WOODY PLANT ENCROACHMENT EFFECTS ON THE HYDROLOGICAL PROPERTIES OF TWO CONTRASTING SOIL TYPES IN BELA-BELA, LIMPOPO PROVINCE

by

REBONE EUTHINE MASHAPA

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SUPERVISOR: **DR PE DLAMINI (UL)**

CO-SUPERVISOR: **DR SS MTHIMKHULU (MUT)**

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Declaration

I declare that the mini-dissertation hereby submitted to the University of Limpopo, for the degree of Master of Science in Agriculture (Soil Science) has not previously been submitted by me for a degree at this or any other university; that it is my work in design and in execution, and that all materials contained herein have been duly acknowledged.

Mashapa RE (Miss) 23/04/2021

Dedication

I dedicate this dissertation to my parents Alfred Mandy and Matshidisho Eugide Mashapa and my siblings Tumisho and Surprise Mashapa.

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Abstract

Woody plant encroachment results in the degradation of grasslands. It is defined here as the increase in density, cover and biomass of woody plants into formerly open grasslands, reducing grassland productivity. Globally, many arid and semi-arid savanna grasslands are affected by this land cover transformation which changes the vegetation structure by altering the ratio of woody plants relative to grass species and influences soil hydrology. In the existing literature there is limited information on the effects of woody plant encroachment on soil physical and hydrological properties, especially in savanna grasslands. This study quantified and compared the soil physical and hydrological properties in the topsoil and subsoil of open and woody plant encroached grassland sites located on two contrasting soil forms, namely Bainsvlei and Rensburg. To achieve this objective, the two soils were sampled at various depth intervals from dug soil profiles at both sites at Towoomba Research Station in Bela-Bela, Limpopo Province, South Africa. Soil physical properties including bulk density, porosity and aggregate stability as well as hydrological properties (water retention and hydraulic conductivity) were determined from collected samples. Compared to open grassland, soil bulk density was 11% and 10% greater in the topsoil and subsoil, while porosity was respectively 6% and 9% lower in the topsoil and subsoil of woody plant encroached grassland for Rensburg soils. In Bainsvlei soil, there was a minimal increase and decrease in the soil bulk density and porosity, respectively. Soil aggregate stability increased by 38% in the subsoil of woody plant encroached grasslands in Rensburg soil, due to increasing clay content with depth. In Bainsvlei soil, the soil aggregate stability was 9% and 13% lower in the topsoil and subsoil of the woody plant encroached grasslands compared to open grassland. Furthermore, the results revealed that in both soils, there was lower soil water retention and hydraulic conductivity in the topsoil and subsoil layers of woody plant encroached grassland than in open grasslands. There were no significant differences observed for soil hydraulic conductivity in the Bainsvlei and Rensburg topsoil. The subsoil hydraulic conductivity decreased by 24% in Bainsvlei and 44% in Rensburg soils in the woody plant encroached grassland. The soil water retention (SWR) decreased with an increase in woody plants. Specifically, there was 25% and 42% decrease in SWR with woody plant encroachment in the topsoil and subsoil of Bainsvlei soil, respectively. The same trend was observed in the Rensburg soils with 50% and 19% decrease in

SWR in the topsoil and subsoil, respectively. Overall, the results revealed that soil type and depth influenced soil physical and hydrological properties in the studied woody plant encroached savanna grassland. As such, interventions aimed at controlling woody plant encroachment need to factor in soil type and depth in the development of management practices tailored to improve the soil hydrology of savanna grasslands.

Keywords: woody plant encroachment, soil physical properties, soil hydrological properties, soil water retention, soil depth, soil type.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Woody plant encroachment is an increase in the density and cover of woody plants in grasslands (van Auken, 2000). It is a land cover transformation that mostly occurs naturally and often results in the degradation of grasslands (Li *et al*., 2016). This land cover change has occurred in many grassland regions around the world over the last 100-150 years (van Auken, 2000). The annual rate of encroachment ranges from 0.1 to 0.4% in Africa (Acharya *et al*., 2018). In grasslands of semi-arid areas, woody plant encroachment has been correlated to higher runoff associated with reduced grass cover (Scott *et al*., 2006).

Woody plant encroachment into formerly open grasslands alters ecosystem structure and function. Changes in vegetation structure, following encroachment, is often characterized by a reduction in herbaceous cover and increased heterogeneity in both soil and vegetation resources (Puttock *et al*., 2014). The encroachment of trees can modify the stability of aggregates through the alteration of nitrogen (N), carbon (C) and organic matter levels (Liaoa *et al*., 2006).

Long-term prohibition of fire and continuous grazing of the communal rangelands have been reported to have induced the encroachment of woody plants to a level of more than 60% (Oba, 1998; Oba and Kotile, 2001)**.** Intensive grazing leads to bare soil surfaces which in turn increases erosion potential and causes unfavourable changes in soil chemical and physical properties (Castellano and Valone, 2007; Stavi *et al*., 2008). Soil compaction caused by livestock grazing (Geissen *et al*., 2009), depends on animal size, stocking density, soil texture, soil moisture and vegetation cover (Bilotta *et al*., 2007). Hoof action compacts soil through reduction in pore spaces (Drewry, 2006), which increases bulk density, especially on the soil surface (Liebig *et al*., 2006). Soil compaction, leads to reduced water infiltration and an increased surface water runoff (Asner *et al*., 2004) during rainfall.

1.2 Problem statement

Over the last decade, grasslands and savannas have been undergoing land cover change due to woody plant encroachment (Mureva *et al*., 2018). This landscape transformation is a major global challenge as woody plants become denser and are continually expanding beyond their range (Thompson *et al*., 2017). In South Africa, woody plant encroachment affects 10-20 million ha, seriously reducing the grassland productivity (Ward, 2005). This is a major problem for a country where more than 70% of its agricultural area is dominated by grazing lands (Hoffman and Ashwell, 2001). Woody plant encroachment into formerly open grasslands alters ecosystem structure and function. Changes in structure, following encroachment, is often characterized by a reduction in herbaceous vegetation cover and increased heterogeneity in both soil and vegetation resources (Puttock *et al*., 2014). Encroachment by woody plants particularly in dry semi-arid grasslands has been shown to influence soil hydrology, nutrient cycling, and ultimately land productivity (Hibbard *et al*., 2001). With regard to soil hydrology, woody plant encroachment alters soil infiltration rates, soil water storage, transpiration, interception, and subsurface pathways which affect groundwater recharge (Acharya *et al*., 2018). Of particular concern is its impact on deep drainage of water. Woody plants on average have larger and deeper rooting systems than herbaceous plants (Jackson *et al*., 1996), thus accessing water from deeper layers within the soil profile. Consequently, woody plant encroachment into open grasslands has the potential to reduce groundwater recharge, especially in water limited regions (Acharya *et al*., 2017). Increases in the density of woody plants in formerly open grasslands has important ecological, hydrological, and socio-economic implications (Huxman *et al*., 2005). Woody plant encroachment has profound impacts on the sustainable management of water resources (Acharya *et al*., 2018). Therefore, improving the understanding of how woody plants encroachment into open grasslands alter hydrological soil properties and processes is vital for effective management of water and vegetation.

1.3 Rationale

The impact of a land cover transformation on soil hydrology associated with woody plant encroachment is a major global research area. Open savanna grasslands are under rapid transition to woody plant encroached grasslands, which has raised interest in understanding the plant, soil and water nexus in these ecosystems (Acharya *et al*., 2017). Woody plant encroachment influences different components of the soil water balance including evapotranspiration, surface run-off and drainage. These effects vary with climate, vegetation and edaphic factors (Huxman *et al*., 2005; Moore and

Heilman, 2011). Some studies have reported that conversion of herbaceous vegetation to woody life forms increases water loss by transpiration and evaporation (Caterina *et al*., 2014; Zou *et al*., 2015; Liu *et al*., 2017). An increase in evapotranspiration is likely to occur in semi-arid and sub-humid regions as the ratio of bare ground to vegetated ground decreases with encroachment (Huxman *et al*., 2005). Woody plant encroachment alters transpiration, interception (Zou *et al*., 2015; Acharya *et al*., 2017) and soil physical properties, which in turn leads to changes in soil infiltration rate, soil water storage (Zou *et al*., 2015), and subsurface flow pathways (Qiao *et al*., 2017). All these factors affect stream flow and water drainage (Wilcox, 2002; Qiao *et al*., 2015). The impact of woody plants on drainage and water retention varies with soil type, texture and depth (Huang *et al*., 2006; Schwinning, 2008; Moore *et al*., 2012; Wilcox *et al*., 2017). With woody plant encroachment, the vertical movement of water in deep soil matrix is interfered by the change in rooting pattern or depth, which results from the change in plant functional type.

Changes in ecosystem productivity and biogeochemical cycling have been widely reported when herbaceous vegetation is replaced by woody plants, but limited information is available on how woody plant encroachment alters soil hydrological properties. As such, the link between woody plant encroachment and soil hydrology in savanna grasslands has not been well established. An improved understanding of woody plant encroachment effects on physical and hydrological properties is necessary to ensure sustainable functions of savanna grasslands and to develop land-based mitigation and adaptation strategies (Acharya *et al*., 2018).

1.4 Purpose of the study

1.4.1 Aim

This project seeks to provide an improved understanding on how an increase in woody plant encroachment affects soil physical and hydrological properties in semi-arid savanna grasslands.

1.4.2 Objectives

The specific objective of the study was:

a. To determine the effects of woody plant encroachment on physical and hydrological properties in the topsoil and subsoil of two contrasting soil types.

1.4.3 Research questions

This study seeks to address the following research questions.

a. How are the soil physical and hydrological properties of two contrasting soil types affected by woody plant encroachment in a savanna grassland?
b. How do the soil physical and hydrological properties vary in the topsoil and subsoil layers of the woody plant encroached grassland?

1.4.4 Dissertation structure

This dissertation is organized into four chapters, with chapter 1 providing a background of woody plant encroachment, its causes and effects on soil physical and hydrological properties. The chapter also presents the objectives of the study, the aim and research questions. Chapter 2 provides a detailed literature review on the causes of woody plant encroachment and its effects on the soil physical and hydrological properties. Chapter 3 addresses the two research questions, with research question 1 describing the effects of woody plant encroachment on the physical and hydrological properties of soil and research question 2 describing the effects of different soil types on soil physical and hydrological properties in woody plant encroached grasslands. The chapter also discuss the findings from the research. Chapter 4 provides a summary and conclusion on the findings of the study.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Increase in woody species in savannas has been evident over the last century (Moleele and Perkins, 1998; Devine *et al*., 2017). Woody plant encroachment is facilitated by several factors such as rainfall, fire suppression, and grazing. It is considered a threat to grasslands because of the suppression of productivity of herbaceous plant species (Ward, 2005). This has resulted in reduced grass cover, poor range condition, and subsequently poor livestock productivity (de Klerk, 2004; Espach, 2006).

2.2 Causes of woody plant encroachment in savanna grasslands

2.2.1 Rainfall

Rainfall seasonality reduces the rate of canopy closure (Sarmiento, 1984) and increases fire frequency (Archibald *et al*., 2009). Fires can occur more frequently since fuel drying is promoted by pronounced seasonality in rainfall, affecting the spatial distribution and temporal availability of fuel (Bradstock, 2010). In addition, the presence or absence of savanna vegetation is related to inter-annual rainfall variability and the probability of drought. Drought can increase tree seedling mortality and decrease the growth rate of adult trees (Fensham *et al*., 2009). In arid and semi-arid environments, the woody cover and density tend to increase with increasing mean annual precipitation (Sankaran *et al*., 2005). Increased soil moisture availability, particularly when there is limited competition from grasses, allows woody plant seedlings to survive and grow into bush thickets. Grasses have adventitious roots which rely on the topsoil moisture for growth. Thus, during dry seasons, the topsoil moisture gets depleted and if the season is prolonged, the grasses may wither and die. The influence of drought on woody plant encroachment varies with the type of encroaching species. For example, relatively drought-sensitive *Eucalyptus* largely decline during dry seasons while high drought tolerant species such as *Allocasuarina* stand. *Eucalyptus* decline was attributed to competition for soil moisture beneath encroaching *Allocasuarina* (Withers and Ashton, 1977).

2.2.2 Fire suppression

Fire is one of the drivers of the structure of savanna grasslands (Scholes and Archer, 1997). In order for fire to occur, the source of ignition as well as fuel that is adequately dry, abundant and dense enough to sustain its spread across a landscape are needed. Fire therefore typically occurs in regions with between 450 and 1 800 mm of annual rainfall and in particular, a prolonged dry season in which fuel has the opportunity to dry out sufficiently to burn grasslands (Scholes and Archer, 1997). On the drier end of the range at the transition into semi-arid woodland, low annual rainfall limits the growth and accumulation of a fuel load that is adequate enough to sustain fire. On the wetter end of range, at the boundary between dry forests and moist forests, fuel loads are generally too moist year-round to allow fire to occur. This is often not only a result of the amount of rainfall, but also its seasonality. Outside of moist forests, a single wet season and importantly a prolonged dry season of 7–8 months, provides enough time for fuel to dry sufficiently to burn (Turpie *et al*., 2019).

