, 1998-2018 and 1993-2018. Potential driving factors of BE were sourced from various sources and used to analyse the bush spread and determine the driving factor/s of the specific spread of bush from 1993 to 2018 on a provincial scale. Improved detail on mean annual precipitation (MAP) as a driving factor of BE was included by using long-term precipitation data obtained from the South African Weather Service (SAWS) (2021).

The results indicated that on provincial scale, MAP was the main driving factor of BE, while on regional scale for the significant areas, MAP and land-use were the main driving factors of BE and soil types were a minor driving factor in the NWP from 1993 to 2018. The four largest bioregions of the NWP have been identified as BE zones and was not considered a driving factor of BE, but did give an indication of BE extent in areas with these bioregions. The possible high numbers of livestock in the NWP, as well as the low MAP in previous years, likely led to overgrazing in many parts of the province, which might have led to the proliferation of woody plant seedlings and a reduction in the cover and density of palatable, perennial grasses. The lower MAP, together with overgrazing which lead to a decrease in grass cover, benefitting the deeper rooted woody plants and with the absence of fire, might have led to the densification of woody plants, causing BE. This led to the proliferation of woody plant seedlings and encroachment of bushes, especially in the Taung area of the NWP. There was no clear driver of BE identified for the other significant areas, however, there was a significant increase of bush lessening (BL) in the Pilanesberg and Rustenburg areas. The decrease of bush density was likely caused by browser animals (such as goats and wildlife) in both these areas. The precipitation data acquired also further substantiated the decrease of mean MAP regarding all significant areas, which could have been attributed to droughts occurring in the NWP.

The effect of different soil types and properties on BE attributes were also determined by a vegetation survey and soil observations at three study sites, which were selected by the DFFE.

From the vegetation survey, *D*. *cinerea* and *D*. *lycioides* can be regarded as the main woody encroacher species as *D*. *cinerea* occurred at all study sites and *D*. *lycioides* that encroached significantly at the Kgomo-Kgomo study site. The other recognized woody encroaching species in the study sites include: *G*. *flava*, *G*. *flavescens*, *S*. *mellifera*, *V*. *karroo*, *V*. *tortillis* and *Ziziphus mucronata*. Soil types and properties did not have a significant influence on all the woody species identified at each study site, but rather on specific encroacher species causing BE in the NWP. The results indicated that the higher clay content of the Kgomo-Kgomo study site had a definite relationship with *D*. *lycioides* and *G. flava*, as most of these species occurred on that study site. Soil depth was correlated with the occurrence of *V. tortillis*, *C. apiculatum*, *C. inberbe* and *C. hereroense* also had a relationship, with all these species occurring on shallow soils. The encroacher species, *D*. *lycioides*, had a good relationship with subsoil pH, while *D*. *lycioides* and *D*. *cinerea* were also correlated with soil EC. The high subsoil pH indicated that the soil had more nutrients and carbonates and that most macronutrients were likely available for root uptake. This, along with no competition from grass for soil water and nutrients, further increased the establishment and growth of *D*. *lycioides* at the Kgomo-Kgomo study site. The high EC of the first transect of the Pilanesberg study site indicated a high amount of nutrients, which likely led to the high abundance of *D*. *cinerea*. There was no clear relationship between the soil water retention and the TSA of all the woody species or specific woody species of the three study sites, indicating soil moisture retention did not influence BE at the three study sites. There was, however, a relationship between *D*. *lycioides* and *G*. *flava* and Pb, as most of these species were found on the transects at the Kgomo-Kgomo study site, which had the highest Pbs regarding all study sites. The RDA ordination also further substantiated the correlation between the total woody species found and Pb at the Kgomo-Kgomo study site. As there was almost no grass cover within the three transects of the Kgomo-Kgomo study site, trampling and overgrazing might have contributed to the high bulk density (Pb) values, which resulted in restricted root growth. This influenced encroacher species, such as *G*. *flava* and *D*. *lycioides*, which were likely more adapted to survive in these compacted soils compared to other woody species, causing BE. These two woody encroacher species could have extracted water in the compacted soils, which may have led to a competitive advantage over other woody- and grass species.

## 5.2 Recommendations

### 5.2.1 Recommendations for implementations

Land-managed areas that experience BE should in general be considered as important future restoration and/or research study sites. Areas where deep soils occur, with predominantly sandy or sandy loam textures, should be regarded as priority areas.

Restoration actions that could be considered in the priority areas include:

- Apply manual, mechanical, chemical, biological or a combination of these methods in BE areas to stimulate the growth of grasses.
- Removed woody biomass can be sold as firewood or for construction purposes.
- To improve soil condition for grass growth, soil organic matter in the form of livestock manure could be added to the topsoil instead of fertilizer, as fertilizers are usually too expensive for land managers.
- Areas with decreased grass cover with bare patches could be re-sown with perennial, palatable grass species, depending on the degree of degradation and soil condition.
- Implement a long-term monitoring and management plan to prevent BE, especially after the woody shrubs have been controlled and rehabilitation strategies implemented.
- Implement a knowledge, training and skills development program to land managers.

### 5.2.2 Recommendations for future research

It is recommended that future research be conducted on the following aspects:

- Determining the main driving factors of BE of other provinces, such as Limpopo and Northern Cape.
- The use of more potential driving factor of BE maps or layers, such as fire, atmospheric $CO_2$ and livestock (goats and cattle) for GIS studies.
- Dividing the specific bush spread into more detailed categories, such as severe, intermediate and slight bush spread for higher detailed results on regional scale.
- Determine the correlations of each specific potential driving factor of BE category with each specific bush spread across the different time frames.

- Using different GIS methods for determining the main driving factors of BE on provincial and regional scale.
- The effect of different soil horizons and horizon properties on BE.
- The effect of other soil properties on woody species causing BE, such as:
    - Soil chemical properties, including macro- and micro-elements,
    - Soil temperature, and
    - Soil organic matter.
- The effect of soil properties on other vegetation attributes, such as:
    - Evapotranspiration rate,
    - Root structure and growth,
    - Leaf size, shape and growth,
    - Age, and
    - Stem growth.

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# ANNEXURES

**Appendix A: The catalogue of states for the proposed conceptual model regarding bush encroachment in the Highland savanna of Namibia (Joubert *et al*., 2008).**

| States | Description |
|---|---|
| **Grassy States 1 and 2** | These two states can be viewed as a continuum. |
| **State 1** | Dense grass sward of climax grass, scattered cover of a variety of trees and shrubs. |
| **State 2** | Sparse grass cover (mainly pioneer annuals), scattered cover of a variety of trees and shrubs. Erosion is evident. |
| **State 3** | Unstable state between grassy States 1 and 2 and woody States 4 and 5, many *S*. *mellifera* seedlings in grass sward. |
| **Bushy states 4 and 5** | These two states can be viewed as a continuum. |
| **State 4** | High density monostands of vigorously growing *S*. *mellifera* bushes with little grass cover. |
| **State 5** | Senescent (aging) stand of mature *S*. *mellifera* trees with a good herbaceous cover. |

**Appendix B: The catalogue of transitions for the proposed conceptual model regarding bush encroachment in the Highland savanna of Namibia (Joubert *et al*., 2008).**

| Transition | Description |
|---|---|
| **Transition 1 (from State 1 to State 2)** | Typical retrogressive succession in a grass dominated sward, promoted by excessive and continuous grazing, and drought periods. |
| **Transition 2 (from State 2 to State 1)** | Typical succession towards a climax state from a pioneer state in a grass dominated sward, promoted by high rainfall years and lenient grazing. The most important management practice would be to provide adequate rest to the grass sward. It occurs over many years and is not assured. Active management, including overseeding, may be necessary to speed up the transition to a time frame acceptable for resource managers. Few documented data are available regarding successional processes in the grass layer of the Highland Savanna. |
| **Transition 3 (from State 1 or 2 to State 3)** | Occurs with three consecutive years of high rainfall, for seed production, seedling survival and establishment of *S*. *mellifera*. |

**Appendix C: The catalogue of transitions for the proposed conceptual model regarding bush encroachment in the Highland savanna of Namibia (Joubert *et al*., 2008) (Continued).**

| Transition | Description |
|---|---|
| **Transition 4 (from State 3 to State 1)** | Caused by a fire hot enough to kill seedlings and young saplings of *S*. *mellifera*. There is a high probability of such a fire owing to the likely high grass biomass. |
| **Transition 5 (from State 3 to State 2)** | Has a low probability of occurring since the annual grass biomass may not be sufficient to sustain an effective fire. |
| **Transition 6 (from State 3 to State 4)** | Occurs in the absence of fire. Browsing by small herbivores may reduce the final density of the thicket. |
| **Transition 7 (from State 4 to State 5)** | A gradual almost deterministic successional process as trees grow, self-thin and eventually senesce. Can self-perpetuate through seed with three seasons of good rainfall (Transition 8) and, in exceptional rainfall years, may burn and revert to State 1 or 2 (Transition 10 or 11). |
| **Transition 8 (from State 5 to State 4)** | Occurs with two to three consecutive years of high rainfall, for seed production, seedling survival and establishment of *S*. *mellifera* within an existing thicket. It can be viewed as a cyclic self-perpetuation of the bushy state. |
| **Transition 9 (from State 5 to State 2)** | Triggered by the senescence of mature trees in the presence of poor grass cover and may occur in drought years. Dead branches act as a mulch and nursery for grass seedlings. |
| **Transition 10 (from state 5 to State 1)** | Triggered by the senescence of mature trees in the presence of high biomass of climax grass cover and may occur in good rainfall years. Dead branches act as a mulch and nursery for grass seedlings. There are a range of transitional variations depending upon the grass biomass existing under the senescing trees. Reseeding with climax grasses, as well as other interventions, may be necessary to ensure a transition to State 1. Transitions 9 and 10 are transitions back to the grassy state. |
| **Transition 11 (from State 4 to State 2)** | Has a low probability of occurring without intervention (stem burning, chopping and the application of arboricides). Sufficient grass biomass to allow a fierce fire to occur that kills some of the A. mellifera shrub might only occur under exceptional rainfall conditions. |

**Appendix D: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the North West Province (NWP) for time frame one (1993-1998).**

| | BE | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1 | 0.12 | 0 | 0 | 0.12 | 0.15 | 0.33 | 0.07 |
| **MAP** | 0.12 | 1 | 0 | 0 | 0.75 | 0.28 | 0.30 | 0.38 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.12 | 0.75 | 0 | 0 | 1 | 0.29 | 0.29 | 0.35 |
| **Land Types** | 0.15 | 0.28 | 0 | 0 | 0.29 | 1 | 0.28 | 0.35 |
| **Land Cover** | 0.33 | 0.30 | 0 | 0 | 0.29 | 0.28 | 1 | 0.11 |
| **Geology** | 0.07 | 0.38 | 0 | 0 | 0.35 | 0.35 | 0.11 | 1 |

**Appendix E: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the North West Province (NWP) for time frame two (1998-2018).**

| | BE | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1 | 0.19 | 0 | 0 | 0.19 | 0.15 | 0.37 | 0.08 |
| **MAP** | 0.19 | 1 | 0 | 0 | 0.73 | 0.34 | 0.32 | 0.38 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.19 | 0.73 | 0 | 0 | 1 | 0.30 | 0.22 | 0.32 |
| **Land Types** | 0.15 | 0.34 | 0 | 0 | 0.30 | 1 | 0.33 | 0.37 |
| **Land Cover** | 0.37 | 0.32 | 0 | 0 | 0.22 | 0.33 | 1 | 0.13 |
| **Geology** | 0.08 | 0.38 | 0 | 0 | 0.32 | 0.37 | 0.13 | 1 |

**Appendix F: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the North West Province (NWP) for time frame three (1993-2018).**

| | BE | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1 | 0.10 | 0 | 0 | 0.10 | 0.12 | 0.29 | 0.04 |
| **MAP** | 0.10 | 1 | 0 | 0 | 0.74 | 0.31 | 0.28 | 0.37 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.10 | 0.74 | 0 | 0 | 1 | 0.29 | 0.23 | 0.33 |
| **Land Types** | 0.12 | 0.31 | 0 | 0 | 0.29 | 0 | 0.28 | 0.54 |
| **Land Cover** | 0.29 | 0.28 | 0 | 0 | 0.23 | 0.28 | 1 | 0.11 |
| **Geology** | 0.04 | 0.37 | 0 | 0 | 0.33 | 0.54 | 0.11 | 1 |

**Appendix G: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the North West Province (NWP) for time frame one (1993-1998).**

| | BL | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1 | 0.08 | 0 | 0 | 0.14 | 0.12 | 0.07 | 0.04 |
| **MAP** | 0.08 | 1 | 0 | 0 | 0.74 | 0.45 | 0.31 | 0.37 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.14 | 0.74 | 0 | 0 | 1 | 0.60 | 0.30 | 0.52 |
| **Land Types** | 0.12 | 0.45 | 0 | 0 | 0.6 | 1 | 0.40 | 0.26 |
| **Land Cover** | 0.07 | 0.31 | 0 | 0 | 0.30 | 0.40 | 1 | 0.17 |
| **Geology** | 0.04 | 0.37 | 0 | 0 | 0.52 | 0.26 | 0.17 | 1 |

**Appendix H: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the North West Province (NWP) for time frame two (1998-2018).**

| | BL | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1 | 0.21 | 0 | 0 | 0.25 | 0.24 | 0.13 | 0.12 |
| **MAP** | 0.21 | 1 | 0 | 0 | 0.75 | 0.41 | 0.33 | 0.38 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.25 | 0.75 | 0 | 0 | 1 | 0.59 | 0.37 | 0.36 |
| **Land Types** | 0.24 | 0.41 | 0 | 0 | 0.59 | 1 | 0.37 | 0.26 |
| **Land Cover** | 0.13 | 0.33 | 0 | 0 | 0.37 | 0.37 | 1 | 0.18 |
| **Geology** | 0.12 | 0.38 | 0 | 0 | 0.36 | 0.26 | 0.18 | 1 |

