THE EFFECT OF LONG-TERM FIRE FREQUENCIES ON SOIL HYDRAULIC PROPERTIES IN SEMI-ARID SAVANNAS IN KRUGER NATIONAL PARK

by

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PREFACE

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ABSTRACT

Soils are vital in supporting healthy and functioning ecosystems. Thus when soils are degraded, important ecosystem services are affected. In African savannas where fire is a key driver controlling ecosystem composition and structure, there is a lack in current understanding regarding the impacts of long-term fire management on soil hydrology. The Experimental Burn Plots (EBPs) in Kruger National Park (KNP), a long-term fire experiment initiated in the 1950's, offered a unique opportunity to determine the effects of long-term fire treatments (i.e. annual burn vs. no burn) compared to a "variable" fire regime (VFR) outside of the EBPs on soil hydraulic properties in semi-arid savannas. This study was conducted during October 2012- May 2013 on different soil types stemming from the two dominant geologies in KNP, i.e. granites and basalts.

This study revealed that it is rather the time following a fire and not necessarily frequency which resulted in decreased soil infiltration, with slowest infiltration rates immediately after the fire. Findings suggested that fire only affected infiltration rates at the soil surface and that these fire effects would dissipate within approximately two years— suggesting the soil's ability to recover; at least in terms of their hydrological function. Soil compaction, which is recognized for impeding soil infiltration, was measured. The research presented in this thesis indicates that surface compaction may be due to soil processes such as raindrop impact and splash but deeper compaction is attributed to high herbivore concentrations trampling the soil. Interestingly, the extent of soil compaction caused by high densities of herbivores does not result in significantly reduced soil infiltration rates.

In addition, long-term fire management effects on soil organic matter content and soil water retention was investigated. Besides promoting soil fertility, soil organic matter is considered hydrophilic and aids in soil water retention. Although alluding to greater organic matter on the fire-suppressed plot on the granitic EBPs, there were no statistically-significant differences found across the varying fire frequencies. However on the basaltic EBPs, organic matter content varied between the various fire frequencies. Unlike the granitic plots where it is believed that fire intensities are not substantial enough to transfer heat deep into the soil and consume organic matter, it is thought that the huge contrast in above-ground biomass between the basaltic burn plots is in fact responsible for the contrast in organic matter contents. Consequently, soil water retention was found to be greatest on the fire-suppressed no burn plots. The ability of the soil to retain moisture, especially at low water contents, is crucial in a post-fire environment in order to facilitate re-establishment of vegetation.

Fire impacts on soil hydraulic processes ultimately influence soil water balances. These impacts may have cascading effects on large-scale catchment processes. This study provides valuable insight not only into the relationship between water and fire but also how other factors such as soil, vegetation and herbivores all interact within a water-controlled savanna landscape.

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ANOVA - Analysis of Variance
BoAr - Bonheim- Arcadia
BoSw - Bonheim- Swartland
dCl - Deep Clovelly
DPM - Disc Pasture Meter
dRs - Deep Red Sands
EBPs - Experimental Burn Plots
Es - Estcourt
HSD - Honest Significant Difference
KNP - Kruger National Park
K_{sat} - Saturated Hydraulic Conductivity
K_{unsat} - Unsaturated Hydraulic Conductivity
mdShSw - Moderately Deep Shortlands- Swartland
PCA - Principle Components Analysis
PVC - Polyvinyl Chloride
SAM - Strategic Adaptive Management
sCl - Shallow Clovelly
VFR - Variable Fire Regime

1. INTRODUCTION

Soil is a natural resource which forms an essential component of the earth's biosphere and is vital in supporting healthy and functioning ecosystems. Besides providing a medium for plant growth, soils play a major role in ecosystem functioning by cycling nutrients and filtering water through the system (Erickson and White, 2008). When soils are degraded, important ecosystem services are affected. Degraded soils may not be able to store and filter water as efficiently thereby affecting water quantity and quality. This in turn has a detrimental effect on catchment hydrological processes. Hydrologically, soil partitions water. Rain water is partitioned into overland flow and infiltrated water. Infiltrated water is then partitioned into water available to vegetation for root uptake and drained water. While the ecosystem services of overland flow is focussed on stream flow, the infiltrated water impacts the vitality of vegetation and the broader ecosystem. Van Tol *et al.* (2010) describe the complex relationship between soil and water as *interactive* meaning that the physical, chemical and biological properties of soil influence the manner in which water is transported and stored within the landscape which impacts the ecosystem.