The canopy in savanna and woodlands is generally not continuous, and often being deciduous, loses a potential leaf fuel load during the dry season in which fire may occur. These factors limit the potential for intense canopy fires in South African rangelands (Turpie *et al*., 2019). However, a number of factors can lead to a decrease in fuel loads and the intensity of surface fires, which in turn allow woody plants to survive and thrive over time. Perhaps the most prominent factors are the consumption of the grass layer by grazing herbivores as well as early-season burns that combust the grass layer in a low-intensity manner before a substantial fuel load can accumulate (Turpie *et al*., 2019). A further driver that is particularly pertinent to woody plant encroachment, is the suppression of the grass layer under the canopy of trees. As the canopy cover increases, the amount of light and precipitation reaching the grass layer decreases. This leads to a tree-dominated state where a lack of fire allows the further survival and growth of trees, which further suppresses the grass layer and the probability of fire (Turpie *et al*., 2019).

2.2.3 Grazing

The amount of grazing versus browsing pressure within a savanna grassland has the ability to shift the observed balance between grasses and woody plants. An increase in grazing pressure has the ability to hinder the growth of grasses as well as the opportunity for intense fires as grass fuel loads are reduced (Lesoli *et al*., 2013). In time, this may result in the grassland shifting to a more bush encroached state. This scenario is often observed on commercial cattle farms, where grazing pressure is often increased significantly and sustained for a longer portion of the year. With no corresponding increase in browsing pressure, this often leads to a more woody plant encroached grassland (Moleele *et al*., 2002; Scholes, 2009). In a study of South African grassy biomes, Skowno *et al*. (2016) noted that the area of closed woodland on commercial farms and traditional grasslands increased by 0.19% per year over the period 1990–2013.

The opposite trend may also occur where browsing pressure increases excessively to grazing pressure. Within conservation areas, an increase in elephant browsing pressure and their ability to uproot adult trees can lead to the gradual opening up of woodlands to a more open savanna state (Stevens *et al*., 2016). Skowno *et al*. (2016) found that the area of woodlands in protected areas with elephants decreased by 0.43% per year over the 23-year period of their study. The decrease in tree canopy cover may allow grasses to flourish, which in turn may lead to more intense fires and the shift of the grasslands into a more open state over time.

2.2.4 Soil properties

Soil texture is the main soil property that affects the encroachment of woody plants in savanna grasslands. It regulates the hydraulic conductivity and water retention, resulting in differential access to subsurface water based on life-form rooting patterns of deeply rooted shrubs versus shallow rooted grasses (Jackson *et al*., 1996). Generally, coarse-textured soils favour woody plants while finer-textured soils favour grasses (Scholes and Archer, 1997). This is because course textured soils are dominated by macropores, which allow free movement of water into deeper horizons (Walker and Noy-Meir, 1982) where it can be easily accessed by plant roots. In contrast, fine textured soils are dominated by micropores, which hinder the percolation of water into deeper soil horizons. The micropores increase water retention capacity of soils in the upper horizons (Dye and Spear, 1982) favouring the growth and development of grasses.

2.3 Impacts of woody plant encroachment on soil physical properties

2.3.1 Bulk density

The reduction of the vegetation cover as a result of woody plant encroachment increases bare soil surfaces, which in turn increases bulk density and decreases water infiltration as well as nutrient concentration (Castellano and Valone, 2007; Stavi *et al*., 2008). An increase in the soil bulk density results in the reduction of pore sizes, which increase surface runoff during rainfall. Mzezewa (2009) observed a higher bulk density of >1.6 g cm^{-3} under woody plant encroachment compared to open savanna grasslands, in a study that was conducted in the Bulawayo Syndicate Block and Shangani Farm, Zimbabwe. The soils on the study sites are developed on gneissic granite parent material and they are generally shallow with a sandy texture. A study by Snyman and Du Preez (2005) found that woody plant encroached soils have low organic matter content due to reduced grass cover, which results in increased soil bulk density. A study by Mesele *et al*. (2006) observed a higher bulk density in the sandy loam soils of woody plant encroached areas (1.70 g cm^{-3}) than in the clay loam soils of open grasslands (1.37 g cm^{-3}) sampled at 0-20 cm in the Borana Plateau, Ethiopia. In agreement to these findings, Parizek *et al.* (2002) also observed slightly higher bulk density (1.10 g cm^{-3}) under woody plant encroachment than in open grassland (1.06 g cm^{-3}) in the topsoil (0-5 cm) of Xeric Calciargids of Patagonia.

2.3.2 Aggregate stability

The organic matter added to the soil is reduced by the reduction of grass cover in areas encroached by woody plants and subsequently contribute to reduced soil structural stability, protection against rainfall impact and infiltration rate (Roose and Barthes, 2001; Snyman and Du Preez, 2005). Once continuous grass cover is fragmented, exposure of the soil surface to raindrop impact, wind, and overland flow across interconnected bare areas causes erosion (Wilcox *et al*. 2003). Increased erosion further depletes soil organic matter, while inputs are reduced due to the absence of plant cover leading to a decline in soil microbial populations that stabilize soil macro aggregates (Tisdall and Oades, 1982; Oades, 1984; Emerson *et al*., 1986; Oades and Waters, 1991). Consequently, soil structure breaks down, infiltration rate diminishes, and resources that support local grass reproduction decline, feeding back to increased erosion rates (Cerda, 1998).

A study by Podwojewski *et al*. (2014) reported higher soil aggregate stability (3.17 ± 0.16 mm), estimated by mean weight diameter, in open grasslands compared to woody plant encroached (2.96 ± 0.16 mm) areas. Pierson *et al*. (2010) determined the effect of woody plant encroachment on soil aggregate stability in areas under tree canopy versus areas between the canopies (inter-canopy). In their study, they observed that in areas under tree canopy, the plant litter offer soil protection from rain splash effects, provide rainfall storage, improves water infiltration and favours greater aggregate stability. In their aggregate stability tests, Pierson *et al*. (2010) observed soil aggregate stability of 25–75% under tree canopies and less than 10% stable on interspace areas.

2.4 Woody plant encroachment impact on soil hydrological properties

2.4.1 Hydraulic conductivity

The soil hydraulic conductivity refers to the ease with which water moves through the soil pore spaces, and is affected by soil structure as well as by texture (Bhattacharyya *et al*., 2006). Soil hydraulic conductivity is greater in highly porous and aggregated soils than in tightly compacted and dense soils. It was observed in several studies that woody plant encroachment leads to high soil compaction and bulk density, which then reduces the soil pore sizes. Soils under woody plant encroachment, therefore, have low hydraulic conductivity as a result of reduced pore sizes (Bhattacharyya *et al*., 2006).

Woody plant encroachment alters transpiration, interception (Zou *et al*., 2015; Acharya *et al*., 2017) and soil physical properties which in turn leads to changes in soil hydraulic conductivity, soil water storage (Zou *et al*., 2015), and subsurface flow pathways (Qiao *et al*., 2017); all of which affect stream flow and water drainage (Wilcox, 2002; Qiao *et al*., 2015). A study by Bhattacharyya *et al*. (2006) stated that highly porous and aggregated soils have greater hydraulic conductivity than compacted and dense soils. Changes in vegetation type influence carbon accumulation in the soil, which could seriously influence soil organic matter content and soil bulk density (Zhang *et al.*, 2001). Once these properties are altered, soil hydraulic characteristics will change, leading to different soil water storage capacities and hydrological processes (Green *et al*., 2003).

Studies have found higher hydraulic conductivity in open grassland soils due to a number of factors including the protection of the soil surface by grass cover, enhanced aggregation of soil particles, and more developed macropore networks (Dunkerley, 2000; Wilcox *et al*., 2003). Owing to these effects, the magnitude of hydraulic conductivity and soil moisture has been shown to be higher under open grassland than woody plant encroached areas in certain conditions (Bhark and Small, 2003). Overall, it is reported that the impacts of woody plant encroachment on hydraulic conductivity are mixed, depending on climate, vegetation types, vegetation canopy cover and grazing regime (Bhark and Small, 2003).

2.4.2 Drainage and water retention

The impact of woody plant encroachment on drainage and water retention varies with soil type, texture and depth (Richardson *et al*., 1979; Huang *et al*., 2006; Schwinning, 2008; Moore *et al*., 2012; Wilcox *et al*., 2017). Soil texture and soil depth affect pore size distribution in soil, water retention capacity and water available for transpiration, all of which affect drainage. Fine textured soils have higher water retention capacity than coarse-textured soils due to more pore space. Clayey soils have more micropores and thus higher plant available water than coarse-textured soils. However, water may move slowly through clayey soils due to small grain size and greater surface area, which renders lower specific yield and drainage (Acharya *et al*., 2018). A study by Jobbágy and Jackson (2004) reported that coarse-textured soils with higher hydraulic conductivity had higher drainage, while in fine-textured soils drainage was negligible. Kennett-Smith *et al*. (1994) reported that drainage decreases as clay content increases from 0 to 25% in the top 2 meters soil profile. Increasing depth of layers with low permeability will reduce the downward flux of water. Kim and Jackson (2012) reported 50% more drainage in sandy soils compared to clayey soils.

Several studies showed high water retention in open grassland than in woody plant encroached grassland. This may be as a result of compaction caused by removal of grass cover with encroachment. Compaction reduces soil water retention through its adverse effects on both field capacity and permanent wilting point (USDA, 2005). Compaction reduces total pore volume, consequently reducing water retention when the soil is at field capacity. Compaction also crushes large soil pores into much smaller micropores. Since micropores hold water more tightly than larger pores, more water is held in soil at its permanent wilting point (USDA, 2005).

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CHAPTER 3

DIFFERENTIAL EFFECTS OF WOODY PLANT ENCROACHMENT ON PHYSICAL AND HYDROLOGICAL PROPERTIES IN THE TOPSOIL AND SUBSOIL LAYERS OF CONTRASTING SOILS IN A SAVANNA GRASSLAND

Abstract

There is limited information in arid and semi-arid savannas on the impacts of woody plant encroachment on soil physical and hydrological properties. The objective of the study was to determine the impacts of woody plant encroachment on soil physical and hydrological properties of Bainsvlei and Rensburg soils in a savanna grassland at Towoomba Research Station in Bela-Bela, Limpopo Province in South Africa. The vertical distribution of soil aggregate stability, bulk density, porosity and hydraulic conductivity was quantified in woody plant encroached grassland and compared to adjacent open grassland sites from the contrasting soils. Soil bulk density increased while porosity and aggregate stability decreased with depth in both open and woody plant encroached grassland soils. In the Rensburg soil, bulk density was 11% and 10% greater in the topsoil and subsoil, while porosity was 6% and 9% lower in the topsoil and subsoil of woody plant encroached grassland compared to open grassland. In Bainsvlei soils, there was a slight increase and decrease in the soil bulk density and porosity, respectively. The soil aggregate stability was 38% higher in the Rensburg subsoil in the woody plant encroached grassland due to increasing clay content with depth. In Bainsvlei soils, the soil aggregate stability was 9% and 13% lower in the topsoil and subsoil of woody plant encroached grasslands, respectively. The soil hydraulic conductivity decreased by 24% and 44% in the subsoils of Bainsvlei and Rensburg, respectively as a result of woody plant encroachment. Compared to open grasslands, woody plant encroachment led to 25% and 42% decrease in SWR in the topsoil and subsoil of Bainsvlei soils, respectively. The same trend was observed in the Rensburg soils with 50% and 19% decrease in the topsoil and subsoil, respectively. The results showed that woody plant encroachment has a negative impact on the soil hydrological properties since it reduced the SWR in all soil types in the topsoil and subsoil. An improved understanding on how woody plant encroachment affects soil hydrological and physical properties is very important for proper management of grasslands.

Keywords: woody plant encroached grassland, soil physical properties, soil hydrological properties, soil depth, soil type.

3.1 Introduction

Savanna grasslands are described as landscapes with continuous grass cover and scattered trees (Mishra and Young, 2014). They cover approximately 52 million km^2, which is approximately 40% of global land surface (White *et al*., 2000; Gibson, 2009). Global changes in the form of precipitation, temperature regimes, elevated atmospheric CO_2 and atmospheric N and P deposition have emerged as major threats to the ecological integrity of savanna grasslands (Bond and Midgley, 2012; Midgley and Bond, 2015). Savanna grasslands are important to the variety of ecosystem services because they provide livestock grazing areas and water catchments.

Woody plant encroachment is a widespread and severe phenomenon resulting in the degradation of savanna grasslands worldwide. In southern Africa, 13 million hectares are subject to bush encroachment (Trollope *et al*., 1989), and, along with the loss of savanna systems, are believed to affect more than two billion people worldwide (Adeel, 2008). Fire suppression, increased atmospheric CO_2 concentrations and decreased grazing have all been suggested to encourage woody plant encroachment (van Auken, 2009). Woody plant encroachment alters water and nutrient availability (Schlesinger *et al*., 1990; Scholes and Archer, 1997), which are the key resources for many savanna grassland species (Chapin, 1980; Knapp and Smith, 2001). Vegetation structure is closely linked to hydrological processes, and several studies have shown that increasing woody plant cover on savanna grasslands causes a decrease in water yield (Calder, 1998; Doody *et al*., 2011; Le Maitre *et al*., 2015)

Savanna grasslands have the highest saturated hydraulic conductivities (K_{sat}) because of their high porosities (Liu *et al*., 2015). Woody plant encroached grasslands have the lowest since they are less productive ecosystems and their soils are often shallow, poorly structured, less permeated by roots and soil organisms that develop macroporosity. The K_{sat} rates for most savanna grasslands range from 8 to 612 mm hr^{-1} (Liu *et al*., 2015). Heavily grazed grasslands can have significantly lower rates due to compaction from animal traffic.