**Appendix I: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the North West Province (NWP) for time frame three (1993-2018).**

| | BL | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1 | 0.15 | 0 | 0 | 0.19 | 0.13 | 0.09 | 0.07 |
| **MAP** | 0.15 | 1 | 0 | 0 | 0.75 | 0.45 | 0.35 | 0.42 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.19 | 0.75 | 0 | 0 | 1 | 0.63 | 0.38 | 0.36 |
| **Land Types** | 0.13 | 0.45 | 0 | 0 | 0.63 | 1 | 0.41 | 0.24 |
| **Land Cover** | 0.09 | 0.35 | 0 | 0 | 0.38 | 0.41 | 1 | 0.21 |
| **Geology** | 0.07 | 0.42 | 0 | 0 | 0.36 | 0.24 | 0.21 | 1 |

**Appendix J: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the North West Province (NWP) for time frame one (1993-1998).**

| | NC | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1 | 0.03 | 0 | 0 | 0.03 | 0.05 | 0.04 | 0.01 |
| **MAP** | 0.03 | 1 | 0 | 0 | 0.74 | 0.42 | 0.31 | 0.41 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.03 | 0.74 | 0 | 0 | 1 | 0.57 | 0.30 | 0.34 |
| **Land Types** | 0.05 | 0.42 | 0 | 0 | 0.57 | 1 | 0.35 | 0.26 |
| **Land Cover** | 0.04 | 0.31 | 0 | 0 | 0.30 | 0.35 | 1 | 0.14 |
| **Geology** | 0.01 | 0.41 | 0 | 0 | 0.34 | 0.26 | 0.14 | 1 |

**Appendix K: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the North West Province (NWP) for time frame two (1998-2018).**

| | NC | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1 | 0.04 | 0 | 0 | 0.03 | 0.04 | 0.03 | 0.02 |
| **MAP** | 0.04 | 1 | 0 | 0 | 0.74 | 0.42 | 0.33 | 0.43 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.03 | 0.74 | 0 | 0 | 1 | 0.60 | 0.36 | 0.53 |
| **Land Types** | 0.04 | 0.42 | 0 | 0 | 0.60 | 1 | 0.37 | 0.41 |
| **Land Cover** | 0.03 | 0.33 | 0 | 0 | 0.36 | 0.37 | 1 | 0.16 |
| **Geology** | 0.02 | 0.43 | 0 | 0 | 0.53 | 0.41 | 0.16 | 1 |

**Appendix L: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the North West Province (NWP) for time frame three (1993-2018).**

| | NC | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1 | 0.02 | 0 | 0 | 0.02 | 0.05 | 0.02 | 0.02 |
| **MAP** | 0.02 | 1 | 0 | 0 | 0.74 | 0.44 | 0.32 | 0.38 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.02 | 0.74 | 0 | 0 | 1 | 0.60 | 0.35 | 0.35 |
| **Land Types** | 0.05 | 0.44 | 0 | 0 | 0.60 | 1 | 0.38 | 0.27 |
| **Land Cover** | 0.02 | 0.32 | 0 | 0 | 0.35 | 0.38 | 1 | 0.15 |
| **Geology** | 0.02 | 0.38 | 0 | 0 | 0.35 | 0.27 | 0.15 | 1 |

**Appendix M: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the North West Province (NWP) for time frame one (1993-1998).**

| | BT | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1 | 0.45 | 0 | 0 | 0.43 | 0.22 | 0.17 | 0.19 |
| **MAP** | 0.45 | 1 | 0 | 0 | 0.73 | 0.38 | 0.31 | 0.37 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.43 | 0.73 | 0 | 0 | 1 | 0.52 | 0.32 | 0.34 |
| **Land Types** | 0.22 | 0.38 | 0 | 0 | 0.52 | 1 | 0.26 | 0.25 |
| **Land Cover** | 0.17 | 0.31 | 0 | 0 | 0.32 | 0.26 | 1 | 0.16 |
| **Geology** | 0.19 | 0.37 | 0 | 0 | 0.34 | 0.25 | 0.16 | 1 |

**Appendix N: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the North West Province (NWP) for time frame two (1998-2018).**

| | BT | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1 | 0.45 | 0 | 0 | 0.44 | 0.23 | 0.15 | 0.20 |
| **MAP** | 0.45 | 1 | 0 | 0 | 0.73 | 0.41 | 0.28 | 0.35 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.44 | 0.73 | 0 | 0 | 1 | 0.54 | 0.28 | 0.32 |
| **Land Types** | 0.23 | 0.41 | 0 | 0 | 0.54 | 1 | 0.24 | 0.32 |
| **Land Cover** | 0.15 | 0.28 | 0 | 0 | 0.28 | 0.24 | 1 | 0.10 |
| **Geology** | 0.20 | 0.35 | 0 | 0 | 0.32 | 0.32 | 0.10 | 1 |

**Appendix O: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the North West Province (NWP) for time frame three (1993-2018).**

| | BT | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1 | 0.46 | 0 | 0 | 0.45 | 0.24 | 0.16 | 0.21 |
| **MAP** | 0.46 | 1 | 0 | 0 | 0.74 | 0.39 | 0.27 | 0.37 |
| **MAT** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Topography** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Bioregions** | 0.45 | 0.74 | 0 | 0 | 1 | 0.52 | 0.26 | 0.34 |
| **Land Types** | 0.24 | 0.39 | 0 | 0 | 0.52 | 1 | 0.26 | 0.24 |
| **Land Cover** | 0.16 | 0.27 | 0 | 0 | 0.26 | 0.26 | 1 | 0.12 |
| **Geology** | 0.21 | 0.37 | 0 | 0 | 0.34 | 0.24 | 0.12 | 1 |

**Appendix P: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Taung area for time frame one (1993-1998).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.14 | 0.18 | 0.17 | 0.23 | 0.27 | 0.23 | 0.17 |
| **MAP** | 0.14 | 1.00 | 0.81 | 0.81 | 0.50 | 0.52 | 0.22 | 0.75 |
| **MAT** | 0.18 | 0.81 | 1.00 | 0.95 | 0.65 | 0.62 | 0.38 | 0.90 |
| **Topography** | 0.17 | 0.81 | 0.95 | 1.00 | 0.62 | 0.64 | 0.36 | 0.90 |
| **Vegetation units** | 0.23 | 0.50 | 0.65 | 0.62 | 1.00 | 0.54 | 0.51 | 0.39 |
| **Land Types** | 0.27 | 0.52 | 0.62 | 0.64 | 0.54 | 1.00 | 0.49 | 0.30 |
| **Land Cover** | 0.23 | 0.22 | 0.38 | 0.36 | 0.51 | 0.49 | 1.00 | 0.21 |
| **Geology** | 0.17 | 0.75 | 0.90 | 0.90 | 0.39 | 0.30 | 0.21 | 1.00 |

**Appendix Q: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Taung area for time frame two (1998-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.26 | 0.28 | 0.27 | 0.43 | 0.40 | 0.34 | 0.22 |
| **MAP** | 0.26 | 1.00 | 0.80 | 0.80 | 0.58 | 0.49 | 0.25 | 0.76 |
| **MAT** | 0.28 | 0.80 | 1.00 | 0.95 | 0.72 | 0.57 | 0.37 | 0.88 |
| **Topography** | 0.27 | 0.80 | 0.95 | 1.00 | 0.70 | 0.61 | 0.38 | 0.88 |
| **Vegetation units** | 0.43 | 0.58 | 0.72 | 0.70 | 1.00 | 0.54 | 0.59 | 0.50 |
| **Land Types** | 0.40 | 0.49 | 0.57 | 0.61 | 0.54 | 1.00 | 0.52 | 0.20 |
| **Land Cover** | 0.34 | 0.25 | 0.37 | 0.38 | 0.59 | 0.52 | 1.00 | 0.16 |
| **Geology** | 0.22 | 0.76 | 0.88 | 0.88 | 0.50 | 0.20 | 0.16 | 1.00 |

**Appendix R: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Taung area for time frame three (1993-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.16 | 0.21 | 0.20 | 0.31 | 0.47 | 0.23 | 0.11 |
| **MAP** | 0.16 | 1.00 | 0.80 | 0.80 | 0.53 | 0.50 | 0.24 | 0.74 |
| **MAT** | 0.21 | 0.80 | 1.00 | 0.95 | 0.66 | 0.60 | 0.37 | 0.89 |
| **Topography** | 0.20 | 0.80 | 0.95 | 1.00 | 0.63 | 0.62 | 0.36 | 0.89 |
| **Vegetation units** | 0.31 | 0.53 | 0.66 | 0.63 | 1.00 | 0.55 | 0.56 | 0.38 |
| **Land Types** | 0.47 | 0.50 | 0.60 | 0.62 | 0.55 | 1.00 | 0.52 | 0.25 |
| **Land Cover** | 0.23 | 0.24 | 0.37 | 0.36 | 0.56 | 0.52 | 1.00 | 0.19 |
| **Geology** | 0.11 | 0.74 | 0.89 | 0.89 | 0.38 | 0.25 | 0.19 | 1.00 |

**Appendix S: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Taung area for time frame one (1993-1998).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.22 | 0.25 | 0.26 | 0.36 | 0.13 | 0.15 | 0.21 |
| **MAP** | 0.22 | 1.00 | 0.84 | 0.87 | 0.77 | 0.56 | 0.31 | 0.83 |
| **MAT** | 0.25 | 0.84 | 1.00 | 0.94 | 0.81 | 0.62 | 0.38 | 0.86 |
| **Topography** | 0.26 | 0.87 | 0.94 | 1.00 | 0.82 | 0.63 | 0.38 | 0.87 |
| **Vegetation units** | 0.36 | 0.77 | 0.81 | 0.82 | 1.00 | 0.42 | 0.49 | 0.73 |
| **Land Types** | 0.13 | 0.56 | 0.62 | 0.63 | 0.42 | 1.00 | 0.48 | 0.28 |
| **Land Cover** | 0.15 | 0.31 | 0.38 | 0.38 | 0.49 | 0.48 | 1.00 | 0.30 |
| **Geology** | 0.21 | 0.83 | 0.86 | 0.87 | 0.73 | 0.28 | 0.30 | 1.00 |

**Appendix T: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Taung area for time frame two (1998-2018).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.12 | 0.10 | 0.11 | 0.13 | 0.10 | 0.12 | 0.10 |
| **MAP** | 0.12 | 1.00 | 0.81 | 0.85 | 0.63 | 0.63 | 0.31 | 0.79 |
| **MAT** | 0.10 | 0.81 | 1.00 | 0.93 | 0.72 | 0.64 | 0.38 | 0.83 |
| **Topography** | 0.11 | 0.85 | 0.93 | 1.00 | 0.71 | 0.66 | 0.35 | 0.84 |
| **Vegetation units** | 0.13 | 0.63 | 0.72 | 0.71 | 1.00 | 0.44 | 0.43 | 0.57 |
| **Land Types** | 0.10 | 0.63 | 0.64 | 0.66 | 0.44 | 1.00 | 0.43 | 0.37 |
| **Land Cover** | 0.12 | 0.31 | 0.38 | 0.35 | 0.43 | 0.43 | 1.00 | 0.30 |
| **Geology** | 0.10 | 0.79 | 0.83 | 0.84 | 0.57 | 0.37 | 0.30 | 1.00 |

**Appendix U: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Taung area for time frame three (1993-2018).**

| | BL | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.15 | 0.17 | 0.18 | 0.25 | 0.14 | 0.15 | 0.24 |
| **MAP** | 0.15 | 1.00 | 0.83 | 0.86 | 0.70 | 0.62 | 0.28 | 0.78 |
| **MAT** | 0.17 | 0.83 | 1.00 | 0.95 | 0.81 | 0.65 | 0.40 | 0.81 |
| **Topography** | 0.18 | 0.86 | 0.95 | 1.00 | 0.80 | 0.67 | 0.36 | 0.82 |
| **Bioregions** | 0.25 | 0.70 | 0.81 | 0.80 | 1.00 | 0.40 | 0.50 | 0.70 |
| **Land Types** | 0.14 | 0.62 | 0.65 | 0.67 | 0.40 | 1.00 | 0.46 | 0.32 |
| **Land Cover** | 0.15 | 0.28 | 0.40 | 0.36 | 0.50 | 0.46 | 1.00 | 0.26 |
| **Geology** | 0.24 | 0.78 | 0.81 | 0.82 | 0.70 | 0.32 | 0.26 | 1.00 |

**Appendix V: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Taung area for time frame one (1993-1998).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.05 | 0.05 | 0.05 | 0.07 | 0.11 | 0.04 | 0.06 |
| **MAP** | 0.05 | 1.00 | 0.82 | 0.84 | 0.74 | 0.56 | 0.30 | 0.79 |
| **MAT** | 0.05 | 0.82 | 1.00 | 0.93 | 0.76 | 0.61 | 0.38 | 0.86 |
| **Topography** | 0.05 | 0.84 | 0.93 | 1.00 | 0.77 | 0.63 | 0.37 | 0.86 |
| **Vegetation units** | 0.07 | 0.74 | 0.76 | 0.77 | 1.00 | 0.50 | 0.57 | 0.63 |
| **Land Types** | 0.11 | 0.56 | 0.61 | 0.63 | 0.50 | 1.00 | 0.49 | 0.25 |
| **Land Cover** | 0.04 | 0.30 | 0.38 | 0.37 | 0.57 | 0.49 | 1.00 | 0.27 |
| **Geology** | 0.06 | 0.79 | 0.86 | 0.86 | 0.63 | 0.25 | 0.27 | 1.00 |

**Appendix W: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Taung area for time frame two (1998-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.04 | 0.04 | 0.06 | 0.04 | 0.05 | 0.10 | 0.04 |
| **MAP** | 0.04 | 1.00 | 0.82 | 0.83 | 0.72 | 0.55 | 0.31 | 0.77 |
| **MAT** | 0.04 | 0.82 | 1.00 | 0.93 | 0.75 | 0.64 | 0.43 | 0.85 |
| **Topography** | 0.06 | 0.83 | 0.93 | 1.00 | 0.75 | 0.64 | 0.42 | 0.85 |
| **Vegetation units** | 0.04 | 0.72 | 0.75 | 0.75 | 1.00 | 0.50 | 0.57 | 0.61 |
| **Land Types** | 0.05 | 0.55 | 0.64 | 0.64 | 0.50 | 1.00 | 0.50 | 0.25 |
| **Land Cover** | 0.10 | 0.31 | 0.43 | 0.42 | 0.57 | 0.50 | 1.00 | 0.35 |
| **Geology** | 0.04 | 0.77 | 0.85 | 0.85 | 0.61 | 0.25 | 0.35 | 1.00 |