As with many other biomes around the world, the structure and production of semi-arid African savannas are controlled by the spatio-temporal availability of water. These savannas are considered complex and dynamic systems which are co-dominated by grasses and trees (Scholes and Archer, 1997; Sankaran *et al.*, 2004). There are two opposing models believed to facilitate this co-existence, i.e. equilibrium and disequilibrium models (Scholes and Archer, 1997). Walter (1971) suggests an equilibrium model whereby the co-existence of tree and grasses are due to different rooting niches and accessing soil moisture at contrasting depths. Supporting evidence from Sarmiento and Monesterio (1975), Walker (1979), Harris (1980), Medina (1980) and Walter (1971), as cited in Walker and Noy-Meir (1982), were used in order to understand this equilibrium model. Due to the naturally-alternating wet and dry soil phases, soil moisture dynamics vary with depth. The surface layers, where grass roots are located, dry out first while the deeper layers, where only tree roots are found, retain moisture for much longer. However, according to Walter (1971), the deeper layers remain above wilting point all year round. In the surface layers, grasses dominate and out-compete trees for water due to the nature of their root systems. Therefore, savanna structure is controlled by the competition for available soil water between woody and grass plants (Walker and Noy-Meir, 1982). Alternatively, Higgins *et al.* (2000) propose a disequilibrium model stating that there is no steady-state and that various frequent disturbances alternatively bias either trees or grasses by facilitating the competition for resources (Govender *et al.*, 2006). Furthermore, Higgins *et al.* (2000) suggest that the life-history strategy of trees, that have the ability to occasionally re-sprout and survive fires, enables the co-existence of both trees and grasses.

Fire, along with fluctuations in rainfall, nutrients and herbivory is regarded as one of the primary drivers responsible for controlling these heterogeneous savanna systems (Walker and Noy-Meir, 1982; Van Wilgen *et al.*, 2000; Kraaij and Govender, 2010). Savanna fires can be ignited either by anthropogenic activities, whether accidentally or purposefully, or naturally through lightning (Archibald *et al.*, 2009). Ignition by lightning is less common and these fires do not often burn through extensive areas of natural woodland (Walter, 1971). Although savanna vegetation is resilient and relatively well-adapted to fire (Furley *et al.*, 2008), it is believed that frequently-recurring fires can prompt long-term soil degradation, changing the soil hydrology and ultimately reducing ecosystem productivity (Cerda *et al.*, 1995). The frequency of savanna fires are highly variable and influenced by factors such as preceding annual rainfall and pressure from herbivores (Trollope, 1993; Van Wilgen *et al*., 2004). Both of these factors directly impact the fuel load that is required to support veld-burning.

In the Kruger National Park (KNP), fire is used as a critical management tool to help control the vegetation structure in these dynamic savannas (Smit *et al.*, 2010). The Experimental Burn Plots (EBP) is a long-term fire experiment, initiated in the early 1950s, with the aim of assessing the impacts of fire on ecosystem dynamics and functioning (Biggs *et al*., 2003). Numerous studies have focused on fire impacts on various vegetation characteristics (e.g. Gertenbach and Potgieter, 1979; Enslin *et al.*, 2000; Higgins *et al.*, 2007; Smit *et al*., 2010), soil nutrients (Webber, 1979; Mills and Fey, 2003) and small mammals (e.g. Kern, 1981). A lack of information on the impacts of long-term fire on soil hydrology in semi-arid savannas creates a critical gap in the current understanding of savanna ecosystem dynamics. The EBPs offered a unique opportunity to determine the effects of long-term fire treatments on soil hydraulic properties. Since fire is implemented as a management tool, KNP management could benefit from this study by improving fire policies and making better informed decisions. This will aid in ensuring that catchment hydrological properties are not adversely affected by unsuitable burning regimes.