Water availability, disturbance (e.g. fire, grazing) and nutrient availability are considered to be the three major factors determining the structure and function of savanna ecosystems (Scholes and Archer, 1997). For example, English *et al*. (2005) revealed that different grassland cover influenced soil moisture at different soil depths in a semi-arid environment. Wang *et al*. (2015) showed that woody plant encroachment reduced the temporal stability of soil moisture. Acharya *et al*. (2016) found that eastern redcedar (*Juniperus virginiana*) encroachment resulted in a more frequent depletion of soil water at the 80 cm soil depth. O ̈zkan and Go ̇kbulak, (2017) compared the effects of woody and herbaceous vegetation cover on soil moisture, and they reported that the removal of woody vegetation significantly increased the overall mean daily moisture of the soils from 32% to 48% (Yang *et al*., 2018).

Researchers have focused on the influence of woody plant encroachment on soil moisture and have found that different plant species can affect the temporal and spatial characteristics of the soil water content (Musa *et al*., 2014; Zhuang *et al*., 2015). The temporal and spatial characteristics of soil water content are variable under different vegetation types (Chen *et al*., 2007; Yang *et al*., 2014). Vegetation distribution also affects the spatial changes in SWC patterns (Kong *et al*., 2009; Zhao *et al*., 2010; Wang *et al*., 2015). These studies illustrated that woody plant encroachment can consume great amounts of soil moisture and cause soil drying (Yang *et al*., 2018). Woody plant encroachment into previously open grasslands is widespread but the effect of this encroachment on soil hydrological properties is less known. This gap creates uncertainty in understanding the effects of woody plant encroachment on hydrological properties and hinders management of encroached savanna grasslands. The study seeks to understand how woody plant encroachment affects soil physical and hydrological properties of two contrasting soil types in a savanna grassland.

3.2 Methodology

3.2.1 Site description

The study was conducted at Towoomba Research Station (28°19’26.69 S, -24°53’53.61 E) at Bela-Bela, in the Limpopo Province of South Africa. The site is located on a relatively flat (0 - 2%) landscape position, with an altitude of 1184 m above sea level. The long-term annual rainfall is 639 mm, and daily average temperatures vary between 23.9ºC in December to 12ºC in July (Mills *et al*., 2017). The northern and north-western parts of site are dominated by Bainsvlei soil form of Moorfield family (Soil Classification Working Group, 1991) derived from a dolerite parent material (Fey, 2010). The vegetation of the study area is classified as Springbokvlakte Thornveld (Mucina and Rutherford, 2006). The woody plant layer on the Bainsvlei soil is dominated by *Dichrostachys cinerea* and *Vachellia* (*Acacia) hebeclada* and the grass layer is dominated by *Eragrostis species* (*E.barbinodis* and *E.rigidior*), *Panicum maximum*, *Themeda triandra* and *Heteropogon contortus* (Mucina and Rutherford, 2006). The southern and south-eastern parts of the site are dominated by Rensburg soil form of Greendale family (Soil Classification Working Group, 1991) derived from basalt parent material (Fey, 2010). The woody plant layer in the Rensburg soil is dominated by *Vachellia* (*Acacia) hebeclada*, *Grewi*, *Gymnosporia* and *Rhus species*, while the grass layer is dominated by species such as *Aristida bipartita*, *Themeda triandra*, *Iscaemum* and *Setaria* (Mucina and Rutherford, 2006).

3.2.2 Experimental design and sampling in the field

A soil and vegetation survey were carried out in 2018 at the Towoomba Research Station in a woody-encroached grassland (Figure 1). Eight 10 m × 10 m plots were set up along the woody plant encroachment grassland in open and intensively woody plant encroached sites following Dlamini *et al*. (2019). During the vegetation survey, tree density, which is an estimate of the number of individual trees per plot was determined and used to categorize the sites into two woody plant encroachment levels; open and intensive according to Mogashoa *et al*. (2020). The savanna grassland was characterized into two categories, viz, <450 trees ha^{-1} representing open grassland and >450 representing woody plant encroached grassland. Within each plot, woody plants were identified and described following van Wyk and van Wyk (1997), while grasses were identified following van Oudtshoorn (2014).

Four plots (10 m × 10 m) were randomly selected within each soil type and marked from each encroachment level, with open grasslands serving as the reference site (Dlamini *et al*., 2019). Soil sampling was then done on Bainsvlei and Rensburg soil forms. In each soil type, four soil pits were randomly dug, with two pits in open grassland and the other two in woody plant encroached grassland sites, yielding a total of eight pits across the study site. The pits were excavated down to the limiting layer of Bainsvlei and Rensburg soils. In each soil pit, soil samples were collected in 5 cm (0-5, 5-10) and 10 cm (10-20) depth intervals in the topsoil (0-20 cm) and 20 cm depth intervals in the subsoil (20-100 cm) at interstitial areas beyond woody plant canopies but within the range of extension of the root zone following Dlamini *et al*. (2019). Three replicate bulk samples (represented by pit phases A, B and C) were collected from each of the two soil types at 0-5, 5-10, 10-20, 20-40, 40-60 cm depth for Bainsvlei soils and 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, 80-100 cm depth for Rensburg soils. Three additional undisturbed soil cores were collected for bulk density at each depth by inserting a metallic core ring (0.05 m height and 0.078 m diameter) into the soil using a core sleeve guide and hammer to insert the core ring to the correct depth. The ringed cores were trimmed to equal the ring equivalent volume. This was done to ensure that no excess soil protruded out from the ring face. Overall, 60 bulk samples were collected in the Bainsvlei soil and 84 in the Rensburg soil, making a total of 144 bulk samples, with 264 additional samples for bulk density. Compared to Rensburg soils, Bainsvlei soils were sampled up to 60 cm depth because of the plinthites. This was done to ensure that no additional mass was added to the soil sample as a result of plinthites which may increase the bulk density.

Four undisturbed cores samples were collected from one phase (i.e. phase A) of each pit, where two samples were collected within the first 10 cm depth of the topsoil and the other two within the first 20 cm depth of the subsoil. The number of undisturbed core samples collected per pit were four, making a total number of 32 undisturbed core samples collected from the study area, which were then taken to the South African Sugarcane Research Institute (SASRI) for analysis of the soil water retention and hydraulic conductivity.

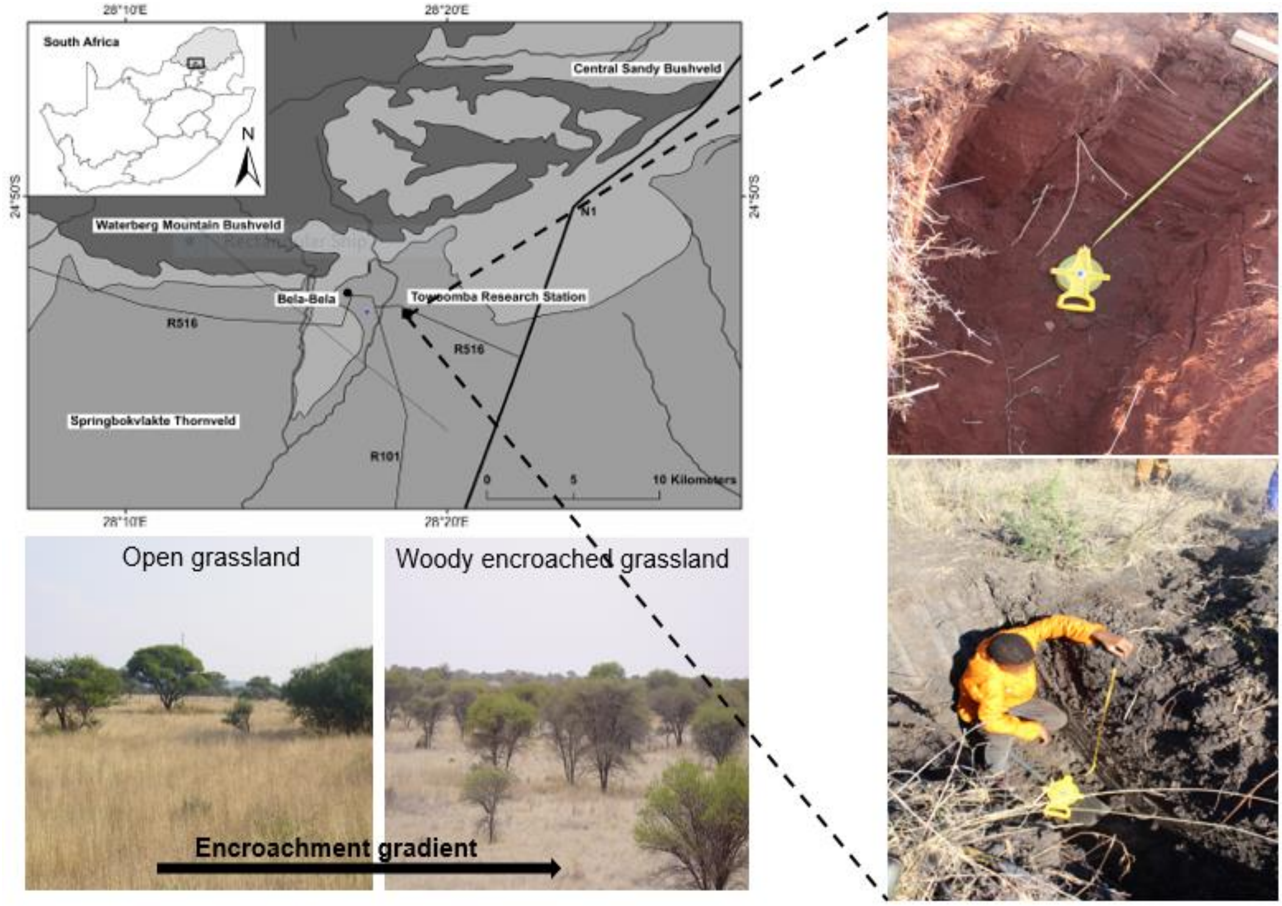

Figure 1. Location of Towoomba Research Station in the Southern Springbok Flats of Limpopo Province in South Africa. The location map was sourced from Mills *et al*., (2017).

3.3 Laboratory analysis

3.3.1 Determination of soil physical and chemical properties

Particle size distribution was determined using the hydrometer method (Bouyoucos, 1962). Soil aggregate stability was determined using the wet -sieving method by (Six *et al*., 1998). Soil colour was determined using the Munsell soil colour chart (Munsell Colour Company Incorporation, 1988). Soil pH was determined using Hanna Edge pH model through the electrometric method (Rhoades, 1982).

Undisturbed soil core samples used to determine bulk density and total porosity were dried in an oven at 105°C for 48 hours to obtain total mass of dry soil within the core (Blake and Hartge, 1986). Subsequently, soil bulk density defined as the mass per unit volume of dry soil was determined using equation 1:

$$\rho_s = \frac{M_s}{V_c} \qquad \text{Equation 1}$$

Where: ρ_s = soil bulk density (g cm^{-3}); M_s = dry soil mass (g); V_c = core volume (cm^3). Thereafter, porosity defined as the ratio of pore volume to total soil volume was calculated using equation 2:

$$\varphi = \left[1 - \left(\frac{\rho_s}{\rho_p}\right)\right] \times 100 \qquad \text{Equation 2}$$

Where: φ = total porosity; ρ_s = soil bulk density (g cm^{-3}); ρ_p = soil particle density (g cm^{-3}). The particle density for porosity measurement was assumed to be 2.65 g cm^{-3} which is a constant value for arable, mineral soils (Schjønning *et al*., 2016).

3.3.2 Determination of soil hydrological properties

The soil water retention and saturated hydraulic conductivity were analysed according to Klute (1965). The soil water release characteristics are defined here as the relationship between water and porosity. A tension table apparatus was used at the laboratory facilities of the South African Sugarcane Research Institute (SASRI). In the laboratory, the undisturbed trimmed core samples were weighed for the calculation of initial water content. The cores were then saturated by standing them in a trough, with gradual addition of water until the water level was about 3 mm from the top of the core. Samples were wetted from the bottom in order to avoid wetting the upper soil surface and to minimize air-entrapment. The cores were then left to soak overnight until they were saturated. For measurement of water retention in the 0-1.0 m (0-10 kPa) tension range, the core and the lid were removed from the water while dripping wet and weighed on a top pan balance. The core was then transferred to the tension table, with the tension set at 0.10 m. The top of the tension cable was covered with a Perspex sheet in order to minimize evaporation. The core was weighed after 48 hours and replaced on the tension table with applied pressure to achieve good soil bed contact. The procedure was repeated for tensions 0.30, 0.40, 0.50, 0.75 and 1.00 m of water pressure.

For measurement of water retention in the 10-100 kPa range, the cores were transferred to the pressure pot, placing each core on a saturated disc filter paper on the 100 kPa ceramic plate. The lid of the chamber was closed and a pressure of 50 kPa was applied by adjusting the pressure regulator. The outlet from the ceramic plate was connected to an external burette to allow the monitoring of water outflow from the soil cores in response to the applied pressure. When there was no change in the level of water in the burette over an 8-hour period, it was taken that equilibrium has been reached. It usually takes 7-10 days for equilibrium to be reached. The core samples were then returned to the chamber and the process was repeated at a pressure of 100 kPa. After weighing each core, the nylon cloth and rubber band were carefully removed and weighed, and the inverted core placed in the oven. The cores were then dried at 105 °C for at least 4 days, and then weighed after cooling. The lid and the sleeve were also weighed in order to calculate the volume of the sleeve from the height and radius. These measurements were then used to calculate the bulk density, water content at the various matric potentials and the pore size distribution.