**Appendix X: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Taung area for time frame three (1993-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.07 | 0.07 | 0.06 | 0.06 | 0.08 | 0.03 | 0.08 |
| **MAP** | 0.07 | 1.00 | 0.83 | 0.86 | 0.77 | 0.56 | 0.34 | 0.80 |
| **MAT** | 0.07 | 0.83 | 1.00 | 0.94 | 0.79 | 0.62 | 0.44 | 0.85 |
| **Topography** | 0.06 | 0.86 | 0.94 | 1.00 | 0.78 | 0.62 | 0.41 | 0.86 |
| **Vegetation units** | 0.06 | 0.77 | 0.79 | 0.78 | 1.00 | 0.46 | 0.59 | 0.69 |
| **Land Types** | 0.08 | 0.56 | 0.62 | 0.62 | 0.46 | 1.00 | 0.50 | 0.24 |
| **Land Cover** | 0.03 | 0.34 | 0.44 | 0.41 | 0.59 | 0.50 | 1.00 | 0.35 |
| **Geology** | 0.08 | 0.80 | 0.85 | 0.86 | 0.69 | 0.24 | 0.35 | 1.00 |

**Appendix Y: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Taung area for time frame one (1993-1998).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.19 | 0.22 | 0.20 | 0.22 | 0.25 | 0.25 | 0.09 |
| **MAP** | 0.19 | 1.00 | 0.82 | 0.84 | 0.65 | 0.62 | 0.43 | 0.78 |
| **MAT** | 0.22 | 0.82 | 1.00 | 0.91 | 0.71 | 0.65 | 0.44 | 0.84 |
| **Topography** | 0.20 | 0.84 | 0.91 | 1.00 | 0.71 | 0.65 | 0.47 | 0.85 |
| **Vegetation units** | 0.22 | 0.65 | 0.71 | 0.71 | 1.00 | 0.47 | 0.35 | 0.48 |
| **Land Types** | 0.25 | 0.62 | 0.65 | 0.65 | 0.47 | 1.00 | 0.38 | 0.39 |
| **Land Cover** | 0.25 | 0.43 | 0.44 | 0.47 | 0.35 | 0.38 | 1.00 | 0.49 |
| **Geology** | 0.09 | 0.78 | 0.84 | 0.85 | 0.48 | 0.39 | 0.49 | 1.00 |

**Appendix Z: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Taung area for time frame two (1998-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.20 | 0.24 | 0.22 | 0.17 | 0.41 | 0.21 | 0.14 |
| **MAP** | 0.20 | 1.00 | 0.83 | 0.86 | 0.61 | 0.60 | 0.37 | 0.80 |
| **MAT** | 0.24 | 0.83 | 1.00 | 0.92 | 0.65 | 0.64 | 0.39 | 0.87 |
| **Topography** | 0.22 | 0.86 | 0.92 | 1.00 | 0.68 | 0.65 | 0.41 | 0.88 |
| **Vegetation units** | 0.17 | 0.61 | 0.65 | 0.68 | 1.00 | 0.45 | 0.26 | 0.49 |
| **Land Types** | 0.41 | 0.60 | 0.64 | 0.65 | 0.45 | 1.00 | 0.40 | 0.41 |
| **Land Cover** | 0.21 | 0.37 | 0.39 | 0.41 | 0.26 | 0.40 | 1.00 | 0.45 |
| **Geology** | 0.14 | 0.80 | 0.87 | 0.88 | 0.49 | 0.41 | 0.45 | 1.00 |

**Appendix AA: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Taung area for time frame three (1993-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.18 | 0.15 | 0.17 | 0.07 | 0.19 | 0.39 | 0.17 |
| **MAP** | 0.18 | 1.00 | 0.83 | 0.85 | 0.62 | 0.61 | 0.42 | 0.80 |
| **MAT** | 0.15 | 0.83 | 1.00 | 0.91 | 0.67 | 0.64 | 0.43 | 0.87 |
| **Topography** | 0.17 | 0.85 | 0.91 | 1.00 | 0.69 | 0.65 | 0.46 | 0.87 |
| **Vegetation units** | 0.07 | 0.62 | 0.67 | 0.69 | 1.00 | 0.46 | 0.33 | 0.49 |
| **Land Types** | 0.19 | 0.61 | 0.64 | 0.65 | 0.46 | 1.00 | 0.39 | 0.39 |
| **Land Cover** | 0.39 | 0.42 | 0.43 | 0.46 | 0.33 | 0.39 | 1.00 | 0.50 |
| **Geology** | 0.17 | 0.80 | 0.87 | 0.87 | 0.49 | 0.39 | 0.50 | 1.00 |

**Appendix BB: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Mafikeng area for time frame one (1993-1998).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.16 | 0.17 | 0.18 | 0.21 | 0.28 | 0.28 | 0.07 |
| **MAP** | 0.16 | 1.00 | 0.81 | 0.62 | 0.63 | 0.47 | 0.20 | 0.38 |
| **MAT** | 0.17 | 0.81 | 1.00 | 0.91 | 0.88 | 0.70 | 0.27 | 0.68 |
| **Topography** | 0.18 | 0.62 | 0.91 | 1.00 | 0.64 | 0.66 | 0.27 | 0.71 |
| **Vegetation units** | 0.21 | 0.63 | 0.88 | 0.64 | 1.00 | 0.91 | 0.28 | 0.44 |
| **Land Types** | 0.28 | 0.47 | 0.70 | 0.66 | 0.91 | 1.00 | 0.34 | 0.17 |
| **Land Cover** | 0.28 | 0.20 | 0.27 | 0.27 | 0.28 | 0.34 | 1.00 | 0.28 |
| **Geology** | 0.07 | 0.38 | 0.68 | 0.71 | 0.44 | 0.17 | 0.28 | 1.00 |

**Appendix CC: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Mafikeng area for time frame two (1998-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.16 | 0.23 | 0.21 | 0.30 | 0.36 | 0.30 | 0.13 |
| **MAP** | 0.16 | 1.00 | 0.73 | 0.54 | 0.66 | 0.53 | 0.14 | 0.47 |
| **MAT** | 0.23 | 0.73 | 1.00 | 0.91 | 0.89 | 0.73 | 0.18 | 0.75 |
| **Topography** | 0.21 | 0.54 | 0.91 | 1.00 | 0.68 | 0.73 | 0.21 | 0.81 |
| **Vegetation units** | 0.30 | 0.66 | 0.89 | 0.68 | 1.00 | 0.91 | 0.26 | 0.43 |
| **Land Types** | 0.36 | 0.53 | 0.73 | 0.73 | 0.91 | 1.00 | 0.34 | 0.28 |
| **Land Cover** | 0.30 | 0.14 | 0.18 | 0.21 | 0.26 | 0.34 | 1.00 | 0.15 |
| **Geology** | 0.13 | 0.47 | 0.75 | 0.81 | 0.43 | 0.28 | 0.15 | 1.00 |

**Appendix DD: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Mafikeng area for time frame three (1993-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.16 | 0.22 | 0.21 | 0.27 | 0.26 | 0.32 | 0.10 |
| **MAP** | 0.16 | 1.00 | 0.80 | 0.60 | 0.67 | 0.52 | 0.19 | 0.43 |
| **MAT** | 0.22 | 0.80 | 1.00 | 0.91 | 0.89 | 0.72 | 0.22 | 0.72 |
| **Topography** | 0.21 | 0.60 | 0.91 | 1.00 | 0.66 | 0.68 | 0.22 | 0.75 |
| **Vegetation units** | 0.27 | 0.67 | 0.89 | 0.66 | 1.00 | 0.91 | 0.27 | 0.44 |
| **Land Types** | 0.26 | 0.52 | 0.72 | 0.68 | 0.91 | 1.00 | 0.34 | 0.21 |
| **Land Cover** | 0.32 | 0.19 | 0.22 | 0.22 | 0.27 | 0.34 | 1.00 | 0.18 |
| **Geology** | 0.10 | 0.43 | 0.72 | 0.75 | 0.44 | 0.21 | 0.18 | 1.00 |

**Appendix EE: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Mafikeng area for time frame one (1993-1998).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.06 | 0.16 | 0.15 | 0.13 | 0.13 | 0.14 | 0.09 |
| **MAP** | 0.06 | 1.00 | 0.66 | 0.52 | 0.59 | 0.46 | 0.20 | 0.43 |
| **MAT** | 0.16 | 0.66 | 1.00 | 0.92 | 0.89 | 0.72 | 0.25 | 0.74 |
| **Topography** | 0.15 | 0.52 | 0.92 | 1.00 | 0.85 | 0.79 | 0.26 | 0.80 |
| **Vegetation units** | 0.13 | 0.59 | 0.89 | 0.85 | 1.00 | 0.90 | 0.32 | 0.52 |
| **Land Types** | 0.13 | 0.46 | 0.72 | 0.79 | 0.90 | 1.00 | 0.42 | 0.27 |
| **Land Cover** | 0.14 | 0.20 | 0.25 | 0.26 | 0.32 | 0.42 | 1.00 | 0.13 |
| **Geology** | 0.09 | 0.43 | 0.74 | 0.80 | 0.52 | 0.27 | 0.13 | 1.00 |

**Appendix FF: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Mafikeng area for time frame two (1998-2018).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.13 | 0.17 | 0.19 | 0.17 | 0.14 | 0.11 | 0.04 |
| **MAP** | 0.13 | 1.00 | 0.72 | 0.64 | 0.57 | 0.48 | 0.41 | 0.36 |
| **MAT** | 0.17 | 0.72 | 1.00 | 0.92 | 0.78 | 0.64 | 0.32 | 0.50 |
| **Topography** | 0.19 | 0.64 | 0.92 | 1.00 | 0.73 | 0.74 | 0.34 | 0.66 |
| **Vegetation units** | 0.17 | 0.57 | 0.78 | 0.73 | 1.00 | 0.88 | 0.31 | 0.48 |
| **Land Types** | 0.14 | 0.48 | 0.64 | 0.74 | 0.88 | 1.00 | 0.46 | 0.18 |
| **Land Cover** | 0.11 | 0.41 | 0.32 | 0.34 | 0.31 | 0.46 | 1.00 | 0.24 |
| **Geology** | 0.04 | 0.36 | 0.50 | 0.66 | 0.48 | 0.18 | 0.24 | 1.00 |

**Appendix GG: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Mafikeng area for time frame three (1993-2018).**

| | BL | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.10 | 0.22 | 0.28 | 0.22 | 0.11 | 0.09 | 0.14 |
| **MAP** | 0.10 | 1.00 | 0.64 | 0.58 | 0.60 | 0.46 | 0.33 | 0.36 |
| **MAT** | 0.22 | 0.64 | 1.00 | 0.92 | 0.86 | 0.68 | 0.27 | 0.66 |
| **Topography** | 0.28 | 0.58 | 0.92 | 1.00 | 0.82 | 0.79 | 0.30 | 0.76 |
| **Bioregions** | 0.22 | 0.60 | 0.86 | 0.82 | 1.00 | 0.89 | 0.35 | 0.46 |
| **Land Types** | 0.11 | 0.46 | 0.68 | 0.79 | 0.89 | 1.00 | 0.46 | 0.24 |
| **Land Cover** | 0.09 | 0.33 | 0.27 | 0.30 | 0.35 | 0.46 | 1.00 | 0.11 |
| **Geology** | 0.14 | 0.36 | 0.66 | 0.76 | 0.46 | 0.24 | 0.11 | 1.00 |

**Appendix HH: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Mafikeng area for time frame one (1993-1998).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.05 | 0.04 | 0.06 | 0.07 | 0.05 | 0.03 | 0.05 |
| **MAP** | 0.05 | 1.00 | 0.71 | 0.56 | 0.66 | 0.52 | 0.26 | 0.41 |
| **MAT** | 0.04 | 0.71 | 1.00 | 0.91 | 0.88 | 0.72 | 0.21 | 0.69 |
| **Topography** | 0.06 | 0.56 | 0.91 | 1.00 | 0.83 | 0.76 | 0.22 | 0.75 |
| **Vegetation units** | 0.07 | 0.66 | 0.88 | 0.83 | 1.00 | 0.90 | 0.29 | 0.46 |
| **Land Types** | 0.05 | 0.52 | 0.72 | 0.76 | 0.90 | 1.00 | 0.38 | 0.24 |
| **Land Cover** | 0.03 | 0.26 | 0.21 | 0.22 | 0.29 | 0.38 | 1.00 | 0.10 |
| **Geology** | 0.05 | 0.41 | 0.69 | 0.75 | 0.46 | 0.24 | 0.10 | 1.00 |

**Appendix II: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Mafikeng area for time frame two (1998-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.05 | 0.04 | 0.05 | 0.07 | 0.06 | 0.05 | 0.04 |
| **MAP** | 0.05 | 1.00 | 0.68 | 0.58 | 0.64 | 0.50 | 0.33 | 0.37 |
| **MAT** | 0.04 | 0.68 | 1.00 | 0.92 | 0.85 | 0.70 | 0.25 | 0.63 |
| **Topography** | 0.05 | 0.58 | 0.92 | 1.00 | 0.80 | 0.76 | 0.27 | 0.73 |
| **Vegetation units** | 0.07 | 0.64 | 0.85 | 0.80 | 1.00 | 0.89 | 0.31 | 0.44 |
| **Land Types** | 0.06 | 0.50 | 0.70 | 0.76 | 0.89 | 1.00 | 0.43 | 0.25 |
| **Land Cover** | 0.05 | 0.33 | 0.25 | 0.27 | 0.31 | 0.43 | 1.00 | 0.18 |
| **Geology** | 0.04 | 0.37 | 0.63 | 0.73 | 0.44 | 0.25 | 0.18 | 1.00 |