This dissertation focuses on how contrasting fire frequencies affect various soil hydraulic properties by studying these effects on long-term experimental burn plots. Existing literature directed at fire effects on soil properties, and the methods and statistical analyses previously applied has been reviewed and summarised in Chapter 1. Following the literature review, this chapter concludes stating the overall objectives of this study and the hypotheses. Chapter 2 describes the study site in KNP as well as a brief description of the EBPs' history and design. Chapter 3 follows and describes which EBPs this research project concentrated on and the sampling design applied. Furthermore, the methodology and equations used to address the objectives are discussed. Chapter 4 is divided into two sections, each addressing the objectives on different EBPs on the two different geological substrates. These sections involve basic statistical analyses on the effect of fire frequency on soil hydraulic properties as well as a more advanced statistical method of analysing which environmental variable influences how fire affects soil hydraulic properties. The entire thesis is synthesised and discussed in Chapter 5, followed by a conclusion and further recommendations for future research in Chapter 6.

1.1 Literature Review: The Effects of Fire on Soil Properties

As mentioned above, it has been established that there is a critical need for fire and hydrology linked research in African savannas. Since the majority of the work relating to fire effects on soil properties has been conducted in other landscapes around the world, most of the literature presented below stems from these studies abroad. Literature has been reviewed in order to generate an understanding regarding the topic, to formulate hypothesises and to review the methodological approaches used in other studies.

1.1.1 Introduction

Fires can be both constructive and destructive to soils, depending on perspective as well as scale (Erickson and White, 2008). One of the key advantages of fire is an increase in soil fertility (Erickson and White, 2008) whilst potential disadvantages include water repellency (Scott, 1993; Ice *et al.*, 2004), loss in nutrients (DeBano and Conrad, 1978), decreased soil water retention (Stoof *et al.*, 2010) or decreased infiltration rates (Martin and Moody, 2001). Fire-induced changes to vegetation and soil properties result in changes to the hydrological cycle of a specific location or at a local scale, which in turn alters the movement of water and sediment through watersheds at a larger scale (Swanson, 1981). Fires stimulate critical changes in the soil and the microclimate associated with the soil surface (Mallik *et al.*, 1984) which in turn influences the hydrological cycle and chemistry of the soil (Thonicke *et al.*, 2001). According to Certini (2005), and Doerr and Cerda (2005), soil properties can endure short-term, long-term or permanent fire-induced changes; of course, this depends on factors such as the type of soil property, intensity and frequency of fires as well as the post-fire climatic conditions.

1.1.2 Water repellency

Water-repellent (hydrophobic) layers reduce soil infiltration and percolation. Fires may prompt or facilitate hydrophobicity by heating the hydrophobic organic compounds found at the soil surface (Doerr *et al*., 2009; Martinez-Murillo *et al*., 2014). Some of those organic compounds include hydrocarbons (DeBano, 2000) as well as fulvic and humic acids (Giovannini and Lucchesi, 1984;

cited by DeBano, 2000). According to Ice *et al.* (2004), when volatized organic compounds condense on cooler soil particles, negatively-charged layers repel water. The extent of the water-repellent layer depends on the steepness of the temperature gradient near the soil surface, soil moisture as well as the physical properties of the soil (DeBano, 1990). After fires, water repellency is more likely to occur in coarse-textured than fine-textured soils and in areas of high burn severity (Erickson and White, 2008). Furthermore, less intense fires that burn over moist soils tend to produce less water repellency than intense fires over dry soils (Ice *et al*., 2004). Occasionally, strong surface water repellent layers may not exist, but it is possible that water repellent layers may be present below the soil surface (Lewis *et al.*, 2006). As water content increases within the soil, soil from both burned and unburned areas may become less hydrophobic or may even lose its hydrophobic characteristic completely (Doerr *et al*., 2009).

It is worth noting that not all water repellent layers are fire-induced but are naturally-occurring due to the soil texture and presence of hydrophobic organic matter. Some studies have attempted using fire to destroy water repellent layers in the soil. DeBano and Krammes (1966) suggest that the naturally-occurring non-wettability of the top few centimetres of the soil surface may be destroyed by fire temperatures high and deep enough to which non-wettability is destroyed. This depends on the intensity and duration of the fire. Furthermore, they believe that the temperatures of the fire are sometimes not intense enough to destroy the non-wettability but instead to intensify it. It is critical to note that this conclusion was based on laboratory experiments and may not be applicable to fire burning in the savanna landscape.