For measurement of water retention at 1500 kPa tension, the retaining rings (10 mm high × 50 mm diameter) were placed on discs of filter paper with a ceramic plate set up in the high-pressure chamber. The rings were filled with air-dried <2 mm soil, and compact slightly with a rubber bung. Water was applied to the ceramic plate to slowly wet up the soil by capillary movement. The soil was allowed to soak for about 30 minutes, after which the chamber was closed and a pressure of 1500 kPa was applied. The water level in the burette connected to the outlet from the ceramic plate was observed until equilibrium was reached. After equilibrium was reached, the pressure was released and the lid was removed from the pressure chamber. The soil from each sample was then transferred to a 50 mL beaker and oven dried for measurement of the water content.

The saturated hydraulic conductivity (K_{sat}) was determined directly after the measurements of water retention. It was measured using a brass permeameter with the undisturbed soil core sample that was supported vertically on the outflow funnel and then water was admitted into the top of the permeameter (US Salinity Laboratory Staff, 1954). A fixed head of water was maintained (30 mm) in the top of the permeameter using a Marriott bottle system. The time water was first admitted and time taken to percolate through the base was recorded. At regular intervals (± 2 or 3 times a day) the amount of water percolating per unit time was measured. This was continued until the volume percolating in a fixed time remained constant. The K_{sat} was calculated using Equation 3.

$$K_{sat}\ (\text{cm hr}^{-1}) = \left[\left(\frac{V}{A \times t}\right) \times \left(\frac{L}{\Delta H}\right)\right] \qquad \text{Equation 3}$$

Where: V is the volume of water (mm) collected for time period of t (minutes), A is the cross sectional area of the core (mm^2), L is the length of the soil core (mm) and ΔH is the hydraulic head (mm).

3.4 Statistical analysis

Basic statistics (minimum, maximum, average, median, standard deviation and standard error) were computed following Webster (2001). Difference between means was used to generate a scatter with straight line and markers with error bars, showing a comparison for vertical distribution of the physical and hydrological properties in both open and woody plant encroached grassland. For each soil type, two-way analysis of variance (ANOVA) was conducted to determine the effects of encroachment level and soil depth on soil physical and hydrological properties using Genstat (18th edition). These soil properties were compared among open and woody-encroached grasslands using Tukey's HSD (Honestly Significant Difference) post hoc tests at $P < 0.05$. Graphs showing the vertical distribution of the measured soil properties were generated using Microsoft Excel.

3.5 Results

3.5.1 The morphological characteristics of Bainsvlei and Rensburg soil profiles.

As indicated in Table 1, the Bainsvlei soil was characterized by a dark reddish brown (2.5YR 2.5/4) Orthic A horizon (0-20 cm), with a weak sub-angular blocky structure. The horizon is underlain by a Red Apedal B horizon (20-40 cm). Underlying this horizon is the Soft plinthic B horizon (40-60 cm). The dominating textural class in the open and encroached grassland is loamy sand and sandy loam, respectively. Particle size distribution in the open grassland ranged between 6-14% clay, 3-7% silt and 80-90% sand while in the encroached grassland it ranged from 7-21% clay, 7-13% silt and 70-86% sand. The Bainsvlei soil had a pH (KCL) ranging between 4.32-4.84. The Rensburg soil was characterized by a very dark grey (2.5Y 3/1) Vertic A horizon (0-20 cm), with a strong blocky structure. The horizon is underlain by G horizon (20-100 cm). The dominating textural class in both open and encroached grassland is sandy clay loam. Particle size distribution in the open grassland ranged between 20-47% clay, 6-21% silt and 38-64% sand while in the woody encroached grassland it ranged from 9-41% clay, 5-20% silt and 54-77% sand. The Rensburg soil was characterised by a pH (KCL) varying between 5.48 and 7.

Table 1. Morphological characteristics of Bainsvlei and Rensburg soil profiles sampled from open and woody plant encroached grassland sites.

PROFILE	Soil type	Sites	Depth (cm)	Thickness (cm)	pH (KCl)		Dry colour	%Clay	%Silt	%Sand	Textural class
1	Bainsvlei	Open	0-5	5	4.84	2.5YR2.5/4	Dark reddish brown	7	3	90	Sand
1	Bainsvlei	Open	5-10	5	4.76	2.5YR2.5/4	Dark reddish brown	6	4	90	Sand
1	Bainsvlei	Open	10-20	10	4.77	2.5YR2.5/4	Dark reddish brown	10	4	86	Loamy sand
1	Bainsvlei	Open	20-40	20	4.65	2.5YR2.5/4	Dark reddish brown	14	3	83	Loamy sand
1	Bainsvlei	Open	40-60	20	4.48	2.5YR2.5/4	Dark reddish brown	13	7	80	Loamy sand
2	Bainsvlei	Open	0-5	5	4.75	2.5YR2.5/4	Dark reddish brown	8	5	87	Loamy sand
2	Bainsvlei	Open	5-10	5	4.73	2.5YR2.5/4	Dark reddish brown	7	7	87	Loamy sand
2	Bainsvlei	Open	10-20	10	4.71	2.5YR2.5/4	Dark reddish brown	11	5	85	Loamy sand
2	Bainsvlei	Open	20-40	20	4.65	2.5YR2.5/4	Dark reddish brown	10	7	83	Loamy sand
2	Bainsvlei	Open	40-60	20	4.49	2.5YR2.5/4	Dark reddish brown	13	7	80	Sandy loam
5	Rensburg	Open	0-5	5	6.23	2.5Y3/1	Very dark gray	20	16	64	Sandy clay loam
5	Rensburg	Open	5-10	5	6.46	2.5Y3/1	Very dark gray	23	15	62	Sandy clay loam
5	Rensburg	Open	10-20	10	6.75	2.5Y3/1	Very dark gray	31	12	56	Sandy clay loam
5	Rensburg	Open	20-40	20	6.90	2.5Y3/1	Very dark gray	39	10	51	Sandy clay
5	Rensburg	Open	40-60	20	6.90	2.5Y3/1	Very dark gray	37	11	52	Sandy clay
5	Rensburg	Open	60-80	20	6.94	2.5Y3/1	Very dark gray	44	6	50	Sandy clay
5	Rensburg	Open	80-100	20	6.94	2.5Y3/1	Very dark gray	43	8	49	Sandy clay
6	Rensburg	Open	0-5	5	5.48	2.5Y3/1	Very dark gray	34	16	50	Sandy clay loam
6	Rensburg	Open	5-10	5	5.56	2.5Y3/1	Very dark gray	43	13	44	Sandy clay
6	Rensburg	Open	10-20	10	5.71	2.5Y3/1	Very dark gray	32	21	47	Sandy clay loam
6	Rensburg	Open	20-40	20	5.97	2.5Y3/1	Very dark gray	35	19	46	Sandy clay loam
6	Rensburg	Open	40-60	20	6.26	2.5Y3/1	Very dark gray	41	17	42	Clay
6	Rensburg	Open	60-80	20	6.43	2.5Y3/1	Very dark gray	45	17	38	Clay
6	Rensburg	Open	80-100	20	6.61	2.5Y3/1	Very dark gray	47	13	40	Clay
3	Bainsvlei	Encro	0-5	5	4.46	2.5YR2.5/4	Dark reddish brown	7	7	86	Loamy sand
3	Bainsvlei	Encro	5-10	5	4.37	2.5YR2.5/4	Dark reddish brown	12	7	81	Loamy sand
3	Bainsvlei	Encro	10-20	10	4.47	2.5YR2.5/4	Dark reddish brown	11	13	76	Sandy loam
3	Bainsvlei	Encro	20-40	20	4.34	2.5YR2.5/4	Dark reddish brown	15	7	77	Sandy loam
3	Bainsvlei	Encro	40-60	20	4.49	2.5YR2.5/4	Dark reddish brown	21	9	70	Sandy clay loam
4	Bainsvlei	Encro	0-5	5	4.33	2.5YR2.5/4	Dark reddish brown	13	7	80	Sandy loam
4	Bainsvlei	Encro	5-10	5	4.32	2.5YR2.5/4	Dark reddish brown	13	9	78	Sandy loam
4	Bainsvlei	Encro	10-20	10	4.37	2.5YR2.5/4	Dark reddish brown	16	7	77	Sandy loam
4	Bainsvlei	Encro	20-40	20	4.42	2.5YR2.5/4	Dark reddish brown	19	7	75	Sandy loam
4	Bainsvlei	Encro	40-60	20	4.54	2.5YR2.5/4	Dark reddish brown	15	12	73	Sandy loam
7	Rensburg	Encro	0-5	5	7.06	2.5Y3/1	Very dark gray	9	14	77	Sandy loam
7	Rensburg	Encro	5-10	5	7.14	2.5Y3/1	Very dark gray	17	20	63	Sandy clay loam
7	Rensburg	Encro	10-20	10	7.12	2.5Y3/1	Very dark gray	26	11	63	Sandy clay loam
7	Rensburg	Encro	20-40	20	7.15	2.5Y3/1	Very dark gray	25	9	67	Sandy clay loam
7	Rensburg	Encro	40-60	20	7.13	2.5Y3/1	Very dark gray	24	9	67	Sandy clay loam
7	Rensburg	Encro	60-80	20	7.15	2.5Y3/1	Very dark gray	41	5	54	Sandy clay
7	Rensburg	Encro	80-100	20	7.17	2.5Y3/1	Very dark gray	40	6	54	Sandy clay
8	Rensburg	Encro	0-5	5	6.13	2.5Y3/1	Very dark gray	22	9	69	Sandy clay loam
8	Rensburg	Encro	5-10	5	6.64	2.5Y3/1	Very dark gray	27	13	60	Sandy clay loam
8	Rensburg	Encro	10-20	10	6.57	2.5Y3/1	Very dark gray	30	11	58	Sandy clay loam
8	Rensburg	Encro	20-40	20	6.97	2.5Y3/1	Very dark gray	30	9	61	Sandy clay loam
8	Rensburg	Encro	40-60	20	7.25	2.5Y3/1	Very dark gray	33	9	58	Sandy clay loam
8	Rensburg	Encro	60-80	20	6.99	2.5Y3/1	Very dark gray	27	7	66	Sandy clay loam
8	Rensburg	Encro	80-100	20	7.47	2.5Y3/1	Very dark gray	38	6	56	Sandy clay

3.5.2 Vertical distribution of soil bulk density along Bainsvlei and Rensburg soil profiles.

Figure 2 compares the vertical distribution of soil bulk density along Bainsvlei and Rensburg soil profiles in open and woody plant encroached grassland. Analysis of variance (ANOVA) revealed that there were no statistical differences in soil bulk density in woody-encroached when compared to open grassland (Appendix 1 and 2). Notably, in both Bainsvlei and Rensburg soils, there was a general increase in bulk density with the soil depth (Figure 2). The soil bulk density data was then pooled into topsoil and subsoil layers of the Bainsvlei and Rensburg soils. The obtained results revealed that woody plant encroachment resulted in an increase in the soil bulk density in the Rensburg soil while Bainsvlei soil showed no clear and consistent trend (Figures 2A and B).

Specifically, in the Rensburg soil (Figure 2 A), the soil bulk density of the open grassland slightly increased from 1.10 g cm^{-3} to 1.11 g cm^{-3} while that of the encroached grassland increased from 0.97 g cm^{-3} to 1.16 g cm^{-3} in the topsoil (0-20 cm). In the subsoil (20-100 cm), the bulk density of open grassland further increased to 1.25 g cm^{-3} between 20-80 cm and then reduced to 1.18 g cm^{-3} between 80-100 cm depth while that of the encroached grassland increased from 1.16 g cm^{-3} to 1.35 g cm^{-3} between 20 and 60 cm depth, then reduced to 1.28 g cm^{-3} from 60-80 cm and lastly increased to 1.41 g cm^{-3} between depth of 80-100 cm. In figure 2B of the Rensburg soils, the soil bulk density of open grassland increased from 0.72 g cm^{-3} to 1.07 g cm^{-3} while that of the encroached grassland increased from 1.04 g cm^{-3} to 1.27 g cm^{-3} in the topsoil (0-20 cm). The bulk density of open grassland further increased to 1.12 g cm^{-3} between 20-40 cm depth and then decreased to 1.08 g cm^{-3} between 40-100 cm depth of the subsoil while the soil bulk density of the encroached grassland reduced from 1.27 g cm^{-3} to 1.22 g cm^{-3} between 20-100 cm in the subsoil.