**Appendix JJ: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Mafikeng area for time frame three (1993-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 | 0.02 | 0.04 |
| **MAP** | 0.03 | 1.00 | 0.67 | 0.56 | 0.64 | 0.50 | 0.31 | 0.40 |
| **MAT** | 0.02 | 0.67 | 1.00 | 0.92 | 0.86 | 0.70 | 0.22 | 0.69 |
| **Topography** | 0.03 | 0.56 | 0.92 | 1.00 | 0.82 | 0.78 | 0.25 | 0.75 |
| **Vegetation units** | 0.03 | 0.64 | 0.86 | 0.82 | 1.00 | 0.90 | 0.31 | 0.46 |
| **Land Types** | 0.03 | 0.50 | 0.70 | 0.78 | 0.90 | 1.00 | 0.43 | 0.24 |
| **Land Cover** | 0.02 | 0.31 | 0.22 | 0.25 | 0.31 | 0.43 | 1.00 | 0.13 |
| **Geology** | 0.04 | 0.40 | 0.69 | 0.75 | 0.46 | 0.24 | 0.13 | 1.00 |

**Appendix KK: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Mafikeng area for time frame one (1993-1998).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.28 | 0.32 | 0.34 | 0.18 | 0.29 | 0.23 | 0.31 |
| **MAP** | 0.28 | 1.00 | 0.73 | 0.65 | 0.45 | 0.42 | 0.40 | 0.47 |
| **MAT** | 0.32 | 0.73 | 1.00 | 0.91 | 0.74 | 0.62 | 0.37 | 0.64 |
| **Topography** | 0.34 | 0.65 | 0.91 | 1.00 | 0.73 | 0.73 | 0.41 | 0.81 |
| **Vegetation units** | 0.18 | 0.45 | 0.74 | 0.73 | 1.00 | 0.87 | 0.24 | 0.64 |
| **Land Types** | 0.29 | 0.42 | 0.62 | 0.73 | 0.87 | 1.00 | 0.36 | 0.31 |
| **Land Cover** | 0.23 | 0.40 | 0.37 | 0.41 | 0.24 | 0.36 | 1.00 | 0.34 |
| **Geology** | 0.31 | 0.47 | 0.64 | 0.81 | 0.64 | 0.31 | 0.34 | 1.00 |

**Appendix LL: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Mafikeng area for time frame two (1998-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.15 | 0.25 | 0.33 | 0.22 | 0.29 | 0.36 | 0.41 |
| **MAP** | 0.15 | 1.00 | 0.71 | 0.59 | 0.48 | 0.38 | 0.25 | 0.42 |
| **MAT** | 0.25 | 0.71 | 1.00 | 0.91 | 0.84 | 0.68 | 0.25 | 0.67 |
| **Topography** | 0.33 | 0.59 | 0.91 | 1.00 | 0.80 | 0.76 | 0.26 | 0.79 |
| **Vegetation units** | 0.22 | 0.48 | 0.84 | 0.80 | 1.00 | 0.90 | 0.24 | 0.54 |
| **Land Types** | 0.29 | 0.38 | 0.68 | 0.76 | 0.90 | 1.00 | 0.30 | 0.30 |
| **Land Cover** | 0.36 | 0.25 | 0.25 | 0.26 | 0.24 | 0.30 | 1.00 | 0.25 |
| **Geology** | 0.41 | 0.42 | 0.67 | 0.79 | 0.54 | 0.30 | 0.25 | 1.00 |

**Appendix MM: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Mafikeng area for time frame three (1993-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.09 | 0.18 | 0.20 | 0.22 | 0.20 | 0.30 | 0.19 |
| **MAP** | 0.09 | 1.00 | 0.69 | 0.57 | 0.53 | 0.44 | 0.30 | 0.41 |
| **MAT** | 0.18 | 0.69 | 1.00 | 0.91 | 0.84 | 0.69 | 0.26 | 0.71 |
| **Topography** | 0.20 | 0.57 | 0.91 | 1.00 | 0.82 | 0.76 | 0.26 | 0.82 |
| **Vegetation units** | 0.22 | 0.53 | 0.84 | 0.82 | 1.00 | 0.90 | 0.26 | 0.59 |
| **Land Types** | 0.20 | 0.44 | 0.69 | 0.76 | 0.90 | 1.00 | 0.35 | 0.30 |
| **Land Cover** | 0.30 | 0.30 | 0.26 | 0.26 | 0.26 | 0.35 | 1.00 | 0.21 |
| **Geology** | 0.19 | 0.41 | 0.71 | 0.82 | 0.59 | 0.30 | 0.21 | 1.00 |

**Appendix NN: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Pilanesberg area for time frame one (1993-1998).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.17 | 0.18 | 0.16 | 0.25 | 0.05 | 0.17 | 0.08 |
| **MAP** | 0.17 | 1.00 | 0.94 | 0.84 | 0.96 | 0.86 | 0.61 | 0.74 |
| **MAT** | 0.18 | 0.94 | 1.00 | 0.91 | 0.96 | 0.82 | 0.70 | 0.74 |
| **Topography** | 0.16 | 0.84 | 0.91 | 1.00 | 0.93 | 0.79 | 0.61 | 0.76 |
| **Vegetation units** | 0.25 | 0.96 | 0.96 | 0.93 | 1.00 | 0.55 | 0.91 | 0.75 |
| **Land Types** | 0.05 | 0.86 | 0.82 | 0.79 | 0.55 | 1.00 | 0.49 | 0.98 |
| **Land Cover** | 0.17 | 0.61 | 0.70 | 0.61 | 0.91 | 0.49 | 1.00 | 0.53 |
| **Geology** | 0.08 | 0.74 | 0.74 | 0.76 | 0.75 | 0.98 | 0.53 | 1.00 |

**Appendix OO: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Pilanesberg area for time frame two (1998-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.19 | 0.20 | 0.21 | 0.22 | 0.19 | 0.25 | 0.32 |
| **MAP** | 0.19 | 1.00 | 0.92 | 0.84 | 0.74 | 0.80 | 0.69 | 0.75 |
| **MAT** | 0.20 | 0.92 | 1.00 | 0.85 | 0.83 | 0.74 | 0.66 | 0.68 |
| **Topography** | 0.21 | 0.84 | 0.85 | 1.00 | 0.83 | 0.75 | 0.60 | 0.63 |
| **Vegetation units** | 0.22 | 0.74 | 0.83 | 0.83 | 1.00 | 0.54 | 0.62 | 0.54 |
| **Land Types** | 0.19 | 0.80 | 0.74 | 0.75 | 0.54 | 1.00 | 0.74 | 0.93 |
| **Land Cover** | 0.25 | 0.69 | 0.66 | 0.60 | 0.62 | 0.74 | 1.00 | 0.68 |
| **Geology** | 0.32 | 0.75 | 0.68 | 0.63 | 0.54 | 0.93 | 0.68 | 1.00 |

**Appendix PP: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Pilanesberg area for time frame three (1993-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.20 | 0.21 | 0.20 | 0.15 | 0.17 | 0.15 | 0.08 |
| **MAP** | 0.20 | 1.00 | 0.93 | 0.84 | 0.95 | 0.86 | 0.61 | 0.74 |
| **MAT** | 0.21 | 0.93 | 1.00 | 0.91 | 0.95 | 0.81 | 0.69 | 0.73 |
| **Topography** | 0.20 | 0.84 | 0.91 | 1.00 | 0.93 | 0.79 | 0.61 | 0.76 |
| **Vegetation units** | 0.15 | 0.95 | 0.95 | 0.93 | 1.00 | 0.53 | 0.90 | 0.75 |
| **Land Types** | 0.17 | 0.86 | 0.81 | 0.79 | 0.53 | 1.00 | 0.49 | 0.98 |
| **Land Cover** | 0.15 | 0.61 | 0.69 | 0.61 | 0.90 | 0.49 | 1.00 | 0.53 |
| **Geology** | 0.08 | 0.74 | 0.73 | 0.76 | 0.75 | 0.98 | 0.53 | 1.00 |

**Appendix QQ: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Pilanesberg area for time frame one (1993-1998).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.17 | 0.17 | 0.15 | 0.24 | 0.14 | 0.25 | 0.07 |
| **MAP** | 0.17 | 1.00 | 0.90 | 0.82 | 0.71 | 0.78 | 0.56 | 0.68 |
| **MAT** | 0.17 | 0.90 | 1.00 | 0.87 | 0.81 | 0.72 | 0.51 | 0.60 |
| **Topography** | 0.15 | 0.82 | 0.87 | 1.00 | 0.82 | 0.71 | 0.47 | 0.59 |
| **Vegetation units** | 0.24 | 0.71 | 0.81 | 0.82 | 1.00 | 0.40 | 0.77 | 0.43 |
| **Land Types** | 0.14 | 0.78 | 0.72 | 0.71 | 0.40 | 1.00 | 0.71 | 0.88 |
| **Land Cover** | 0.25 | 0.56 | 0.51 | 0.47 | 0.77 | 0.71 | 1.00 | 0.56 |
| **Geology** | 0.07 | 0.68 | 0.60 | 0.59 | 0.43 | 0.88 | 0.56 | 1.00 |

**Appendix RR: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Pilanesberg area for time frame two (1998-2018).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.23 | 0.25 | 0.17 | 0.16 | 0.16 | 0.14 | 0.16 |
| **MAP** | 0.23 | 1.00 | 0.89 | 0.78 | 0.69 | 0.74 | 0.46 | 0.67 |
| **MAT** | 0.25 | 0.89 | 1.00 | 0.87 | 0.81 | 0.72 | 0.53 | 0.67 |
| **Topography** | 0.17 | 0.78 | 0.87 | 1.00 | 0.86 | 0.69 | 0.47 | 0.64 |
| **Vegetation units** | 0.16 | 0.69 | 0.81 | 0.86 | 1.00 | 0.48 | 0.77 | 0.52 |
| **Land Types** | 0.16 | 0.74 | 0.72 | 0.69 | 0.48 | 1.00 | 0.55 | 0.92 |
| **Land Cover** | 0.14 | 0.46 | 0.53 | 0.47 | 0.77 | 0.55 | 1.00 | 0.42 |
| **Geology** | 0.16 | 0.67 | 0.67 | 0.64 | 0.52 | 0.92 | 0.42 | 1.00 |

**Appendix SS: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Pilanesberg area for time frame three (1993-2018).**

| | BL | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.13 | 0.12 | 0.10 | 0.09 | 0.09 | 0.10 | 0.07 |
| **MAP** | 0.13 | 1.00 | 0.90 | 0.79 | 0.63 | 0.77 | 0.53 | 0.66 |
| **MAT** | 0.12 | 0.90 | 1.00 | 0.87 | 0.75 | 0.70 | 0.54 | 0.63 |
| **Topography** | 0.10 | 0.79 | 0.87 | 1.00 | 0.83 | 0.71 | 0.48 | 0.61 |
| **Bioregions** | 0.09 | 0.63 | 0.75 | 0.83 | 1.00 | 0.49 | 0.73 | 0.47 |
| **Land Types** | 0.09 | 0.77 | 0.70 | 0.71 | 0.49 | 1.00 | 0.66 | 0.90 |
| **Land Cover** | 0.10 | 0.53 | 0.54 | 0.48 | 0.73 | 0.66 | 1.00 | 0.47 |
| **Geology** | 0.07 | 0.66 | 0.63 | 0.61 | 0.47 | 0.90 | 0.47 | 1.00 |

**Appendix TT: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Pilanesberg area for time frame one (1993-1998).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.03 | 0.04 | 0.05 | 0.05 | 0.04 | 0.11 | 0.03 |
| **MAP** | 0.03 | 1.00 | 0.90 | 0.81 | 0.70 | 0.77 | 0.48 | 0.65 |
| **MAT** | 0.04 | 0.90 | 1.00 | 0.87 | 0.79 | 0.69 | 0.46 | 0.58 |
| **Topography** | 0.05 | 0.81 | 0.87 | 1.00 | 0.83 | 0.70 | 0.46 | 0.59 |
| **Vegetation units** | 0.05 | 0.70 | 0.79 | 0.83 | 1.00 | 0.40 | 0.80 | 0.46 |
| **Land Types** | 0.04 | 0.77 | 0.69 | 0.70 | 0.40 | 1.00 | 0.59 | 0.90 |
| **Land Cover** | 0.11 | 0.48 | 0.46 | 0.46 | 0.80 | 0.59 | 1.00 | 0.43 |
| **Geology** | 0.03 | 0.65 | 0.58 | 0.59 | 0.46 | 0.90 | 0.43 | 1.00 |

**Appendix UU: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Pilanesberg area for time frame two (1998-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.03 | 0.05 | 0.05 | 0.06 | 0.03 | 0.19 | 0.03 |
| **MAP** | 0.03 | 1.00 | 0.89 | 0.81 | 0.73 | 0.77 | 0.49 | 0.67 |
| **MAT** | 0.05 | 0.89 | 1.00 | 0.89 | 0.83 | 0.74 | 0.53 | 0.65 |
| **Topography** | 0.05 | 0.81 | 0.89 | 1.00 | 0.85 | 0.72 | 0.47 | 0.65 |
| **Vegetation units** | 0.06 | 0.73 | 0.83 | 0.85 | 1.00 | 0.45 | 0.79 | 0.54 |
| **Land Types** | 0.03 | 0.77 | 0.74 | 0.72 | 0.45 | 1.00 | 0.58 | 0.93 |
| **Land Cover** | 0.19 | 0.49 | 0.53 | 0.47 | 0.79 | 0.58 | 1.00 | 0.39 |
| **Geology** | 0.03 | 0.67 | 0.65 | 0.65 | 0.54 | 0.93 | 0.39 | 1.00 |

**Appendix VV: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Pilanesberg area for time frame three (1993-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.04 | 0.06 | 0.04 | 0.03 | 0.03 | 0.08 | 0.04 |
| **MAP** | 0.04 | 1.00 | 0.89 | 0.79 | 0.68 | 0.75 | 0.48 | 0.66 |
| **MAT** | 0.06 | 0.89 | 1.00 | 0.88 | 0.80 | 0.71 | 0.52 | 0.63 |
| **Topography** | 0.04 | 0.79 | 0.88 | 1.00 | 0.83 | 0.70 | 0.47 | 0.59 |
| **Vegetation units** | 0.03 | 0.68 | 0.80 | 0.83 | 1.00 | 0.45 | 0.79 | 0.47 |
| **Land Types** | 0.03 | 0.75 | 0.71 | 0.70 | 0.45 | 1.00 | 0.61 | 0.90 |
| **Land Cover** | 0.08 | 0.48 | 0.52 | 0.47 | 0.79 | 0.61 | 1.00 | 0.41 |
| **Geology** | 0.04 | 0.66 | 0.63 | 0.59 | 0.47 | 0.90 | 0.41 | 1.00 |