1.1.3 Infiltration

With regards to the hydrological cycle, soil infiltration rate is vital in partitioning rainfall into surface runoff and subsurface flows (Cerda and Robichaud, 2009). Infiltration refers to the downward movement of water through the soil surface into the soil medium (Schaetzl and Anderson, 2005). After fires have burned and denuded an area of vegetation, the result may be changes to a number of soil hydrological properties (Scott, 1993; Erickson and White, 2008). Bare soil becomes exposed to natural elements such as direct solar radiation and heat, wind and rainfall. Once fire has removed vegetation cover the soil surface is exposed to raindrop impact and splash which results in the sealing and compaction of surfaces thus reducing infiltration (DeBano, 2000; Ice *et al.*, 2004). In a post-fire environment where soil infiltration rates are low, trees may be hydrologically disadvantaged since water might not be able to penetrate deep enough to reach their roots. Ultimately, this could temporarily interfere with the co-dominance of tree and grasses in savanna systems.

According to Mallik *et al.* (1984), infiltration through burned soil surfaces could be inhibited by the blockage of larger pores by ash particles. Infiltration is characterised by either short- or long-term scale responses. The short-time scale response depends on the relation between sorptivity (ability of soil to absorb moisture) and soil moisture which provides an indication of the infiltrability and capillary forces (which allow for the upward movement of water) acting on the soil (Moody *et al.*, 2009). On the other hand, the long-time scale response depends on the relation between hydraulic conductivity and soil moisture, which provides an indication of the gravitational forces acting on the soil (Moody *et al.*, 2009).

Soil surface compaction results in decreased infiltration rates, increased runoff production and increased erosion rates (Cerda *et al.*, 1995; Snyman, 2002). Often, there is an increase in rill, sheet and mass movement erosion following an intense fire (Swanson, 1981). In cases where the intensity of rainfall is greater than the soil's ability to allow the infiltration of water, Hortonian overland flow will occur and could lead to erosion. According to Sidle *et al.* (2007), the process of Hortonian overland flow occurs in the following sequence of events: (1) a thin layer of water develops on the soil surface and initiates surface runoff (2) surface runoff collects in and fills surface depressions (3) as the surface depressions fills up, they spill over and lead to overland flow (4) this overland flow collects into micro-channels which may result in the formation of rills and gullies (5) these micro-channels direct the flow into streams. Hosseini *et al.* (2014) suggest that the generation of run-off in a post-fire environment is strongly dependent on past fire regimes.

Vegetation cover and soil properties have assorted effects on soil infiltration rates. Soil infiltration is a function of soil porosity and structure, which is facilitated by biological activities (Cerda and Robichaud, 2009). Bioactivities by burrowing worms and insects and the penetration by roots are known to facilitate infiltration by increasing the soil porosity and preferential pathways (Cerda and Robichaud, 2009). In addition to increasing soil infiltration, vegetation cover protects the soil surface from processes such as raindrop impact and splash (DeBano, 2000; Cerda and Robichaud, 2009). Vegetation leads to a soil litter layer which promotes bioactivity, soil aggregation, water storage, and macro- and micro-pore development (Cerda and Robichaud, 2009).

1.1.4 Organic matter

According to Thonicke *et al.* (2001), fire is important in savanna systems because it speeds up the nutrient cycle through the rapid mobilization of nutrients. Even though some nutrients are volatized and lost, the majority of them are made more readily available to the system (DeBano, 1990). Through the burning of organic matter in the soil, important nutrients are released which aids in the regeneration of plants (Nardoto and Bustamante, 2003). Organic matter plays a vital role in the physical, chemical and biological properties and processes of the soil and thereby contributes to overall soil productivity (DeBano, 1990). Snyman (2002) suggests that a significant decrease in soil organic matter will not only initiate a reduction in soil fertility and production, but could also lead to the destruction of soil structure which would inevitably bring about increased runoff and soil erosion.