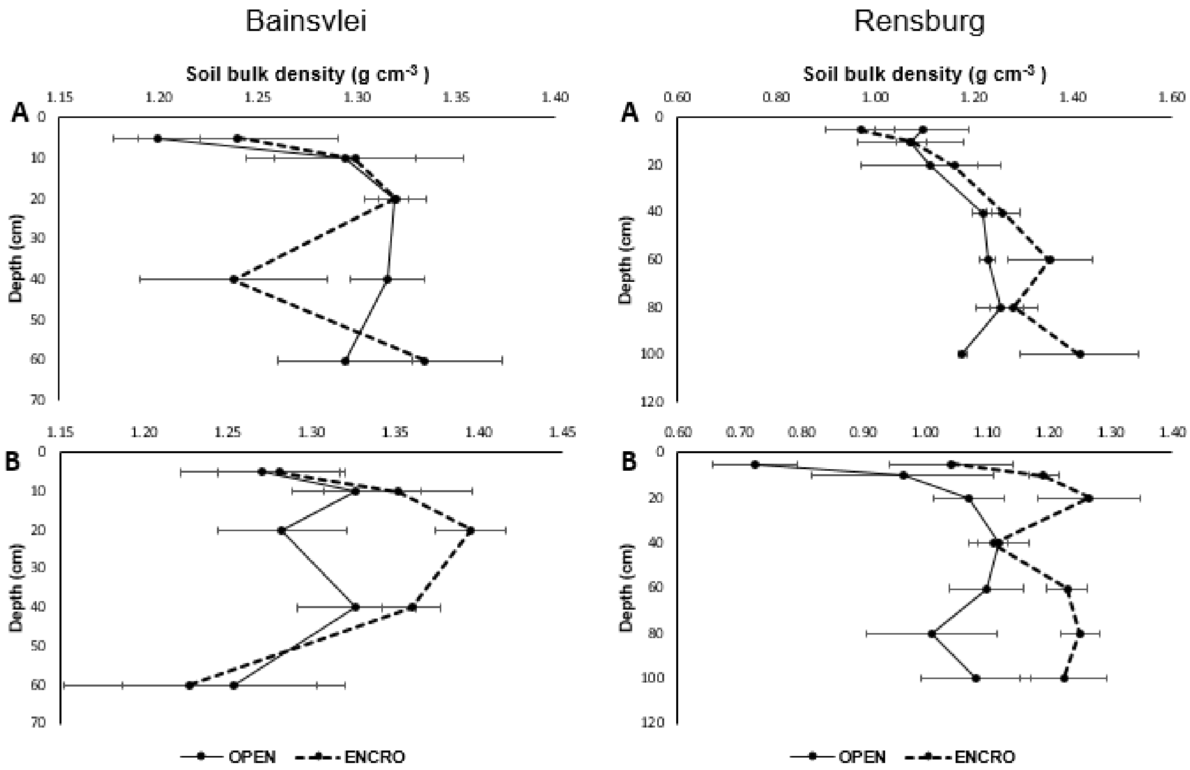

Figure 2. Vertical distribution of mean soil bulk density (g cm^{-3}) along Bainsvlei and Rensburg soil profiles in open and woody plant encroached grassland. The error bars in the graphs represent the standard error of the mean(n=3).

3.5.3 Vertical distribution of soil porosity along Bainsvlei and Rensburg soil profiles.

The Bainsvlei and Rensburg soils showed a general decrease in porosity with the soil depth regardless of the sampling position (Figure 3). However, there was no clear and consistent trend on the effect of woody plant encroachment on porosity in the Bainsvlei soil (Figure 3A and B). A generally lower porosity was observed in the woody plant encroached grassland as compared to open grassland in the Rensburg soil (Figure 3 A and B).

In figure 3A of the Rensburg soils, the soil porosity of open grassland slightly decreased from 58.63 to 58.01% while under encroached grassland it decreased from 63.35 to 56.18% in the topsoil. In the subsoil, soil porosity under open grassland decreased from 58.01 to 52.72% between 20-80 cm and then increased to 55.60% between 80-100 cm depth. The soil porosity of the encroached grassland decreased from 56.18 to 46.63% in the subsoil (20-100 cm). In figure 3B of the Rensburg soil, porosity of open grassland decreased from 72.66 to 59.59% in the topsoil while that of encroached grassland decreased from 60.65 to 52.23%. In the subsoil, the soil porosity under open grassland further decreased to 59.14% between 20-100 cm depth while that under encroached grassland increased from 52.23 to 58.11% between 20-40 cm depth and then decreases to 53.80% between 40-100 cm depth.

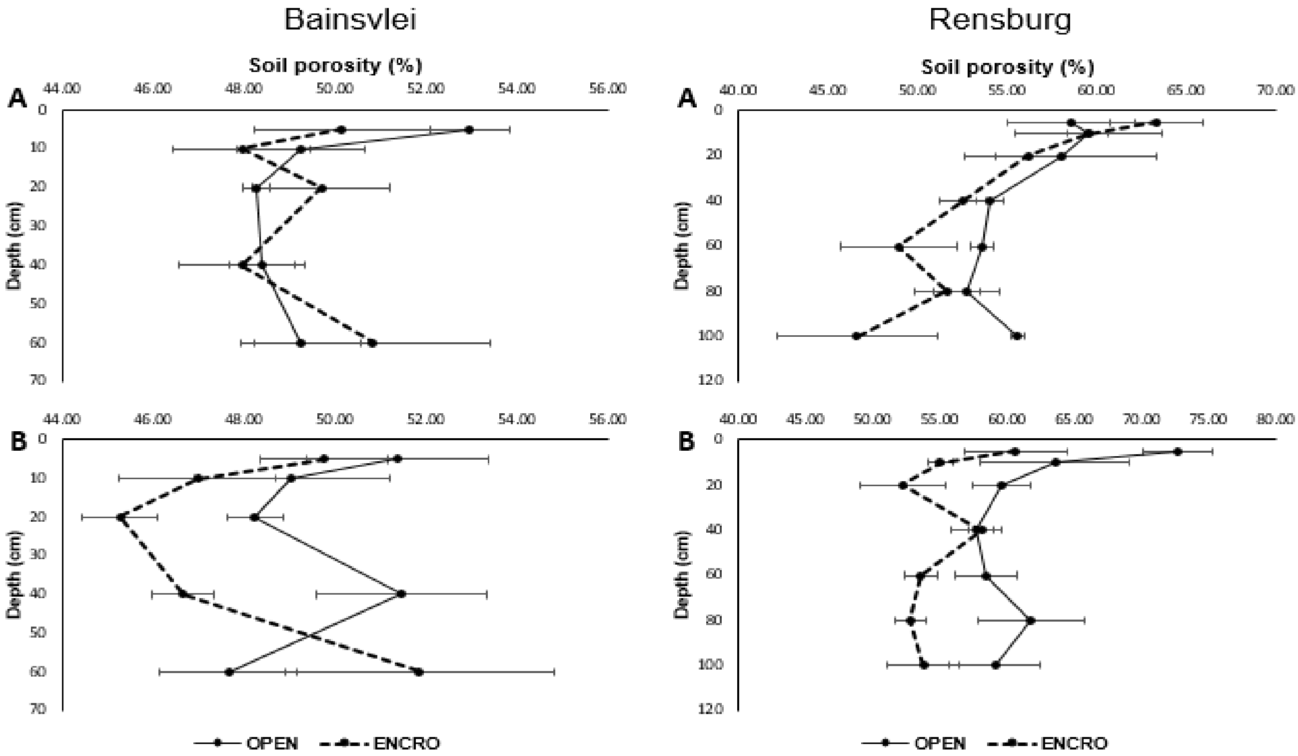

Figure 3. Vertical mean soil porosity (%) distribution along Bainsvlei and Rensburg soil profiles in open and woody plant encroached grasslands. The error bars in the graphs represent the standard error of the mean (n=3).

3.5.4 Vertical distribution of mean weight diameter along Bainsvlei and Rensburg soil profiles.

Figure 4 compares the vertical distribution of mean weight diameter along Bainsvlei and Rensburg soil profile in open and woody plant encroached grassland. In both Bainsvlei and Rensburg soils, there was a general decrease in the mean weight diameter (MWD) with soil depth regardless of the sampling position. In the Bainsvlei soil (Figure 4A and B), there was high MWD in open grassland while the Rensburg soil showed high MWD in woody plant encroached grassland. In figure 4A of Bainsvlei soil, the MWD in open grassland increased from 0.85 to 0.91 mm at 0-20 cm depth while that in woody plant encroached grassland increased from 0.80 to 0.86 mm at 0-

10 cm and then decreased to 0.73 at 10-20 cm depth of the topsoil. In the subsoil, the MWD in open grassland decreased from 0.91 to 0.78 mm at 20-40 cm depth and then slightly increased to 0.80 at 40-60 cm depth. In woody plant encroached grassland, the MWD slightly decreased from 0.73 to 0.71 mm at 20-40 cm and then increased to 0.77 mm at 40-60 cm depth. In figure 4B of Bainsvlei soil, the MWD in open grassland increased from 0.77 to 0.80 mm while that in woody plant encroached grassland decreased from 0.77 to 0.66 mm in the topsoil. In the subsoil, the MWD in open grassland increased from 0.80 to 0.88 mm at 20-40 cm depth and then decreased to 0.84 mm at 40-60 cm depth while that in woody plant encroached grassland increased from 0.66 to 0.71 mm at 20-60 cm depth.

In the Rensburg soil (Figure 4A), MWD in open grassland decreased from 0.65 to 0.59 mm while that in woody plant encroached grassland increased from 0.56 to 0.64 mm in the topsoil (0-20 cm). In the subsoil (20-100 cm), the MWD in open grassland further decreased to 0.41 mm while that in encroached grassland decreased to 0.63 mm at 20-100 cm depth. In figure 4B of Rensburg soils, MWD in open grassland increased from 0.56 to 0.64 mm while that in encroached grassland increased from 0.64 to 0.69 mm in the topsoil. In the subsoil, MWD in open grassland decreased from 0.64 to 0.44 mm at 20-40 cm depth, and then increased to 0.55 mm at 40-60 cm depth, decreased to 0.43 mm at 60-80 cm and lastly increased to 0.46 mm at 80-100 cm depth. In woody plant encroached grassland, the MWD decreased from 0.69 to 0.49 mm at 20-100 cm depth.

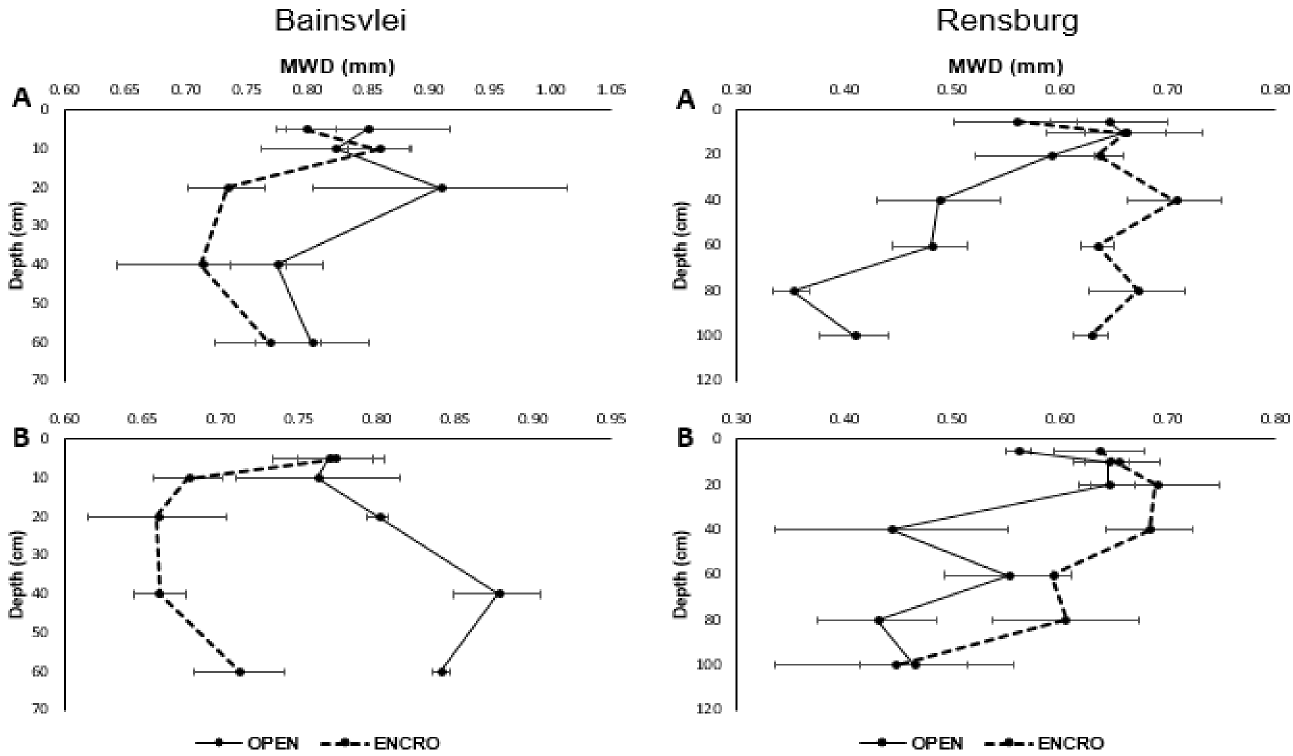

Figure 4. Vertical distribution of mean weight diameter (MWD) along Bainsvlei and Rensburg soil profiles in open and woody plant encroached grasslands. The error bars in the graphs represent the standard error of the mean (n=3).

3.5.5 Comparison of soil physical and hydrological properties in the topsoil and subsoil layers of Bainsvlei and Rensburg soil profiles.

Figure 5 shows the bulk density of Bainsvlei and Rensburg soils in the topsoil and subsoil of open and woody plant encroached grasslands. In comparison to open grassland (1.28 g cm^{-3}), a slightly higher bulk density was recorded in the topsoil of encroached grasslands (1.31 g cm^{-3}) in Bainsvlei soil (Figure 5). The Rensburg soil also had higher bulk density of 1.12 g cm^{-3} in encroached compared to 1.01 g cm^{-3} in open grasslands. Therefore, in comparison to open grassland, woody plant encroachment resulted in a minimal increase of 2% and 11% in the topsoil of Bainsvlei and Rensburg soils, respectively. In the subsoil of Bainsvlei soils, the average soil bulk density was 1.30 g cm^{-3} under open grasslands and 1.29 g cm^{-3} under encroached grasslands, this led to a minimal decrease of 1% with woody plant encroachment. In the subsoil of Rensburg soils, the average soil bulk density was 1.15 g cm^{-3} and 1.27 g cm^{-3} under open and woody plant encroached grasslands, respectively. This reveals that bulk density was 10% greater in the subsoil of woody plant encroached grasslands compared to open grasslands. The changes are, however not statistically significantly different.