**Appendix WW: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Pilanesberg area for time frame one (1993-1998).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.24 | 0.22 | 0.27 | 0.19 | 0.34 | 0.14 | 0.36 |
| **MAP** | 0.24 | 1.00 | 0.89 | 0.79 | 0.71 | 0.74 | 0.46 | 0.67 |
| **MAT** | 0.22 | 0.89 | 1.00 | 0.87 | 0.81 | 0.72 | 0.52 | 0.65 |
| **Topography** | 0.27 | 0.79 | 0.87 | 1.00 | 0.86 | 0.70 | 0.46 | 0.65 |
| **Vegetation units** | 0.19 | 0.71 | 0.81 | 0.86 | 1.00 | 0.47 | 0.76 | 0.52 |
| **Land Types** | 0.34 | 0.74 | 0.72 | 0.70 | 0.47 | 1.00 | 0.51 | 0.93 |
| **Land Cover** | 0.14 | 0.46 | 0.52 | 0.46 | 0.76 | 0.51 | 1.00 | 0.39 |
| **Geology** | 0.36 | 0.67 | 0.65 | 0.65 | 0.52 | 0.93 | 0.39 | 1.00 |

**Appendix XX: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Pilanesberg area for time frame two (1998-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.24 | 0.23 | 0.26 | 0.31 | 0.35 | 0.27 | 0.31 |
| **MAP** | 0.24 | 1.00 | 0.90 | 0.81 | 0.73 | 0.78 | 0.47 | 0.65 |
| **MAT** | 0.23 | 0.90 | 1.00 | 0.88 | 0.81 | 0.73 | 0.50 | 0.56 |
| **Topography** | 0.26 | 0.81 | 0.88 | 1.00 | 0.83 | 0.73 | 0.46 | 0.61 |
| **Vegetation units** | 0.31 | 0.73 | 0.81 | 0.83 | 1.00 | 0.41 | 0.70 | 0.46 |
| **Land Types** | 0.35 | 0.78 | 0.73 | 0.73 | 0.41 | 1.00 | 0.60 | 0.93 |
| **Land Cover** | 0.27 | 0.47 | 0.50 | 0.46 | 0.70 | 0.60 | 1.00 | 0.41 |
| **Geology** | 0.31 | 0.65 | 0.56 | 0.61 | 0.46 | 0.93 | 0.41 | 1.00 |

**Appendix YY: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Pilanesberg area for time frame three (1993-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.14 | 0.15 | 0.09 | 0.26 | 0.10 | 0.15 | 0.09 |
| **MAP** | 0.14 | 1.00 | 0.89 | 0.80 | 0.74 | 0.77 | 0.47 | 0.66 |
| **MAT** | 0.15 | 0.89 | 1.00 | 0.88 | 0.83 | 0.73 | 0.51 | 0.61 |
| **Topography** | 0.09 | 0.80 | 0.88 | 1.00 | 0.86 | 0.73 | 0.47 | 0.64 |
| **Vegetation units** | 0.26 | 0.74 | 0.83 | 0.86 | 1.00 | 0.45 | 0.79 | 0.53 |
| **Land Types** | 0.10 | 0.77 | 0.73 | 0.73 | 0.45 | 1.00 | 0.54 | 0.94 |
| **Land Cover** | 0.15 | 0.47 | 0.51 | 0.47 | 0.79 | 0.54 | 1.00 | 0.40 |
| **Geology** | 0.09 | 0.66 | 0.61 | 0.64 | 0.53 | 0.94 | 0.40 | 1.00 |

**Appendix ZZ: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Rustenburg area for time frame one (1993-1998).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.17 | 0.22 | 0.21 | 0.23 | 0.26 | 0.13 | 0.23 |
| **MAP** | 0.17 | 1.00 | 0.84 | 0.78 | 0.76 | 0.62 | 0.29 | 0.45 |
| **MAT** | 0.22 | 0.84 | 1.00 | 0.91 | 0.69 | 0.73 | 0.42 | 0.61 |
| **Topography** | 0.21 | 0.78 | 0.91 | 1.00 | 0.64 | 0.76 | 0.52 | 0.56 |
| **Vegetation units** | 0.23 | 0.76 | 0.69 | 0.64 | 1.00 | 0.74 | 0.24 | 0.74 |
| **Land Types** | 0.26 | 0.62 | 0.73 | 0.76 | 0.74 | 1.00 | 0.52 | 0.47 |
| **Land Cover** | 0.13 | 0.29 | 0.42 | 0.52 | 0.24 | 0.52 | 1.00 | 0.30 |
| **Geology** | 0.23 | 0.45 | 0.61 | 0.56 | 0.74 | 0.47 | 0.30 | 1.00 |

**Appendix AAA: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Rustenburg area for time frame two (1998-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.15 | 0.24 | 0.29 | 0.15 | 0.27 | 0.11 | 0.19 |
| **MAP** | 0.15 | 1.00 | 0.73 | 0.71 | 0.69 | 0.65 | 0.49 | 0.34 |
| **MAT** | 0.24 | 0.73 | 1.00 | 0.89 | 0.58 | 0.69 | 0.43 | 0.60 |
| **Topography** | 0.29 | 0.71 | 0.89 | 1.00 | 0.68 | 0.76 | 0.53 | 0.54 |
| **Vegetation units** | 0.15 | 0.69 | 0.58 | 0.68 | 1.00 | 0.73 | 0.24 | 0.49 |
| **Land Types** | 0.27 | 0.65 | 0.69 | 0.76 | 0.73 | 1.00 | 0.64 | 0.86 |
| **Land Cover** | 0.11 | 0.49 | 0.43 | 0.53 | 0.24 | 0.64 | 1.00 | 0.43 |
| **Geology** | 0.19 | 0.34 | 0.60 | 0.54 | 0.49 | 0.86 | 0.43 | 1.00 |

**Appendix BBB: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush encroachment (BE) of the Rustenburg area for time frame three (1993-2018).**

| | BE | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BE** | 1.00 | 0.31 | 0.28 | 0.26 | 0.13 | 0.29 | 0.28 | 0.27 |
| **MAP** | 0.31 | 1.00 | 0.83 | 0.77 | 0.75 | 0.63 | 0.31 | 0.45 |
| **MAT** | 0.28 | 0.83 | 1.00 | 0.91 | 0.68 | 0.72 | 0.42 | 0.61 |
| **Topography** | 0.26 | 0.77 | 0.91 | 1.00 | 0.61 | 0.76 | 0.52 | 0.58 |
| **Vegetation units** | 0.13 | 0.75 | 0.68 | 0.61 | 1.00 | 0.73 | 0.24 | 0.72 |
| **Land Types** | 0.29 | 0.63 | 0.72 | 0.76 | 0.73 | 1.00 | 0.55 | 0.49 |
| **Land Cover** | 0.28 | 0.31 | 0.42 | 0.52 | 0.24 | 0.55 | 1.00 | 0.34 |
| **Geology** | 0.27 | 0.45 | 0.61 | 0.58 | 0.72 | 0.49 | 0.34 | 1.00 |

**Appendix CCC: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Rustenburg area for time frame one (1993-1998).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.20 | 0.22 | 0.17 | 0.16 | 0.19 | 0.20 | 0.12 |
| **MAP** | 0.20 | 1.00 | 0.76 | 0.65 | 0.76 | 0.52 | 0.26 | 0.43 |
| **MAT** | 0.22 | 0.76 | 1.00 | 0.85 | 0.67 | 0.65 | 0.39 | 0.69 |
| **Topography** | 0.17 | 0.65 | 0.85 | 1.00 | 0.60 | 0.66 | 0.45 | 0.66 |
| **Vegetation units** | 0.16 | 0.76 | 0.67 | 0.60 | 1.00 | 0.73 | 0.27 | 0.76 |
| **Land Types** | 0.19 | 0.52 | 0.65 | 0.66 | 0.73 | 1.00 | 0.49 | 0.48 |
| **Land Cover** | 0.20 | 0.26 | 0.39 | 0.45 | 0.27 | 0.49 | 1.00 | 0.38 |
| **Geology** | 0.12 | 0.43 | 0.69 | 0.66 | 0.76 | 0.48 | 0.38 | 1.00 |

**Appendix DDD: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Rustenburg area for time frame two (1998-2018).**

| | BL | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.16 | 0.25 | 0.20 | 0.24 | 0.21 | 0.26 | 0.24 |
| **MAP** | 0.16 | 1.00 | 0.79 | 0.71 | 0.69 | 0.58 | 0.30 | 0.53 |
| **MAT** | 0.25 | 0.79 | 1.00 | 0.87 | 0.71 | 0.64 | 0.40 | 0.77 |
| **Topography** | 0.20 | 0.71 | 0.87 | 1.00 | 0.58 | 0.69 | 0.40 | 0.69 |
| **Vegetation units** | 0.24 | 0.69 | 0.71 | 0.58 | 1.00 | 0.74 | 0.36 | 0.93 |
| **Land Types** | 0.21 | 0.58 | 0.64 | 0.69 | 0.74 | 1.00 | 0.44 | 0.50 |
| **Land Cover** | 0.26 | 0.30 | 0.40 | 0.40 | 0.36 | 0.44 | 1.00 | 0.48 |
| **Geology** | 0.24 | 0.53 | 0.77 | 0.69 | 0.93 | 0.50 | 0.48 | 1.00 |

**Appendix EEE: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush lessening (BL) of the Rustenburg area for time frame three (1993-2018).**

| | BL | MAP | MAT | Topography | Bioregions | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BL** | 1.00 | 0.22 | 0.19 | 0.20 | 0.16 | 0.20 | 0.30 | 0.21 |
| **MAP** | 0.22 | 1.00 | 0.78 | 0.73 | 0.72 | 0.58 | 0.31 | 0.49 |
| **MAT** | 0.19 | 0.78 | 1.00 | 0.86 | 0.66 | 0.69 | 0.42 | 0.76 |
| **Topography** | 0.20 | 0.73 | 0.86 | 1.00 | 0.55 | 0.71 | 0.45 | 0.72 |
| **Bioregions** | 0.16 | 0.72 | 0.66 | 0.55 | 1.00 | 0.72 | 0.35 | 0.89 |
| **Land Types** | 0.20 | 0.58 | 0.69 | 0.71 | 0.72 | 1.00 | 0.49 | 0.56 |
| **Land Cover** | 0.30 | 0.31 | 0.42 | 0.45 | 0.35 | 0.49 | 1.00 | 0.48 |
| **Geology** | 0.21 | 0.49 | 0.76 | 0.72 | 0.89 | 0.56 | 0.48 | 1.00 |

**Appendix FFF: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Rustenburg area for time frame one (1993-1998).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.04 | 0.05 | 0.05 | 0.02 | 0.06 | 0.06 | 0.02 |
| **MAP** | 0.04 | 1.00 | 0.77 | 0.66 | 0.74 | 0.53 | 0.21 | 0.42 |
| **MAT** | 0.05 | 0.77 | 1.00 | 0.85 | 0.67 | 0.65 | 0.34 | 0.71 |
| **Topography** | 0.05 | 0.66 | 0.85 | 1.00 | 0.59 | 0.68 | 0.42 | 0.68 |
| **Vegetation units** | 0.02 | 0.74 | 0.67 | 0.59 | 1.00 | 0.75 | 0.26 | 0.78 |
| **Land Types** | 0.06 | 0.53 | 0.65 | 0.68 | 0.75 | 1.00 | 0.46 | 0.50 |
| **Land Cover** | 0.06 | 0.21 | 0.34 | 0.42 | 0.26 | 0.46 | 1.00 | 0.37 |
| **Geology** | 0.02 | 0.42 | 0.71 | 0.68 | 0.78 | 0.50 | 0.37 | 1.00 |

**Appendix GGG: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Rustenburg area for time frame two (1998-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.04 | 0.03 | 0.03 | 0.04 | 0.14 | 0.05 | 0.01 |
| **MAP** | 0.04 | 1.00 | 0.77 | 0.67 | 0.70 | 0.61 | 0.29 | 0.44 |
| **MAT** | 0.03 | 0.77 | 1.00 | 0.87 | 0.71 | 0.65 | 0.38 | 0.73 |
| **Topography** | 0.03 | 0.67 | 0.87 | 1.00 | 0.59 | 0.70 | 0.43 | 0.66 |
| **Vegetation units** | 0.04 | 0.70 | 0.71 | 0.59 | 1.00 | 0.75 | 0.32 | 0.87 |
| **Land Types** | 0.14 | 0.61 | 0.65 | 0.70 | 0.75 | 1.00 | 0.50 | 0.49 |
| **Land Cover** | 0.05 | 0.29 | 0.38 | 0.43 | 0.32 | 0.50 | 1.00 | 0.44 |
| **Geology** | 0.01 | 0.44 | 0.73 | 0.66 | 0.87 | 0.49 | 0.44 | 1.00 |

**Appendix HHH: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with no change (NC) of the Rustenburg area for time frame three (1993-2018).**

| | NC | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.02 | 0.03 | 0.03 | 0.03 | 0.01 | 0.04 | 0.02 |
| **MAP** | 0.02 | 1.00 | 0.80 | 0.71 | 0.72 | 0.57 | 0.28 | 0.51 |
| **MAT** | 0.03 | 0.80 | 1.00 | 0.87 | 0.67 | 0.66 | 0.39 | 0.76 |
| **Topography** | 0.03 | 0.71 | 0.87 | 1.00 | 0.58 | 0.71 | 0.43 | 0.71 |
| **Vegetation units** | 0.03 | 0.72 | 0.67 | 0.58 | 1.00 | 0.74 | 0.32 | 0.88 |
| **Land Types** | 0.01 | 0.57 | 0.66 | 0.71 | 0.74 | 1.00 | 0.46 | 0.52 |
| **Land Cover** | 0.04 | 0.28 | 0.39 | 0.43 | 0.32 | 0.46 | 1.00 | 0.46 |
| **Geology** | 0.02 | 0.51 | 0.76 | 0.71 | 0.88 | 0.52 | 0.46 | 1.00 |