According to DeBano (1990), organic matter plays a critical role in the formation and maintenance of well-aggregated soils since it acts as a cementing agent between soil aggregates. Aggregates stem from the organization of soil mineral and organic particles (Mataix-Solera *et al.*, 2011) and improve soil structure which creates macro pore space, improves soil aeration and increases hydraulic conductivity (DeBano, 1990). Aggregated soils are found to have higher infiltration rates than non-aggregated soil with less organic matter (DeBano, 1990). Aggregate stability can be used as an indicator of the state of soil structure and physical stability since it refers to the soils ability to maintain its structure when exposed to external forces (Mataix-Solera *et al.*, 2011). These external forces may include raindrop impact, moisture or heat from fire. Fire affects soil structure when organic matter, the cementing agent, on or near the soil surface is combusted (DeBano, 1990). This break down in soil structure could lead to increased runoff and soil erosion (Snyman, 2003).

By altering the fire regime in these fire-driven ecosystems such as savannas, there could be either an overall loss or gain in nutrients in the system (Thonicke *et al.*, 2001). Mills and Fey (2003) suggest that it is the first couple of centimetres, also known as the pedoderm, of intact topsoil that houses the majority of nutrients, humus and salts in comparison to the subsequent strata. Therefore, this layer is important in a post-fire environment because it stores critical nutrients required by plants to facilitate regeneration.

1.1.5 Soil water retention

Water is held in soil pore spaces by capillarity, thus smaller pore-sizes result in greater soil water retention (Ubeda and Outeiro, 2009). Soil water retention increases with an increase in clay and organic content since these substances are hydrophilic (Schaetzl and Anderson, 2005). Clays and organic matter are hydrophilic due to the strong attraction between bipolar water molecules and the charged sites on clays and organic matter (Schaetzl and Anderson, 2005). According to Stoof *et al.* (2010), fires are known to change soil properties which in turn influence soil water retention. Water is held in the soil in two forms, i.e. adsorption and absorption (Schaetzl and Anderson, 2005). Due to chemical or physical bonds, water is adsorbed to the surface of soil particles whereas absorbed water is taken up into the solid soil particle (Schaetzl and Anderson, 2005). The loss of soil organic matter and subsequent reduction in structure during a fire results in a decreased soil water retention capacity (Ubeda and Outeiro, 2009). Since soil water retention infers the ability of a soil to store water, it is obvious why it plays a major role in the restoration of plants in a post-fire environment (Stoof *et al.*, 2010).

1.1.6 Review of pyro-hydrology studies in South Africa

There is a scarcity in existing literature where local studies determined the effects of fire on soil properties. A study conducted in a semi-arid grassland, investigated the impact of fire on various soil characteristics such as soil water content, compaction, soil temperature and so forth

(Snyman, 2002). Snyman (2002) found that due to the fire reducing vegetation cover, there was an increase in soil temperature and compaction but a decrease in organic matter content. This in turn resulted in a decrease in soil water content. A study conducted by Scott (1993) in the fynbos catchments of South Africa investigated the effects of fire on soil infiltration rates. He concluded that fires negatively impacted soils by decreasing soil infiltration. Similar studies conducted locally in semi-arid savannas found that fire resulted in crusted and compacted soil surfaces which reduced infiltration (Mills and Fey 2003; Mills and Fey, 2004). The study by Mills and Fey (2004) which concluded that fires would lead to crusted soil surfaces that inhibited soil infiltration was conducted in a laboratory experiment. There is a need to conduct in-situ measurements where soils are not disturbed or manipulated in order to confirm these findings. Furthermore, this study was only conducted on soils derived from one geological substrate only, i.e. the granites in KNP.