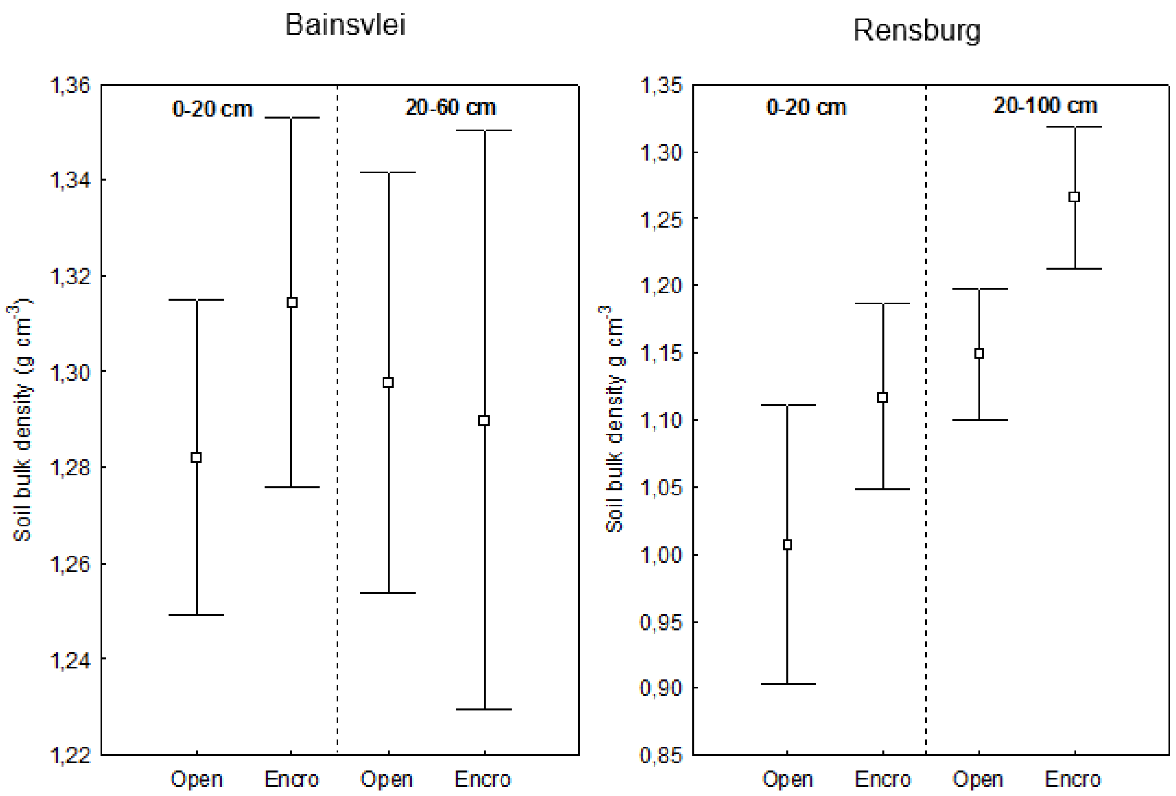

Figure 5. Mean values (n= 3) (square box) and standard errors (vertical bars) of the soil bulk density measured from topsoil and subsoil of Bainsvlei and Rensburg soil forms collected from open and woody plant encroached grasslands.

Figure 6 shows that the soil porosity generally decreased with an increase in the soil depth. For Bainsvlei soils, the average soil porosity was reduced by encroachment from 52% in open grassland to 50%. Similar results were observed in Rensburg soil where porosity decreased from 62 % in open grassland to 58% in the encroached site. Therefore, in comparison to open grassland, woody plant encroachment resulted in a minimal decrease of 2% and 7% in the topsoil of Bainsvlei and Rensburg soils, respectively. In the subsoil of Bainsvlei soils, the average soil porosity was 51% under open grasslands and 51% under woody plant encroached grasslands, this led to a minimal increase of 1% with woody plant encroachment. However, the changes were not statistically significantly different. In the subsoil of Rensburg soils, the average soil porosity was 57% and 52% under open and woody plant encroached grasslands, respectively. This reveals that soil porosity was 8% lesser in the subsoil of woody plant encroached grasslands compared to open grasslands.

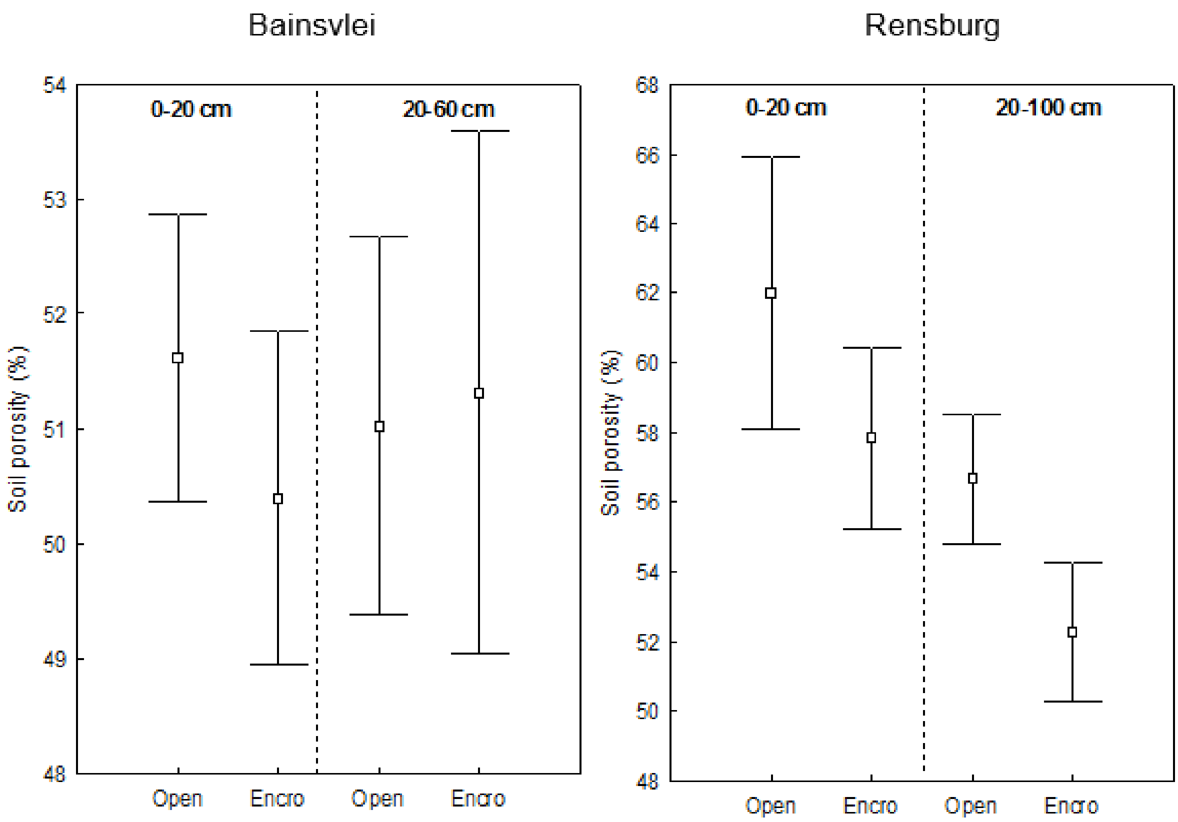

Figure 6. Mean (n= 3) values (square box) and standard errors (vertical bars) of the soil porosity measured from topsoil and subsoil of Bainsvlei and Rensburg soil forms collected from open and woody plant encroached grasslands.

Figure 7 shows the soil aggregate stability measured as the mean weight diameter in the topsoil and subsoil of Bainsvlei and Rensburg soils, under two encroachment densities defined as open grassland and woody plant encroached grassland. For Bainsvlei topsoil, the MWD was 0.82 mm at the open grassland and 0.75 mm in the woody plant encroached grassland. The corresponding values for Rensburg soils were 0.62 mm and 0.64 mm. Therefore, in comparison to the control, woody plant encroachment resulted in a 9% MWD decrease in the topsoil of Bainsvlei soils and slightly increased by 3% in the Rensburg soils. In the subsoil of Bainsvlei soils, MWD values were 0.82 mm and 0.71 mm in the open and woody plant encroached grasslands, respectively. This led to a 13% reduction of MWD with woody plant encroachment. However, the changes were not statistically significantly different. The corresponding values for Rensburg soils were 0.45 mm and 0.62 mm. The MWD was 38% greater in woody plant encroached grassland than in open grasslands.

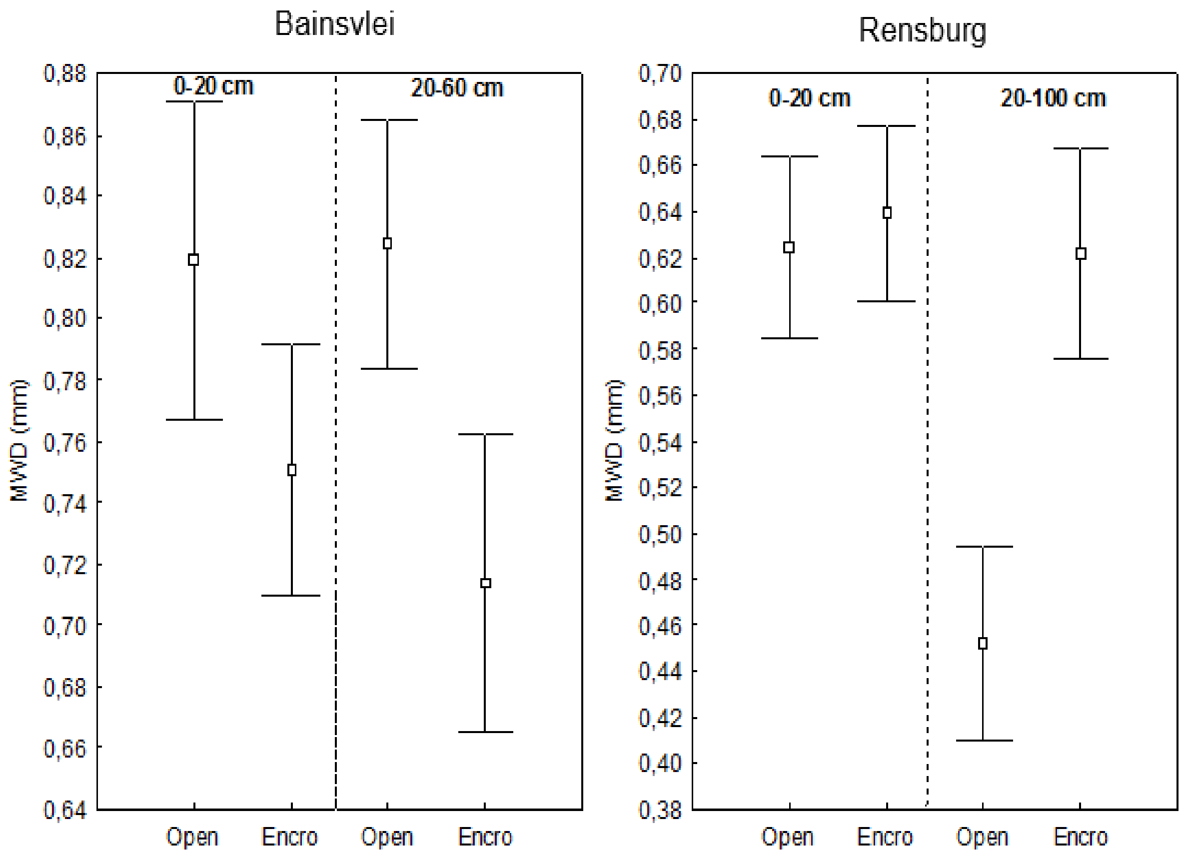

Figure 7. Mean (n= 3) values (square box) and standard errors (vertical bars) of the mean weight diameter (MWD) measured from topsoil and subsoil of Bainsvlei and Rensburg soil forms collected from open and woody plant encroached grasslands.

In both the Bainsvlei and Rensburg soils, saturated hydraulic conductivity was lower in woody plant encroached grasslands than in open grasslands (Figure 8). Overall, the highest values of hydraulic conductivity were observed in the Bainsvlei soils than the Rensburg soils in both the topsoil and subsoil. There were no significant differences in the topsoil for both Bainsvlei and Rensburg soils. The Bainsvlei subsoil had a saturated hydraulic conductivity of 1203 cm h^{-1} in the open grassland and 919 cm h^{-1} in the encroached grassland site, corresponding to a 24% decrease in saturated hydraulic conductivity. The subsoil of Rensburg also had greater saturated hydraulic conductivity in open (637 cm h^{-1}) than in encroached grassland (358 cm h^{-1}), which resulted in 44% decrease in saturated hydraulic conductivity with woody plant encroachment.