**Appendix III: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Rustenburg area for time frame one (1993-1998).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.24 | 0.39 | 0.40 | 0.36 | 0.39 | 0.37 | 0.63 |
| **MAP** | 0.24 | 1.00 | 0.78 | 0.67 | 0.68 | 0.60 | 0.28 | 0.47 |
| **MAT** | 0.39 | 0.78 | 1.00 | 0.87 | 0.71 | 0.64 | 0.39 | 0.74 |
| **Topography** | 0.40 | 0.67 | 0.87 | 1.00 | 0.59 | 0.68 | 0.40 | 0.66 |
| **Vegetation units** | 0.36 | 0.68 | 0.71 | 0.59 | 1.00 | 0.74 | 0.35 | 0.91 |
| **Land Types** | 0.39 | 0.60 | 0.64 | 0.68 | 0.74 | 1.00 | 0.45 | 0.49 |
| **Land Cover** | 0.37 | 0.28 | 0.39 | 0.40 | 0.35 | 0.45 | 1.00 | 0.45 |
| **Geology** | 0.63 | 0.47 | 0.74 | 0.66 | 0.91 | 0.49 | 0.45 | 1.00 |

**Appendix JJJ: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Rustenburg area for time frame two (1998-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.40 | 0.46 | 0.49 | 0.30 | 0.44 | 0.39 | 0.36 |
| **MAP** | 0.40 | 1.00 | 0.76 | 0.63 | 0.69 | 0.61 | 0.27 | 0.35 |
| **MAT** | 0.46 | 0.76 | 1.00 | 0.87 | 0.70 | 0.65 | 0.34 | 0.66 |
| **Topography** | 0.49 | 0.63 | 0.87 | 1.00 | 0.59 | 0.67 | 0.41 | 0.60 |
| **Vegetation units** | 0.30 | 0.69 | 0.70 | 0.59 | 1.00 | 0.75 | 0.29 | 0.82 |
| **Land Types** | 0.44 | 0.61 | 0.65 | 0.67 | 0.75 | 1.00 | 0.47 | 0.45 |
| **Land Cover** | 0.39 | 0.27 | 0.34 | 0.41 | 0.29 | 0.47 | 1.00 | 0.34 |
| **Geology** | 0.36 | 0.35 | 0.66 | 0.60 | 0.82 | 0.45 | 0.34 | 1.00 |

**Appendix KKK: A correlation matrix, indicating the correlation (expressed as $\Phi_K$, between 0.0 and 1) between the potential driving factors of BE with bush thickening (BT) of the Rustenburg area for time frame three (1993-2018).**

| | BT | MAP | MAT | Topography | Vegetation units | Land Types | Land Cover | Geology |
|---|---|---|---|---|---|---|---|---|
| **BT** | 1.00 | 0.16 | 0.22 | 0.22 | 0.20 | 0.27 | 0.24 | 0.24 |
| **MAP** | 0.16 | 1.00 | 0.78 | 0.65 | 0.69 | 0.60 | 0.26 | 0.44 |
| **MAT** | 0.22 | 0.78 | 1.00 | 0.87 | 0.72 | 0.63 | 0.36 | 0.72 |
| **Topography** | 0.22 | 0.65 | 0.87 | 1.00 | 0.59 | 0.67 | 0.38 | 0.63 |
| **Vegetation units** | 0.20 | 0.69 | 0.72 | 0.59 | 1.00 | 0.75 | 0.33 | 0.89 |
| **Land Types** | 0.27 | 0.60 | 0.63 | 0.67 | 0.75 | 1.00 | 0.45 | 0.47 |
| **Land Cover** | 0.24 | 0.26 | 0.36 | 0.38 | 0.33 | 0.45 | 1.00 | 0.41 |
| **Geology** | 0.24 | 0.44 | 0.72 | 0.63 | 0.89 | 0.47 | 0.41 | 1.00 |

**Appendix LLL: Code used for creating the correlation matrixes on provincial and regional scale.**

```
df = pd.read_csv(filename,sep='\t')

print('Dataframe Read')

del df['X']

del df['Y']

print('Columns, deleted')

for col in df.columns:

        df.drop(df.index[df[col]==-9999],inplace=True)

print('Bad data points dropped')

#Georanges will have values, 1.5,2.5,... for each category.

print('Changing geology values')

for i in range(len(georanges)):

        for j in range(len(georanges[i])):

                df[geology_column_name].loc[np.logical_and(df[geology_column_name] > 
georanges[i][j][0],df[geology_column_name] < georanges[i][j][1])] = i+0.5

print('Calculating main phik matrix')

a = phik.phik_matrix(df,interval_cols = df.columns,bins = 
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover
_bins,land_types_column_name:land_types_bins,

ep1_column_name:list(range(-95,105,5)),ep2_column_name:list(range(-95,105,5)),ep3_column_name:list(range(-
95,105,5))})

print('PhiK calculated')

a.to_csv('PhiK_results.csv')

dflessening_ep1 = df.loc[df[ep1_column_name] < 0]

print('Calculating bush lessening ep 1 : Perc of data %.2f'%(len(dflessening_ep1)/len(df)))

del dflessening_ep1[ep2_column_name]

del dflessening_ep1[ep3_column_name]

lessening_ep1 = phik.phik_matrix(dflessening_ep1,interval_cols = dflessening_ep1.columns,bins = 
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover
_bins,land_types_column_name:land_types_bins,

ep1_column_name:list(range(-95,5,5))})
```

**Appendix MMM: Code used for creating the correlation matrixes on provincial and regional scale (Continued).**

```
print('PhiK lessening ep1 calculated')

lessening_ep1.to_csv('PhiK_lesseningep1_results.csv')

dflessening_ep2 = df.loc[df[ep2_column_name] < 0]

print('Calculating bush lessening ep 2: Perc of data %.2f'%(len(dflessening_ep2)/len(df)))

del dflessening_ep2[ep1_column_name]

del dflessening_ep2[ep3_column_name]

lessening_ep2 = phik.phik_matrix(dflessening_ep2,interval_cols = dflessening_ep2.columns,bins =
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover
_bins,land_types_column_name:land_types_bins,

ep2_column_name:list(range(-95,5,5))})

print('PhiK lessening ep2 calculated')

lessening_ep2.to_csv('PhiK_lesseningep2_results.csv')

dflessening_ep3 = df.loc[df[ep3_column_name] < 0]

print('Calculating bush lessening ep 3: Perc of data %.2f'%(len(dflessening_ep3)/len(df)))

del dflessening_ep3[ep1_column_name]

del dflessening_ep3[ep2_column_name]

lessening_ep3 = phik.phik_matrix(dflessening_ep3,interval_cols = dflessening_ep3.columns,bins =
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover
_bins,land_types_column_name:land_types_bins,

ep3_column_name:list(range(-95,5,5))})

print('PhiK lessening ep3 calculated')

lessening_ep3.to_csv('PhiK_lesseningep3_results.csv')

dfenchroachment_ep1 = df.loc[(df[ep1_column_name] >= 0) & (df[ep1_column_name] < 10)]

print('Calculating bush enchroachment ep 1: Perc of data %.2f'%(len(dfenchroachment_ep1)/len(df)))

del dfenchroachment_ep1[ep2_column_name]

del dfenchroachment_ep1[ep3_column_name]

enchroachment_ep1 = phik.phik_matrix(dfenchroachment_ep1,interval_cols = dfenchroachment_ep1.columns,bins
=
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,
```

**Appendix NNN: Code used for creating the correlation matrixes on provincial and regional scale (Continued).**

```
topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover_bins,land_types_column_name:land_types_bins,

ep1_column_name:list(np.arange(0,11,1))})

print('PhiK enchroachment ep1 calculated')

enchroachment_ep1.to_csv('PhiK_enchroachmentep1_results.csv')

dfenchroachment_ep2 = df.loc[(df[ep2_column_name] >= 0) & (df[ep2_column_name] < 10)]

print('Calculating bush enchroachment ep 2: Perc of data %.2f'%(len(dfenchroachment_ep2)/len(df)))

del dfenchroachment_ep2[ep1_column_name]

del dfenchroachment_ep2[ep3_column_name]

enchroachment_ep2 = phik.phik_matrix(dfenchroachment_ep2,interval_cols = dfenchroachment_ep2.columns,bins =
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover_bins,land_types_column_name:land_types_bins,

ep2_column_name:list(range(0,11,1))})

print('PhiK enchroachment ep2 calculated')

enchroachment_ep2.to_csv('PhiK_enchroachmentep2_results.csv')

dfenchroachment_ep3 = df.loc[(df[ep3_column_name] >= 0) & (df[ep3_column_name] < 10)]

print('Calculating bush enchroachment ep 3: Perc of data %.2f'%(len(dfenchroachment_ep3)/len(df)))

del dfenchroachment_ep3[ep1_column_name]

del dfenchroachment_ep3[ep2_column_name]

enchroachment_ep3 = phik.phik_matrix(dfenchroachment_ep3,interval_cols = dfenchroachment_ep3.columns,bins =
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover_bins,land_types_column_name:land_types_bins,

ep3_column_name:list(range(0,11,1))})

print('PhiK enchroachment ep3 calculated')

enchroachment_ep3.to_csv('PhiK_enchroachmentep3_results.csv')

dfthickening_ep1 = df.loc[df[ep1_column_name] >= 10]

print('Calculating bush thickening ep 1: Perc of data %.2f'%(len(dfthickening_ep1)/len(df)))
```

**Appendix OOO: Code used for creating the correlation matrixes on provincial and regional scale (Continued).**

```
del dfthickening_ep1[ep2_column_name]

del dfthickening_ep1[ep3_column_name]

thickening_ep1 = phik.phik_matrix(dfthickening_ep1,interval_cols = dfthickening_ep1.columns,bins =
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover
_bins,land_types_column_name:land_types_bins,

ep1_column_name:list(range(10,105,5))})

print('PhiK thickening ep1 calculated')

thickening_ep1.to_csv('PhiK_thickeningep1_results.csv')

dfthickening_ep2 = df.loc[df[ep2_column_name] >=10]

print('Calculating bush thickening ep 2: Perc of data %.2f'%(len(dfthickening_ep2)/len(df)))

del dfthickening_ep2[ep1_column_name]

del dfthickening_ep2[ep3_column_name]

thickening_ep2 = phik.phik_matrix(dfthickening_ep2,interval_cols = dfthickening_ep2.columns,bins =
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover
_bins,land_types_column_name:land_types_bins,

ep2_column_name:list(range(10,105,5))})

print('PhiK thickening ep2 calculated')

thickening_ep2.to_csv('PhiK_thickeningep2_results.csv')

dfthickening_ep3 = df.loc[df[ep3_column_name] >=10]

print('Calculating bush thickening ep 3: Perc of data %.2f'%(len(dfthickening_ep3)/len(df)))

del dfthickening_ep3[ep1_column_name]

del dfthickening_ep3[ep2_column_name]

thickening_ep3 = phik.phik_matrix(dfthickening_ep3,interval_cols = dfthickening_ep3.columns,bins =
{bioregions_column_name:bioregions_bins,geology_column_name:geology_bins,MAP_column_name:MAP_bins,

topography_column_name:topography_bins,MAT_column_name:MAT_bins,land_cover_column_name:land_cover
_bins,land_types_column_name:land_types_bins,

ep3_column_name:list(range(10,105,5))})

print('PhiK thickening ep3 calculated')

thickening_ep3.to_csv('PhiK_thickeningep3_results.csv')
```

**Appendix PPP: Abbreviations of woody species - Chapter 4.**

*Aloe spp. – Aloe species*

*A. procumbens – Aptosimum procumbens*

*A. spp. – Asparagus species*

*B. spp. – Blepharis species*

*B. albitrunca – Boscia albitrunca*

*C. spp. – Chascanum species*

*C. apiculatum – Combretum apiculatum*

*C. inberbe – Combretum inberbe*

*C. hereroense – Combretum hereroense*

*C. schimperi – Commiphora schimperi*

*C. angustifolia – Crabbea angustifolia*

*D. cinerea – Dichrostachys cinerea*

*D. lycioides – Diospyros lycioides subspecies lycioides*

*D. rotundifolia – Dombreya rotundifolia*

*E. rigida – Ehretia rigida*

*E. crispa – Euclea crispa*

*G. bicolor – Grewia bicolor*

*G. flava – Grewia flava*

*G. flavescens – Grewia flavescens*

*G. monticola – Grewia monticola*

*Indigofera spp. – Indigofera species*

*K. spp. – Kohautia species*

**Appendix QQQ: Abbreviations of species- Chapter 4 (Continued).**

*M. feniospinum - Maytenus feniospinum*

*M. angustifolia – Mondonia angustifolia*

*P. capensis – Pappea capensis*

*S. birrea – Sclerocarya birrea*

*S. leptodictya - Searsia leptodictya*

*S. caffra – Senegalia caffra*

*S. mellifera – Senegalia mellifera*

*Solanum spp. – Solanum species*

*Tephrosia spp. – Tephrosia species*

*V. karroo – Vachellia karroo*

*V. tortillis – Vachellia tortillis*

*Z. mucronata – Ziziphus mucronata*

**Appendix RRR: The total species abundance (TSA) at each study site for height classes 1 to 7.**

| | Height class | | | | | | |
|---|---|---|---|---|---|---|---|
| **Study Site** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **Pilanesberg** | 107 | 39 | 33 | 20 | 17 | 14 | 42 |
| **Legkraal** | 70 | 27 | 29 | 35 | 30 | 27 | 68 |
| **Kgomo-Kgomo** | 287 | 20 | 41 | 29 | 7 | 5 | 13 |