1.1.7 Review of methods applied in similar studies

There are a number of different techniques and methods which can be used to test a number of soil properties with regards to fire effects. Double-ring infiltrometers and cylinder infiltrometers are the most widely used techniques for quantifying soil infiltration rates (Cerda and Robichaud, 2009). Although ring infiltrometers are simple and robust instruments which provide accurate measurements of field-saturated hydraulic conductivity, they are difficult to insert and use in stony, porous soils and may result in soil disturbance during insertion (Reynolds, 1993a). Additionally, these instruments require relatively flat surfaces and soils that are not too sandy which will result in the prevention of ring infiltrometers from ponding and cylinder infiltrometers to leak due to poor contact between the instrument and soil surface (Cerda and Robichaud, 2009). Other instruments such as well permeameters (Elrick and Reynolds, 1992; Adhanom *et al*., 2012) and tension disc infiltrometers (Ankeny *et al*., 1991; Riddell *et al*., 2012) can also be applied to test in situ hydraulic conductivities. The constant-head well permeameter is inserted into an uncased well and maintains a constant depth (head) of water, measuring the flow of water out of the well into unsaturated soil. Initially, the flow rate will decline rapidly before reaching a steady state— which is the desired measurement (Reynolds, 1993b). The well permeameter takes hydrostatic pressure, gravity and capillarity into account when calculating hydraulic conductivities which is generally variable in natural soils (Elrick and Reynolds, 1992). There are many advantages to using well permeameters and tension disc infiltrometers. They are considered as simple, robust instruments which are easy to transport allowing for relatively rapid spatio/temporal replication (Reynolds, 1993b). These versatile instruments generally require low volumes of water and can be applied to a range of soil textures (Reynolds, 1993b) which are critical for remote fieldwork in KNP.

Since infiltration may be inhibited by soil compaction, it is useful to measure the degree of soil compaction. Cone penetrometers are simple instruments which may be used to measure soil compaction (Vaz *et al*., 2001; Herrick and Jones, 2002; Riddell *et al*., 2012). They are cost-effective devices which enable multiple replications over extensive areas and easy interpretation of data.

Soil organic matter content may be analysed using a number of methods such as the loss on ignition method (Stoof *et al*., 2010; Velasco *et al*., 2014), near infrared reflectance (NIR) spectrometry (Yong *et al*., 2005) or the Walkley-Black method involving chemical digestion and titration processes (Hartnett *et al*., 2004; Mills and Fey, 2004). All of these methods are specialised and time-consuming. LECO carbon analysers are instruments which may be used to determine percentage total carbon in soil samples (Wang and Anderson, 1998; Bell *et al*., 2003). This method, on the other hand, is not as time-consuming and more efficient as it requires a smaller sub-sample of soil.

A common technique of determining soil water retention involves using pressurizing plates to subject saturated soil sample to different tensions in a laboratory and then plotting water retention curves (Van Genuchten *et al.*, 1991; Wesseling *et al*., 2009; Stoof *et al*., 2010). Lorentz *et al.* (2003) applied a similar approach using a cell outflow method to determine soil water retention at varying pressures. However, the main disadvantages are that these methods are sensitive and time-consuming.

1.1.8 Review of statistical analyses in similar studies

Statistical analyses are important means of interpreting complex datasets and understanding trends. This section describes how similar studies used different types of statistical analyses in order to aid in the correct interpretation of data.

Previous studies that were conducted on the EBPs utilised various statistical analyses. Many of these studies (Enslin *et al.*, 2000; Shackleton and Scholes, 2000; Higgins *et al*., 2007) used analysis of variance (ANOVA) to analyse various variables in order to determine the differences in variation across the different burn plots. For example, Higgins *et al.* (2007) used ANOVA to analyse three response variables i.e. change in tree density, change in small tree dominance and change in biomass. Two of these variables were Box-Cox transformed in order to normalise data which is a pre-requisite for the ANOVA test. They used two ANOVA models to analyse the three response variables whereby the first model allowed the comparison of the effects of fire exclusion to the effects of burning at various seasons and frequencies. The second model excluded fire exclusion plots and only focused on the fire return intervals. Snyman (2003) investigated the short-term response of soil properties following a rangeland fire and applied a two-way ANOVA for soil water content and soil properties. All other data based on basal cover, soil compaction and soil temperature were tested using a one-way ANOVA.

Enslin *et al.* (2000) carried out a combination of statistical analyses when they investigated the long-term effects of fire frequency and season on woody vegetation dynamics. All their data were analysed using ANOVA. Parameters such as tree density, basal area and tree height in relation to distance from permanent water were tested using linear regressions. Furthermore, T-tests were used to compare mean densities over two years and principle components analysis (PCA) was used to ordinate species community data.