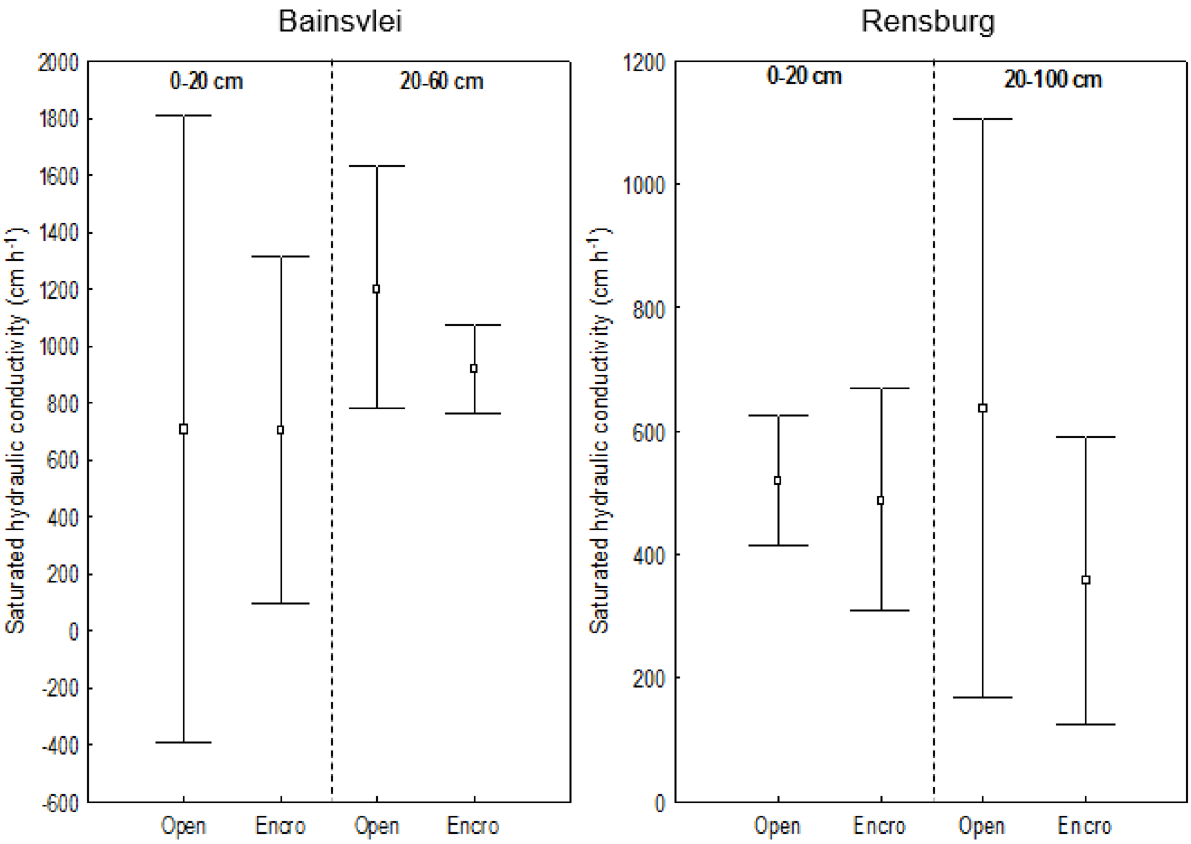

Figure 8: Mean (n= 2) values (square box) and standard errors (vertical bars) of the saturated hydraulic conductivity measured from topsoil and subsoil of Bainsvlei and Rensburg soil forms collected from open and woody plant encroached grasslands.

In both soil types (Bainsvlei and Rensburg), there was high SWR in the open grassland than in the woody plant encroached grassland in both the top and subsoil (Figure 9). In the Bainsvlei topsoil, there was high soil water retention (SWR) 206, 146 and 124 mm m^{-1} at measured matric potentials 10, 100 and 1500 kPa, respectively in the open grasslands compared to 155 mm m^{-1}, 123 mm m^{-1} and 92 mm m^{-1} of the woody plant encroached grassland, respectively. The same trend was observed in the subsoil (20-60 cm depth), where SWR at 10 kPa (326 mm m^{-1}), 100 kPa (269 mm m^{-1}) and 1500 kPa (236 mm m^{-1}) were higher in the open grasslands as compared to those under woody plant encroached grasslands 214 mm m^{-1}, 136 mm m^{-1} and 114 mm m^{-1}, respectively. The Rensburg soils also showed a similar trend to Bainsvlei soils in both the topsoil (0-20 cm depth) and subsoil (20-100 cm depth). In the topsoil, open grasslands had high SWR at matric potentials 10 kPa (645 mm m^{-1}), 100 kPa (556 mm m^{-1}) and 1500 kPa (498 mm m^{-1}) as compared to those of woody plant encroached grasslands; 527 mm m^{-1}, 469 mm m^{-1} and 416 mm m^{-1}, respectively. The subsoil, had high SWR in open grassland at 10 kPa (701 mm m^{-1}), 100 kPa (623 mm m^{-1}) and 1500 kPa (574 mm m^{-1}) as compared to 579 mm m^{-1}, 503 mm m^{-1} and 454 mm m^{-1} in the woody plant encroached grassland, respectively. The results showed high SWR in the Rensburg soils than the Bainsvlei soils in both the topsoil and subsoil (Figure 9). The SWR was observed to decrease with an increase in matric potential. The Bainsvlei topsoil showed a 40% decrease in SWR under open grasslands which is slightly lower than that observed in the woody plant encroached grassland (41%) between 10-1500 kPa matric potentials. The subsoils exhibited 28% decrease in the open grasslands as compared to 47% in the woody plant encroached grasslands with increasing matric potentials (10-1500 kPa). The same trend was observed in the Rensburg soils where high matric potentials led to a decrease in SWR. The topsoil exhibited 23% decrease in the open grasslands as compared to 21% decrease in the woody plant encroached grasslands. In the subsoil, the open grasslands showed to 18% decrease in SWR in the open grasslands as compared to 22% observed in the woody plant encroached grasslands. Compared to open grasslands, woody plant encroachment led to 25% and 42% decrease in SWR in the topsoil and subsoil of Bainsvlei soils, respectively. The same trend was observed in the Rensburg soils with 50% and 19% decrease in the topsoil and subsoil, respectively.

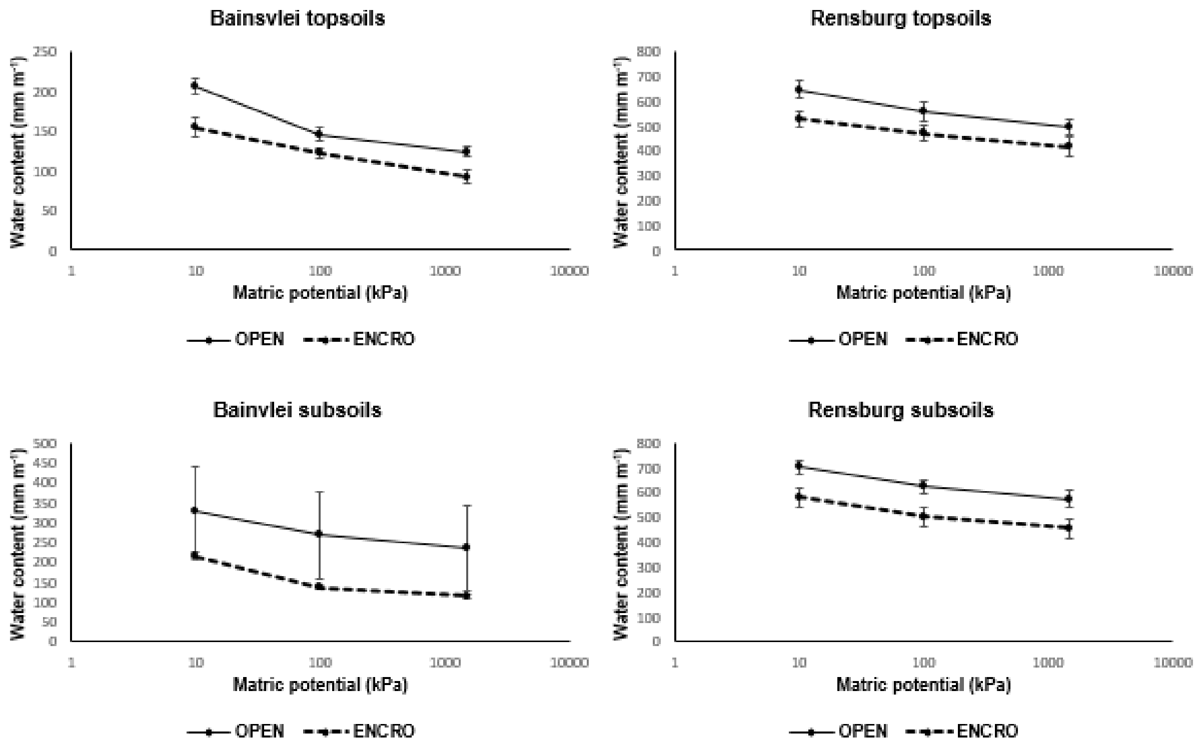

Figure 9: The mean (n= 2) water content recorded at three different matric potentials representing field capacity (-10 kPa), stress point (-100 kPa) and permanent wilting point (-1500 kPa) of Bainsvlei and Rensburg topsoil and subsoil collected from open and woody plant encroached grasslands. The bar gives the standard error of the difference at P<0.05.

3.6 Discussion

3.6.1 Effects of woody plant encroachment on soil bulk density and porosity.

In both soil types, bulk density values were slightly higher in areas with woody plant encroachment than in open grasslands (Figure 2 and 5). Slightly higher bulk density values (> 1.14 g cm^{-3}) and (> 1.28 g cm^{-3}) were observed under Rensburg and Bainsvlei soils, respectively. This is because the study by (Jackson *et al*., 2002) observed that open grasslands have a higher soil organic carbon than those in woody plant encroached grasslands. High soil organic carbon, an indication of high soil organic matter because of their strong positive correlation (Chaudhari *et al*., 2013), results in an improved soil porosity, which in turn reduces the soil bulk density. The study conducted by Jaleta *et al*. (2011) in Chromic Cambisols and Haplic Xerosols, found high organic matter content in open grasslands than in woody plant encroached grasslands. They further explained that woody plant encroachment gradually degrades soil properties by lowering organic matter and increasing bulk density.

Similar results were observed by Mesele *et al*. (2006) who stated that grasslands have more soil organic matter than other land covers.

Other research studies have reported results that are in accord with the findings of the present study. For instance, Mzezewa (2009) observed high bulk densities (1.82 g cm^{-3}) under woody plant encroachment compared to open grasslands (1.57 g cm^{-3}) in a sandy textured soil. In agreement to these findings, Jaleta *et al*. (2011) also observed a slightly higher bulk density in woody plant encroached areas (1.05 g cm^{-3}) than under open grasslands (0.97 g cm^{-3}), and explained that the reason for lower bulk density values in open grasslands is because of high organic matter. Bulk density is influenced by the amount of organic matter in soils, their texture, constituent minerals and porosity. Soil organic matter plays a key role in nutrient cycling and can help improve soil structure. The bulk density depends on several factors such as texture, soil depth, compaction, consolidation and amount of SOC present in the soil but it is highly correlated to the organic carbon content (Morisada *et al*., 2004).

In this study, the soil bulk density values were higher in the Bainsvlei (loamy sand) soils than in the Rensburg (sandy clay loam) soils. These findings are supported in a study by Ahad *et al*. (2015), who observed higher bulk densities (1.46 g cm^{-3}) in sandy soils than in clay soils (1.34 g cm^{-3}). Martin *et al. (*2017) also explained that sandy soils have relatively high bulk density since total pore space in sands is less than silt or clay soils. In their study, they further explained that loose, well-aggregated, porous soils and those rich in organic matter have lower bulk density, hence they observed lower bulk density in clay soils. The low bulk density values observed in the Rensburg soils of this study may be as a result of the high clay content and high amounts of organic matter. High organic matter content in the soil act as a binding agent for soil particles, hence it improves porosity, which in turn lowers the soil bulk density.

The soil bulk density was observed to increase from top to subsoil horizons for all soil types (Figure2 and 5). Bulk density typically increases with soil depth since subsurface layers are more compacted and have less organic matter, less aggregation, and less root penetration compared to surface layers, therefore contain less pore space (Chaudhari *et al*., 2013). In the study of Conforti *et al*. (2016), the soil bulk density varied between 0.23 g cm^{-3} in the topsoil and 1.66 g cm^{-3} in the subsoil of loamy sand soils and showed a tendency to increase gradually with depth. The higher bulk density of loamy sand soils may be related to the lower soil porosity and soil compaction than loam soils. Other studies in forest soils have also confirmed the increase in bulk density with increasing depth (De Vos *et al*., 2005; Schrümpf *et al*., 2011) and according to Grüneberg *et al*. (2014), high bulk density values in deeper soils can be attributable to the weight of the overlying horizons. Mzezewa (2009) also observed high bulk density in the topsoil of woody plant encroached grasslands and explained that the increase in soil bulk density with depth was negatively correlated with soil organic carbon. Low organic carbon levels in the surface horizons of the bush encroachment soils is likely to result in high bulk densities compared to the open savanna grasslands. Figure 2 shows higher bulk density values in plinthic soils (Bainsvlei) compared to vertic soils (Rensburg).

Woody plant encroachment caused the reduction of grass cover, which leaves the soil surface bare and more prone to compaction as a result of direct raindrop impact. More compaction from the woody plant encroached grasslands at our site can be related to less soil carbon content. It has been reported that organic matter makes soil more resistant to compaction (Arvidson, 1997). Low organic matter content in the Bainsvlei soils led to compaction as exhibited by slightly higher soil bulk density of 1.31 g cm^{-3} compared to 1.28 g cm^{-3} found in the Bainsvlei topsoil of woody plant encroached grassland. The corresponding values for Rensburg soils were 1.01 g cm^{-3} and 1.12 g cm^{-3}, respectively, and a decrease in the bulk density values is due to the high organic carbon found in Rensburg soils. In the subsoil of Rensburg soils, bulk density increased to 1.27 g cm^{-3} compared to 1.15 g cm^{-3} in the open grasslands.