**Appendix SSS: The total species abundance (TSA) at each study site of all major woody species from each site.**

| | Sites | | |
|---|---|---|---|
| **Vegetation species** | **Pilanesberg** | **Legkraal** | **Kgomo-Kgomo** |
| ***Dichrostachys cinerea*** | 77 | 84 | 11 |
| ***Diospyros lycioides subs. lycioides*** | 0 | 0 | 123 |
| ***Grewia flava*** | 3 | 9 | 95 |
| ***Grewia flavescens*** | 59 | 0 | 1 |
| ***Senegalia mellifera*** | 0 | 40 | 69 |
| ***Vachellia karroo*** | 21 | 43 | 0 |
| ***Vachellia tortillis*** | 0 | 48 | 52 |
| ***Ziziphus mucronata*** | 0 | 14 | 1 |

**Appendix TTT: The total species abundance (TSA) of single- and multi-stemmed woody plants at each study site transect.**

| | Stem | |
|---|---|---|
| **Transect** | **Single** | **Multi** |
| **Pilanesberg Transect 1** | 20 | 90 |
| **Pilanesberg Transect 2** | 3 | 73 |
| **Pilanesberg Transect 3** | 7 | 78 |
| **Legkraal Transect 1** | 9 | 98 |
| **Legkraal Transect 2** | 30 | 68 |
| **Legkraal Transect 3** | 14 | 69 |
| **Kgomo-Kgomo Transect 1** | 24 | 48 |
| **Kgomo-Kgomo Transect 2** | 27 | 72 |
| **Kgomo-Kgomo Transect 3** | 122 | 109 |

**Appendix UUU: The total species abundance (TSA) of single- and multi-stemmed woody plants at each study site.**

| | Stem | |
|---|---|---|
| **Site** | **Single** | **Multi** |
| **Pilanesberg** | 10 | 80 |
| **Legkraal** | 18 | 78 |
| **Kgomo-Kgomo** | 57 | 76 |

**Appendix VVV: The total species abundance (TSA) of single- and multi-stemmed woody plant species at the Pilanesberg study site.**

| | Pilanesberg | | | | | |
|---|---|---|---|---|---|---|
| | **Transect 1** | | **Transect 2** | | **Transect 3** | |
| **Vegetation species** | **Single** | **Multi** | **Single** | **Multi** | **Single** | **Multi** |
| ***Blepharis spp.*** | 1 | 0 | 0 | 0 | 0 | 0 |
| ***Chascanum spp.*** | 0 | 0 | 1 | 1 | 0 | 24 |
| ***Combretum apiculatum*** | 0 | 0 | 0 | 1 | 2 | 0 |
| ***Combretum inberbe*** | 0 | 3 | 0 | 0 | 4 | 0 |
| ***Combretum hereroense*** | 0 | 1 | 0 | 1 | 0 | 0 |
| ***Combretum angustifolia*** | 0 | 5 | 0 | 0 | 0 | 0 |
| ***Dichrostachys cinerea*** | 8 | 40 | 2 | 7 | 0 | 20 |
| ***Dombeya rotundifolia*** | 0 | 0 | 0 | 5 | 1 | 0 |
| ***Euclea crispa*** | 0 | 12 | 0 | 0 | 0 | 0 |
| ***Grewia bicolor*** | 0 | 2 | 0 | 0 | 0 | 4 |
| ***Grewia flava*** | 0 | 0 | 0 | 0 | 0 | 3 |

**Appendix WWW: The total species abundance (TSA) of single- and multi-stemmed woody plant species at the Pilanesberg study site (Continued).**

| Pilanesberg | | | | | | |
|---|---|---|---|---|---|---|
| | Transect 1 | | Transect 2 | | Transect 3 | |
| Vegetation species | Single | Multi | Single | Multi | Single | Multi |
| *Grewia flavescens* | 1 | 3 | 0 | 42 | 0 | 13 |
| *Grewia monticola* | 0 | 0 | 0 | 1 | 0 | 0 |
| *Indigofera spp.* | 0 | 3 | 0 | 0 | 0 | 2 |
| *Kohautia spp.* | 0 | 4 | 0 | 0 | 0 | 0 |
| *Maytenus feniospinum* | 0 | 0 | 0 | 11 | 0 | 0 |
| *Mondonia angustifolia* | 0 | 2 | 0 | 0 | 0 | 0 |
| *Pappea capensis* | 0 | 3 | 0 | 0 | 0 | 0 |
| *Sclerocarya birrea* | 0 | 1 | 0 | 0 | 0 | 0 |
| *Searsia leptodictya* | 0 | 0 | 0 | 1 | 0 | 0 |
| *Senegalia caffra* | 0 | 0 | 0 | 1 | 0 | 5 |
| *Solanum spp.* | 0 | 3 | 0 | 0 | 0 | 0 |
| *Tephrosia spp.* | 2 | 1 | 0 | 0 | 0 | 1 |
| *Vachellia karroo* | 2 | 11 | 0 | 2 | 0 | 6 |

**Appendix XXX: The total species abundance (TSA) of woody plant species at the Pilanesberg study site transects from height class one to seven.**

| Pilanesberg | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Height class | | | | | | |
| **Transect** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 1 | 30 | 21 | 18 | 5 | 5 | 6 | 26 |
| 2 | 41 | 10 | 8 | 5 | 3 | 2 | 7 |
| 3 | 36 | 8 | 7 | 10 | 9 | 6 | 9 |

**Appendix YYY: The total species abundance (TSA) of single- and multi-stemmed woody plant species at the Legkraal study site.**

| Legkraal | | | | | | |
|---|---|---|---|---|---|---|
| | **Transect 1** | | **Transect 2** | | **Transect 3** | |
| **Vegetation species** | **Single** | **Multi** | **Single** | **Multi** | **Single** | **Multi** |
| ***Aloe spp.*** | 0 | 0 | 2 | 0 | 0 | 0 |
| ***Aptosimum procumbens*** | 0 | 0 | 0 | 19 | 0 | 1 |
| ***Asparagus spp.*** | 11 | 0 | 0 | 8 | 2 | 1 |
| ***Dichrostachys cinerea*** | 2 | 26 | 4 | 26 | 2 | 24 |
| ***Ehretia rigida*** | 0 | 1 | 0 | 0 | 1 | 3 |
| ***Grewia flava*** | 0 | 7 | 0 | 2 | 0 | 0 |
| ***Pappea capensis*** | 0 | 0 | 2 | 0 | 0 | 0 |
| ***Senegalia hereroensis*** | 0 | 0 | 0 | 0 | 2 | 0 |
| ***Senegalia mellifera*** | 0 | 0 | 3 | 5 | 0 | 32 |

**Appendix ZZZ: The total species abundance (TSA) of single- and multi-stemmed woody plant species at the Legkraal study site (Continued).**

| Legkraal | | | | | | |
|---|---|---|---|---|---|---|
| | **Transect 1** | | **Transect 2** | | **Transect 3** | |
| **Vegetation species** | **Single** | **Multi** | **Single** | **Multi** | **Single** | **Multi** |
| ***Tephrosia spp.*** | 0 | 0 | 0 | 0 | 0 | 1 |
| ***Vachellia karroo*** | 5 | 31 | 7 | 0 | 0 | 0 |
| ***Vachellia tortillis*** | 0 | 15 | 14 | 5 | 9 | 5 |
| ***Ziziphus mucronata*** | 0 | 9 | 0 | 4 | 0 | 1 |

**Appendix AAAA: The total species abundance (TSA) of woody plant species at the Pilanesberg study site transects from height class one to seven.**

| Legkraal | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Height class** | | | | | | |
| **Transect** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **1** | 7 | 15 | 8 | 18 | 19 | 12 | 26 |
| **2** | 31 | 8 | 7 | 5 | 3 | 12 | 32 |
| **3** | 32 | 4 | 14 | 12 | 8 | 3 | 10 |

**Appendix BBBB: The total species abundance (TSA) of single- and multi-stemmed woody plant species at the Kgomo-Kgomo study site.**

| Kgomo-Kgomo | | | | | | |
|---|---|---|---|---|---|---|
| | Transect 1 | | Transect 2 | | Transect 3 | |
| **Vegetation species** | **Single** | **Multi** | **Single** | **Multi** | **Single** | **Multi** |
| ***Aloe spp.*** | 3 | 0 | 26 | 0 | 0 | 0 |
| ***Asparagus spp.*** | 0 | 0 | 0 | 0 | 0 | 10 |
| ***Boscia albitrunca*** | 0 | 1 | 0 | 0 | 0 | 0 |
| ***Commiphora schimperi*** | 0 | 7 | 0 | 1 | 0 | 0 |
| ***Dichrostachys cinerea*** | 8 | 0 | 2 | 1 | 0 | 0 |
| ***Diospyros lycioides subs. lycioides*** | 0 | 1 | 0 | 0 | 112 | 10 |
| ***Grewia flava*** | 0 | 27 | 0 | 11 | 0 | 57 |
| ***Grewia flavescens*** | 0 | 1 | 0 | 0 | 0 | 0 |
| ***Senegalia caffra*** | 0 | 0 | 0 | 0 | 0 | 2 |
| ***Senegalia mellifera*** | 7 | 2 | 0 | 43 | 0 | 17 |
| ***Vachellia tortillis*** | 6 | 8 | 0 | 15 | 0 | 23 |
| ***Ziziphus mucronata*** | 0 | 1 | 0 | 0 | 0 | 0 |

**Appendix CCCC: The total species abundance (TSA) of woody plant species at the Kgomo-Kgomo study site transects from height class one to seven.**

| Kgomo-Kgomo | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Height class | | | | | | |
| **Transect** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **1** | 37 | 10 | 12 | 8 | 1 | 2 | 2 |
| **2** | 78 | 0 | 8 | 5 | 3 | 1 | 4 |
| **3** | 172 | 10 | 21 | 16 | 3 | 2 | 7 |

**Appendix DDDD: Soil texture of the sample collected at each transect of the study sites.**

| Sample | Texture class |
|---|---|
| **Pilanesberg Transect 1 topsoil** | Sandy loam |
| **Pilanesberg Transect 2 topsoil** | Sandy loam |
| **Pilanesberg Transect 3 topsoil** | Loamy sand |
| **Pilanesberg Transect 3 subsoil** | Silt loam |
| **Legkraal Transect 1 topsoil (A1)** | Loamy sand |
| **Legkraal Transect 1 topsoil (A2)** | Silt loam |
| **Legkraal Transect 1 subsoil** | Silt loam |
| **Legkraal Transect 2 topsoil (A1)** | Sandy loam |
| **Legkraal Transect 2 topsoil (A2)** | Sandy loam |
| **Legkraal Transect 2 subsoil** | Silt loam |
| **Legkraal Transect 3 topsoil** | Sandy loam |

**Appendix EEEE: Soil texture of the sample collected at each transect of the study sites (Continued).**

| Sample | Texture class |
|---|---|
| **Legkraal Transect 3 subsoil** | Clay |
| **Kgomo-Kgomo Transect 1 topsoil** | Sandy clay loam |
| **Kgomo-Kgomo Transect 1 subsoil** | Sandy clay loam |
| **Kgomo-Kgomo Transect 2 topsoil** | Loamy sand |
| **Kgomo-Kgomo Transect 2 subsoil** | Sandy clay loam |
| **Kgomo-Kgomo Transect 3 topsoil** | Sandy clay loam |
| **Kgomo-Kgomo Transect 3 subsoil (B1)** | Sandy clay loam |
| **Kgomo-Kgomo Transect 3 subsoil (B2)** | Sandy clay loam |

**Appendix FFFF: Soil classification of the Pilanesberg study site.**

| Pilanesberg | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Transect 1 | | | | | | | | | | |
| | | | Colour | | Mottles/concretions | | Structure | | | |
| Horizon | Depth (mm) | Clay (%) | Dry | Wet | Occurrence (%) | Colour | Grade | Size | Type | Diagnostic Horizon |
| A | 300 | 20 | 5 YR 6/2 | 2.5 YR 3/1 | few (< 2%) | black | weak | fine | granular | Orthic A Lithic |
| Soil Form | | | Glenrosa | | | Soil Family | | | 2220 | |
| Transect 2 | | | | | | | | | | |
| | | | Colour | | Mottles/concretions | | Structure | | | |
| Horizon | Depth (mm) | Clay (%) | Dry | Wet | Occurrence (%) | Colour | Grade | Size | Type | Diagnostic Horizon |
| A | 300 | 20 | 5 YR 6/2 | 2.5 YR 3/1 | few (< 2%) | black | weak | fine | granular | Orthic A Lithic |
| Soil Form | | | Glenrosa | | | Soil Family | | | 2220 | |
| Transect 3 | | | | | | | | | | |
| | | | Colour | | Mottles/concretions | | Structure | | | |
| Horizon | Depth (mm) | Clay (%) | Dry | Wet | Occurrence (%) | Colour | Grade | Size | Type | Diagnostic Horizon |
| A | 300 | 10 – 15 | 5 YR 6/2 | 2.5 YR 3/1 | None | None | apedal | fine | granular | Orthic A |
| B | 700 | 10 – 15 | 5 YR 6/2 | 2.5 YR 3/1 | common (10%) | black | medium | fine - medium | massive | Yellow-brown B Lithic |
| Soil Form | | | Clovelly | | | Soil Family | | | 2221 | |