Compaction caused by animal trafficking during grazing probably led to high bulk density in both soil types which then resulted in the reduction of total soil porosity. Figure 3 shows that porosity was low (50%) in woody plant encroached grassland of Bainsvlei soils, reflecting a reduction in macro-porosity and pore space compared to 52% in open grasslands. The corresponding values for Rensburg soils are 58% and 62%, respectively. The Rensburg soils showed a further decrease of soil porosity (52%) with depth (Figures 3 and 6) in the encroached grasslands compared to open grasslands (57%). This can be supported by the study of Martin *et al. (*2017) which explained that there is low organic matter content in the subsoil horizons, hence high compaction and bulk density with increasing soil depth. The study of Mesele *et al*.

(2006) has indicated that grasslands have more soil organic carbon, that is why they show lower values of bulk density as compared to woody plant encroached grasslands.

3.6.2 Effects of woody plant encroachment on soil aggregate stability

The results revealed that the mean weight diameter (MWD), which is the measure of the soil aggregate stability, tended to decrease with soil depth (Figures 4 and 7) in both open and encroached grassland. This is because the surface horizons have more organic matter compared to the subsurface ones, leading to high aggregation since organic matter acts as a binding agent for soil particles. The results also showed high MWD values in the Bainsvlei soil than the Rensburg soil. This may be caused by low clay content in the Bainsvlei soil (Table 1), which allows for movement of soil fauna in the soil matrix, and in turn enhances aggregation through burrowing. Aggregation in the soil may also result indirectly through the accumulation of faecal pellets of earthworms and other invertebrates that feed in the soil (Shipitalo and Le Bayon, 2004). The earthworm burrows provide an easy pathway for roots to take as they grown through the soil, which can improve aggregation by releasing organic compounds that hold soil particles together.

Figure 4 showed a decrease in aggregate stability (MWD) with encroachment in the Bainsvlei soils while the Rensburg soils exhibited high MWD with woody plant encroachment. In the Bainsvlei soils, a higher MWD (0.82 mm) was observed under open grasslands than 0.75 mm in the woody plant encroached grassland, leading to a 9% decline in MWD. The soils show a further decrease in MWD (0.82 mm) (Figures 4 and 7) with depth in the open grassland compared to encroached grassland (0.71 mm). Podwojewski *et al*. (2014) has reported results that are in accord with the findings of the present study. In their study, they observed greater MWD in open grasslands as compared to encroached grasslands. The MWD was significantly more stable in the open grasslands (2.61 mm) compared to woody plant encroached grasslands (2.36 mm).

Podwojewski *et al*. (2014) explained that the strong MWD decrease is very well correlated to a strong decrease in organic matter and fine root contents. The organic matter added to the soil is reduced by the reduction of vegetation cover and subsequently contribute to reduced soil structure stability, protection against rainfall impact and ecosystem activities (Roose and Barthes, 2001; Snyman and Du Preez, 2005). Once continuous grass cover is fragmented, exposure of the soil surface to raindrop impact, wind, and overland flow across interconnected bare areas causes erosion (Wilcox *et al*. 2003). Increased erosion depletes soil organic matter, while inputs are reduced due to the absence of plant cover leading to a decline in soil microbial populations that stabilize soil macroaggregates (Tisdall and Oades, 1982; Oades, 1984; Emerson *et al*., 1986).

In contrast to the Bainsvlei soils, the Rensburg soils had higher MWD (0.64 mm) in the topsoil of woody plant encroached areas than open grasslands (0.62 mm). The corresponding values for the subsoils were 0.62 mm and 0.45 mm respectively (Figure 4). Pierson *et al*. (2010) determined the effect of woody plant encroachment on soil aggregate stability in areas under tree canopy versus areas between the canopies (inter-canopy). They also observed more stable aggregates (25-75%) under tree canopy and less than 10% stable aggregates on interspace areas. They explained that in areas under tree canopy, the plant litter offer soil protection from rain splash effects, provide rainfall storage and favours greater aggregate stability. Blaser *et al*. (2017) also observed 11% greater MWD under tree canopy than in open areas because of high amounts of organic matter under tree canopy.

3.6.3 Effects of woody plant encroachment on soil hydraulic conductivity

Soil hydraulic conductivity is controlled by the pore size distribution and the continuity of pores (Kutilek, 2004). Most natural soils contain macropores (Green *et al*., 2003) which are formed by earthworms and decaying organic material present in undisturbed soils and they affect hydraulic conductivity (Edwards *et al*., 1979; Dick *et al*., 1989). The continuous and intensive grazing in grasslands tends to destroy the continuity of macropores in the topsoil. Thus, water movement from the soil surface through macropore channels in the subsoil is reduced (Bouma *et al*., 1982).

In this study, soil hydraulic conductivity was higher in the Bainsvlei soils than the Rensburg soils (Figure 8). This may be caused by the higher proportion of sand in the Bainsvlei soils and better soil aggregation than in the Rensburg soils which allows free water movement. Bhattacharyya *et al*. (2006) stated that the soil hydraulic conductivity is greater in highly porous and aggregated soils than in tightly compacted and dense soils. The reduced pore spaces by woody plant encroachment led to decreased hydraulic conductivity. According to Maestre *et al*. (2009), an increase in woody plants may result in changes in the hydraulic characteristics of the soil. Zhang *et al.* (2001) found that the changes in vegetation type influence carbon accumulation in the soil. This process could seriously influence soil organic matter content and soil bulk density. Once these properties are altered, soil hydraulic characteristics will change, leading to different soil water storage capacities and hydrological processes (Green *et al*., 2003).

The results obtained from this study showed that woody plant encroachment reduces soil hydraulic conductivity. There was higher hydraulic conductivity (520 cm h^{-1}) in open grassland compared to woody plant encroached grassland (488 cm h^{-1}) in the Rensburg topsoil. In agreement to these findings, Eldridge *et al*. (2015) observed lower hydraulic conductivity under woody plant encroached grassland (48.2 mm h^{-1}) compared to open grassland (50 mm h^{-1}) and explained that tree interspaces were the major driver of lower hydraulic conductivity following encroachment. Similarly, Wine *et al*. (2012) found lower hydraulic conductivity under juniper trees (0.57 cm h^{-1}) compared to grasses (2.52 cm h^{-1}) under dry condition. Recorded lower values of hydraulic conductivity are usually associated with increasing cattle trampling and compaction for the interspace.

3.6.4 Effects of woody plant encroachment on soil water retention (SWR).

The data presented in this study showed that there was slightly higher SWR in open grassland than in woody plant encroached grassland in the topsoil and subsoil of both Bainsvlei and Rensburg soils (Figure 9). The SWR ranged from 124-206 mm m^{-1} in the topsoil of open grassland and from 92-155 mm m^{-1} in the woody plant encroached grassland of Bainsvlei soil. This can be explained by the high bulk density and reduced porosity which were observed in this study as a result of woody plant encroachment. The soil bulk density is an indicator of soil compaction; thus, the higher bulk density indicate that the soil is compacted. In the study of Yadav *et al* (2019), compacted soils exhibited low SWR. This is because compacted soils have a lower soil organic carbon content due to a decline in root growth and plant development, which then results in decreased inputs of organic materials (Chen and Weil, 2011). The reduction of soil organic material (an indicator of soil organic matter, SOM) affects the vulnerability to degradation of soil quality (Lal, 2015b) and reduces the ability of soil to retain more water for plant growth (Reichert *et al*., 2016). Lal (2015a) observed in his study that less compacted soils are better drained compared to more compacted soils.

At any given water potential, Rensburg soil retained more water than the Bainsvlei soil. This may be explained by the higher amount of clay content in the Rensburg soil than the Bainsvlei (Table 1). The data in this study showed greater SWR values in the subsoil than topsoil. This may also be as a result of increased clay content in the subsoil, which impedes the layer, slowing down percolation because of its fine particles and micropore domination.

3.7 Conclusion

This study investigated the effects of woody plant encroachment on soil physical and hydrological properties of Bainsvlei and Rensburg soils. Two main conclusions can be drawn from this study. The first is that soil bulk density and aggregate stability were higher in woody plant encroached Rensburg soils. However, soil porosity reduced with encroaching woody plants. Bainsvlei soils showed no clear trend in soil bulk density and porosity with regard to woody plant encroachment. However, the soil exhibited lower aggregate stability with encroaching woody plants. The second is that woody plant encroachment decreases water retention and hydraulic conductivity in the topsoil and subsoil layers of both Bainsvlei and Rensburg soils. Future research is required to investigate how woody plant encroachment influences the rate of soil infiltration.

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CHAPTER 4

SUMMARY AND CONCLUSIONS

This mini-dissertation was aimed at providing better understanding of how soil physical and hydrological properties are affected by woody plant encroachment in a semi-arid savanna grassland. The first chapter provided a general introduction which provided the background, problem statement and rationale information related to woody plant encroachment and soil physical and hydrological properties. The literature review in the second chapter looked at the causes of woody plant encroachment in savanna grasslands as well as the impacts of woody plant encroachment on soil physical and hydrological properties. In chapter 3, the study examined and compared soil physical and hydrological properties in woody plant encroached and open grasslands sited on Bainsvlei and Rensburg soils at Towoomba Research Station in Bela-Bela, Limpopo Province, South Africa. These two soils of contrasting morphological characteristics were sampled at various depth intervals in the topsoil and subsoil of open and woody plant encroached grassland soils.

The following paragraphs summarise the major findings of this study by addressing the research questions posed in section 1.4.3. How are the soil physical and hydrological properties affected by woody plant encroachment of two contrasting soil types in savanna grasslands? How are the soil physical and hydrological properties affected by different soil types in woody plant encroached grasslands?

Soil physical properties including bulk density, porosity and aggregate stability as well as hydrological properties (water retention and hydraulic conductivity) were determined in profiles of Bainsvlei and Rensburg soil types dug in open and woody plant encroached grasslands. In Rensburg soil, vertical distribution graphs showed higher soil aggregate stability in woody plant encroached grasslands compared to open grassland. Conversely, soil aggregate stability was lower in the woody plant encroached grassland Bainsvlei soil when compared to open grassland. There were no significant differences observed for soil bulk density and porosity. Further, soil bulk density increased, while porosity and aggregate stability decreased with depth in open and woody-encroached grassland soils. Furthermore, the results revealed that in both soils, there was lower soil water retention and hydraulic conductivity in the topsoil and subsoil layers of woody-encroached grassland than in open grassland.

The major contributions of this research work are as follows. First, it has revealed that the effect of woody plant encroachment on soil physical properties is influenced by soil type. Different soil types exhibit different physical properties including bulk density, porosity and mean weight diameter (measure of aggregate stability), which will be impacted differently by woody plant encroachment. Second is that the effect of woody plant encroachment on soil hydrological properties is influenced by soil texture. As explained in sections 2.4.1 and 2.4.2, several studies have observed that soil hydraulic conductivity is favoured by loose and porous soils compared to tight and compacted ones, while soil water retention is high in tightly packed soil particles that are dominated by micropores.

Woody plant encroachment has negative impacts on soil hydrological properties since it leads to compaction of the soil and reduced structural stability. Lower structural stability leads to soil crusting, generating more water surface runoff. Therefore, understanding woody plant encroachment impacts on soil hydrological properties is very essential for proper management of savanna grasslands.

APPENDICES

Appendix 1: Results of ANOVA of soil bulk density, porosity and aggregate stability from Bainsvlei soil form with encroachment density soil depth as factors

Soil bulk density					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Encr_density	1	0.000	0.000	0.01	0.937
Dep	4	0.039	0.010	2.51	0.074
Encr_density.Dep	4	0.014	0.004	0.91	0.476
Residual	20	0.078	0.004		
Total	29	0.131			
Porosity					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Encr_density	1	0.035	0.035	0.01	0.937
Dep	4	55.548	13.887	2.51	0.074
Encr_density.Dep	4	20.152	5.038	0.91	0.476
Residual	20	110.498	5.525		
Total	29	186.234			
MWD					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Encr_density	1	0.025	0.025	2.65	0.119
Dep	4	0.036	0.009	0.94	0.459
Encr_density.Dep	4	0.034	0.009	0.9	0.483
Residual	20	0.192	0.010		
Total	29	0.288			

Appendix 2: Results of ANOVA of soil bulk density, porosity and aggregate stability from Rensburg soil form with encroachment density soil depth as factors

Soil bulk density					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Encr_density	1	0.027	0.027	1.65	0.21
Dep	6	0.424	0.071	4.29	0.003
Encr_density.Dep	6	0.111	0.019	1.13	0.373
Residual	28	0.461	0.016		
Total	41	1.024			
Porosity					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Encr_density	1	38.7	38.7	1.65	0.21
Dep	6	604.47	100.75	4.29	0.003
Encr_density.Dep	6	158.54	26.42	1.13	0.373
Residual	28	657	23.46		
Total	41	1458.71			
MWD					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Encr_density	1	0.164	0.164	27.54	<.001
Dep	6	0.104	0.017	2.91	0.025
Encr_density.Dep	6	0.185	0.031	5.18	0.001
Residual	28	0.166	0.006		
Total	41	0.619			