**Appendix GGGG: Soil classification of the Legkraal study site.**

| Legkraal | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Transect 1** | | | | | | | | | | |
| | | | **Colour** | | **Mottles/concretions** | | **Structure** | | | |
| **Horizon** | **Depth (mm)** | **Clay (%)** | **Dry** | **Wet** | **Occurrence (%)** | **Colour** | **Grade** | **Size** | **Type** | **Diagnostic Horizon** |
| A1 | 200 | 20 | 10 YR 5/4 | 7.5 YR 3/4 | None | None | medium | fine | granular | Orthic A |
| A2 | 600 | 40 | 10 YR 5/4 | 7.5 YR 4/4 | few (< 2%) | black | medium | fine | subangular blocky | Orthic A |
| B | 1 500 | 25 | 7.5 YR 5/6 | 10 YR 6/6 | common (10%) | black and white | medium | fine | single grain | Yellow-brown B |
| **Soil Form** | | | Clovelly | | | **Soil Family** | | | 2221 | |
| **Transect 2** | | | | | | | | | | |
| | | | **Colour** | | **Mottles/concretions** | | **Structure** | | | |
| **Horizon** | **Depth (mm)** | **Clay (%)** | **Dry** | **Wet** | **Occurrence (%)** | **Colour** | **Grade** | **Size** | **Type** | **Diagnostic Horizon** |
| A1 | 200 | 20 | 10 YR 5/4 | 7.5 YR 3/4 | None | None | medium | fine | granular | Orthic A |
| A2 | 1 200 | 40 | 10 YR 5/4 | 7.5 YR 4/4 | few (< 2%) | black | medium | fine | subangular blocky | Orthic A |
| B | 1 500 | 20 | 7.5 YR 5/6 | 10 YR 6/6 | many (40%) | black | weak to medium | fine | granular | Yellow-brown B |
| **Soil Form** | | | Clovelly | | | **Soil Family** | | | 2221 | |
| **Transect 3** | | | | | | | | | | |
| | | | **Colour** | | **Mottles/concretions** | | **Structure** | | | |
| **Horizon** | **Depth (mm)** | **Clay (%)** | **Dry** | **Wet** | **Occurrence (%)** | **Colour** | **Grade** | **Size** | **Type** | **Diagnostic Horizon** |
| A | 400 | 25 | 10 YR 5/4 | 7.5 YR 3/4 | None | None | medium | fine - medium | crumb | Orthic A |
| B1 | 1 500 | 35 | 7.5 YR 5/6 | 10 YR 6/6 | common (10%) | black and yellow | medium | fine - medium | massive | Yellow-brown B |
| **Soil Form** | | | Clovelly | | | **Soil Family** | | | 2221 | |

**Appendix HHHH: Soil classification of the Kgomo-Kgomo study site.**

| Kgomo-Kgomo | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Transect 1** | | | | | | | | | | |
| | | | **Colour** | | **Mottles/concretions** | | **Structure** | | | |
| **Horizon** | **Depth (mm)** | **Clay (%)** | **Dry** | **Wet** | **Occurrence (%)** | **Colour** | **Grade** | **Size** | **Type** | **Diagnostic Horizon** |
| A | 300 | 10 | 5 YR 5/6 | 5 YR 4/6 | None | None | apedal | fine | granular | Orthic A |
| B | 1 200 | 15 | 10 R 7/8 | 10 R 4/4 | few (< 2%) | black | weak - medium | fine | granular | Red apedal B |
| **Soil Form** | | | Hutton | | | **Soil Family** | | | 2210 | |
| **Transect 2** | | | | | | | | | | |
| | | | **Colour** | | **Mottles/concretions** | | **Structure** | | | |
| **Horizon** | **Depth (mm)** | **Clay (%)** | **Dry** | **Wet** | **Occurrence (%)** | **Colour** | **Grade** | **Size** | **Type** | **Diagnostic Horizon** |
| A | 300 | 10 | 5 YR 5/6 | 5 YR 4/6 | None | None | apedal | fine | granular | Orthic A |
| B | 1 200 | 15 | 10 R 7/8 | 10 R 4/4 | few (< 2%) | black | weak - medium | fine | granular | Red apedal B |
| **Soil Form** | | | Hutton | | | **Soil Family** | | | 2210 | |
| **Transect 3** | | | | | | | | | | |
| | | | **Colour** | | **Mottles/concretions** | | **Structure** | | | |
| **Horizon** | **Depth (mm)** | **Clay (%)** | **Dry** | **Wet** | **Occurrence (%)** | **Colour** | **Grade** | **Size** | **Type** | **Diagnostic Horizon** |
| A | 300 | 10 | 5 YR 5/6 | 5 YR 4/6 | None | None | apedal | fine | massive | Orthic A |
| B1 | 600 | 15 | 10 R 7/8 | 10 R 4/4 | None | None | weak - medium | fine - medium | granular | Red apedal B |
| B2 | 1 200 | 15 | 2.5 YR 5/6 | 5 YR 4/4 | common (10%) | black | weak | medium | single grain | Yellow-brown B |
| **Soil Form** | | | Tongwane | | | **Soil Family** | | | 2210 | |

**Appendix IIII: The soil pH and EC from the three study sites.**

| Sample | pH | EC (µS/cm) | EC (mS/m) |
|---|---|---|---|
| **Pilanesberg Transect 1 topsoil** | 5.9 | 409.33 | 40.933 |
| **Pilanesberg Transect 2 topsoil** | 6.05 | 104.93 | 10.493 |
| **Pilanesberg Transect 3 topsoil** | 5.78 | 78.35 | 7.835 |
| **Pilanesberg Transect 3 subsoil** | 6 | 73.63 | 7.363 |
| **Legkraal Transect 1 topsoil (A1)** | 5.53 | 99.97 | 9.997 |
| **Legkraal Transect 1 topsoil (A2)** | 6.34 | 138.63 | 13.863 |
| **Legkraal Transect 1 subsoil** | 6.85 | 140.6 | 14.06 |
| **Legkraal Transect 2 topsoil (A1)** | 5.47 | 112.53 | 11.253 |
| **Legkraal Transect 2 topsoil (A2)** | 5.76 | 222 | 22.2 |
| **Legkraal Transect 2 subsoil** | 6.84 | 130.7 | 13.07 |
| **Legkraal Transect 3 topsoil** | 5.56 | 147.7 | 14.77 |
| **Legkraal Transect 3 subsoil** | 6.71 | 145.16 | 14.516 |
| **Kgomo-Kgomo Transect 1 topsoil** | 5.86 | 88.43 | 8.843 |
| **Kgomo-Kgomo Transect 1 subsoil** | 6.4 | 75.46 | 7.546 |
| **Kgomo-Kgomo Transect 2 topsoil** | 6 | 59.93 | 5.993 |
| **Kgomo-Kgomo Transect 2 subsoil** | 6.7 | 61.3 | 6.13 |
| **Kgomo-Kgomo Transect 3 topsoil** | 5.56 | 63.46 | 6.346 |
| **Kgomo-Kgomo Transect 3 subsoil (B1)** | 6.6 | 99.33 | 9.933 |
| **Kgomo-Kgomo Transect 3 subsoil (B2)** | 7.64 | 261 | 26.1 |

**Appendix JJJJ: The soil texture classes and soil particle distribution from the three study sites.**

| | Particle size distribution (%) | | | | |
|---|---|---|---|---|---|
| **Sample** | **Gravel (> 2 mm)** | **Sand (2 – 0.05 mm)** | **Silt (0.05 – 0.002 mm)** | **Clay (< 0.002 mm)** | **Texture class** |
| **Pilanesberg Transect 1 topsoil** | 21.63 | 56.56 | 36.56 | 6.88 | Sandy loam |
| **Pilanesberg Transect 2 topsoil** | 28.49 | 70.2 | 22.92 | 6.88 | Sandy loam |
| **Pilanesberg Transect 3 topsoil** | 24.97 | 59.84 | 33.28 | 6.88 | Loamy sand |
| **Pilanesberg Transect 3 subsoil** | 66.04 | 41.84 | 49.28 | 8.88 | Silt loam |
| **Legkraal Transect 1 topsoil (A1)** | 5.44 | 77.84 | 15.28 | 6.88 | Loamy sand |
| **Legkraal Transect 1 topsoil (A2)** | 28.4 | 41.84 | 51.28 | 6.88 | Silt loam |
| **Legkraal Transect 1 subsoil** | 36.35 | 39.84 | 53.28 | 6.88 | Silt loam |
| **Legkraal Transect 2 topsoil (A1)** | 5.86 | 62 | 32.56 | 5.44 | Sandy loam |
| **Legkraal Transect 2 topsoil (A2)** | 14.37 | 52 | 42.56 | 5.44 | Sandy loam |
| **Legkraal Transect 2 subsoil** | 27.84 | 42 | 52.56 | 5.44 | Silt loam |
| **Legkraal Transect 3 topsoil** | 12.74 | 54 | 40.56 | 5.44 | Sandy loam |
| **Legkraal Transect 3 subsoil** | 26.15 | 36 | 8.56 | 55.44 | Clay |
| **Kgomo-Kgomo Transect 1 topsoil** | 3.94 | 80 | 0.56 | 19.44 | Sandy clay loam |
| **Kgomo-Kgomo Transect 1 subsoil** | 9.64 | 70 | 2.56 | 27.44 | Sandy clay loam |
| **Kgomo-Kgomo Transect 2 topsoil** | 2.17 | 86 | 0.56 | 13.44 | Sandy clay loam |
| **Kgomo-Kgomo Transect 2 subsoil** | 9.46 | 76 | 4.56 | 17.44 | Loamy sand |
| **Kgomo-Kgomo Transect 3 topsoil** | 3.05 | 80 | 2.56 | 17.44 | Sandy clay loam |
| **Kgomo-Kgomo Transect 3 subsoil (B1)** | 19.83 | 68.56 | 6.56 | 24.88 | Sandy clay loam |
| **Kgomo-Kgomo Transect 3 subsoil (B2)** | 11.85 | 70.56 | 14.56 | 14.88 | Sandy clay loam |

**Appendix KKKK: Soil water retention (Volumetric water content in % at specific suction pressures in Bar) of the undisturbed core samples of the three study sites.**

| | Suction pressures (Bar) | | | |
|---|---|---|---|---|
| **Sample** | **1** | **5** | **10** | **15** |
| **Pilanesberg Transect 1 Middle** | 28.977 | 26.768 | 23.578 | 23.455 |
| **Pilanesberg Transect 1 End** | 30.609 | 30.241 | 28.277 | 28.155 |
| **Pilanesberg Transect 2 Beginning** | 25.607 | 22.908 | 20.331 | 20.208 |
| **Pilanesberg Transect 3 Beginning** | 23.549 | 22.445 | 21.586 | 21.218 |
| **Pilanesberg Transect 3 Middle** | 22.6 | 22.232 | 19.655 | 19.287 |
| **Pilanesberg Transect 3 End** | 32.447 | 32.324 | 32.324 | 32.079 |
| **Legkraal Transect 1 Beginning** | 26.253 | 23.799 | 22.203 | 21.222 |
| **Legkraal Transect 1 Middle** | 30.334 | 29.352 | 28.248 | 28.248 |
| **Legkraal Transect 1 End** | 26.32 | 25.707 | 22.394 | 21.289 |
| **Legkraal Transect 2 Beginning** | 29.703 | 20.623 | 18.414 | 17.923 |
| **Legkraal Transect 2 Middle** | 27.957 | 27.466 | 26.607 | 25.626 |
| **Legkraal Transect 2 End** | 27.702 | 26.72 | 21.198 | 20.83 |
| **Legkraal Transect 3 Beginning** | 26.163 | 23.341 | 22.605 | 22.482 |
| **Legkraal Transect 3 Middle** | 21.656 | 20.184 | 18.711 | 17.975 |
| **Legkraal Transect 3 End** | 24.746 | 23.642 | 21.556 | 21.433 |
| **Kgomo-Kgomo Transect 1 Beginning** | 22.427 | 22.304 | 20.463 | 20.463 |
| **Kgomo-Kgomo Transect 1 Middle** | 22.621 | 22.498 | 20.044 | 19.921 |
| **Kgomo-Kgomo Transect 1 End** | 26.557 | 23.121 | 18.09 | 18.09 |
| **Kgomo-Kgomo Transect 2 Beginning** | 20.322 | 20.322 | 16.396 | 16.396 |
| **Kgomo-Kgomo Transect 2 Middle** | 17.15 | 17.15 | 13.101 | 12.733 |
| **Kgomo-Kgomo Transect 2 End** | 22.622 | 17.836 | 13.051 | 13.051 |
| **Kgomo-Kgomo Transect 3 Beginning** | 25.319 | 18.57 | 17.711 | 17.11 |
| **Kgomo-Kgomo Transect 3 Middle** | 23.466 | 19.171 | 16.84 | 15.736 |
| **Kgomo-Kgomo Transect 3 End** | 25.318 | 24.95 | 22.005 | 21.637 |

**Appendix LLLL: The dry bulk density (Pb) and porosity of the undisturbed core samples taken from the three study sites.**

| | Soil property | |
|---|---|---|
| **Sample** | **Dry bulk density (Pb)** | **Porosity** |
| **Pilanesberg Transect 1 Middle** | 1.417 | 0.465 |
| **Pilanesberg Transect 1 End** | 1.572 | 0.407 |
| **Pilanesberg Transect 2 Beginning** | 1.142 | 0.569 |
| **Pilanesberg Transect 3 Beginning** | 1.285 | 0.515 |
| **Pilanesberg Transect 3 Middle** | 1.413 | 0.467 |
| **Pilanesberg Transect 3 End** | 1.295 | 0.511 |
| **Legkraal Transect 1 Beginning** | 1.153 | 0.565 |
| **Legkraal Transect 1 Middle** | 1.477 | 0.443 |
| **Legkraal Transect 1 End** | 1.285 | 0.515 |
| **Legkraal Transect 2 Beginning** | 1.136 | 0.571 |
| **Legkraal Transect 2 Middle** | 1.182 | 0.554 |
| **Legkraal Transect 2 End** | 1.239 | 0.533 |
| **Legkraal Transect 3 Beginning** | 1.134 | 0.493 |
| **Legkraal Transect 3 Middle** | 1.188 | 0.552 |
| **Legkraal Transect 3 End** | 1.647 | 0.379 |
| **Kgomo-Kgomo Transect 1 Beginning** | 1.902 | 0.282 |
| **Kgomo-Kgomo Transect 1 Middle** | 1.791 | 0.324 |
| **Kgomo-Kgomo Transect 1 End** | 1.704 | 0.357 |
| **Kgomo-Kgomo Transect 2 Beginning** | 1.714 | 0.353 |
| **Kgomo-Kgomo Transect 2 Middle** | 1.702 | 0.358 |
| **Kgomo-Kgomo Transect 2 End** | 1.727 | 0.348 |
| **Kgomo-Kgomo Transect 3 Beginning** | 1.680 | 0.366 |
| **Kgomo-Kgomo Transect 3 Middle** | 1.681 | 0.366 |
| **Kgomo-Kgomo Transect 3 End** | 1.771 | 0.332 |