Hydrological and pedological studies conducted elsewhere were also reviewed in order to gain insight into how these kinds of datasets can be appropriately analysed. In a study by Chaplot *et al.* (2010) aimed at digitally mapping A-horizon thickness, a PCA was used to evaluate the impact of different soil properties such as thickness of the A-horizon, altitude, mean slope gradient, upslope drainage area, top-soil water content and bulk density on soil apparent electrical resistivity. PCA is a variable reduction procedure. Since a number of variables will be used to collect a large amount of data, PCA will be useful in creating artificial variables (principal components) to explain as much of the information in the data set as possible (Fowler *et al*., 1998). The first principal component is used to explain the largest amount of information in the data set while the second principal component, aimed to be as different from the first as possible, is used to describe the second largest amount of information (Fowler *et al*., 1998). Thereby, it would be possible to reduce the observed variables into a smaller number of principal components that will account for most of the variance in the observed variables.

1.1.9 Conclusion

Various studies from different locations around the world deduced that fire can play a major role in soil hydrological properties and processes. Depending on factors such as soil physical properties, fire intensity, fire severity, vegetation biomass and soil moisture amongst others, fire can impact soil hydraulic properties such as infiltration, water repellency, water retention capacities and ultimately, soil water balances both positively and negatively. Fire impacts on these hydraulic properties can lead to major influences on the generation processes of overland flow, runoff amounts and erosion yields. Therefore, the role of fire in the local hydrological cycle can be quite significant.

There were contradictory findings in the literature regarding the effects of fire on soil properties. These contradictions were based on differences in factors such as soil texture, soil type, fire intensity, vegetation cover and above-ground fuel loads. The spatial and temporal variations in post-fire effects were also identified as confounding challenges in these types of studies. These variations in post-fire effects were due to variations in soil and fire intensity caused by differences in pre-fire vegetation cover, fuel load and soil moisture contents (Cerda and Robichaud, 2009).

Considering that most fire and hydrology-linked studies was based on single fires, it would be important to investigate the effects of more than 50 years of continual prescribed fires on soil hydraulic properties. Robichaud and Cerda (2009) also acknowledged the need for continued research investigating the effects of long-term treatments on soil properties. In water-controlled ecosystems such as semi-arid savannas, examining the link between fire and soil hydraulic properties is critical in understanding the vital role of water in these savannas.

1.2 Aim and Objectives

Fire plays a major role in savanna system dynamics and functioning. The long-term EBPs in KNP were used in order to investigate the effects of long-term fire frequencies on soil hydraulic properties. The study focused on the two extreme treatments, namely, the annual burn plots which are exposed annually to hot August fires and the fire-suppressed no burn plots. Furthermore, these extreme treatments are compared to the natural conditions outside of the EBP experiment. These areas are exposed to a more variable fire regime (VFR) with a return interval of approximately 4.5 years (Van Wilgen *et al.*, 2000). However as the need arises, management fires are used in these "variable" areas when fuel loads are too great and poses the risk for uncontrollable, high-intensity fires.

The overall aim of this research project is to determine the effect of long-term fire frequencies (annual burn vs. no burn vs. VFR) on soil hydraulic properties on granitic and basaltic geologies. This project intends to address the following key questions:

- Do different fire frequencies (i.e. annual burn, no burn and VFR) lead to differences in unsaturated hydraulic conductivity (K_{unsat})?
- Do different fire frequencies lead to differences in saturated hydraulic conductivity (K_{sat})?
- How do different fire frequencies affect soil compaction?
- How do varying fire frequencies influence soil organic matter content?
- How do different fire frequencies affect soil water potential?
- Since vegetation plays a role in soil hydraulic processes, how do different fire frequencies influence grass biomass and basal cover?

Based on the literature review, the following hypotheses have been articulated:

- The annual burn plot will have the slowest K_{unsat} and K_{sat} due to changes in the soil structure caused by the frequent fires.
- The soil on the annual burn plot will be the most compacted due to frequent fire altering the chemistry of the soil and denuding an area thus exposing it to processes such as raindrop impact and splash.
- Soil organic matter will be greatest on the no burn plot due to many (> 50) years of fire exclusion.
- Soil water potential will be greatest on the no burn plot since fire exclusion would have allowed for an increase in the organic matter content which is hydrophilic and thus also increases soil water retention.
- Due to the suppression of fire, the no burn plot will have the highest grass biomass and percentage basal cover.

2. STUDY SITE

2.1 Kruger National Park (KNP)

2.1.1 History and location

Even though Sabi Game Reserve was proclaimed in 1898, formal conservation of game only began in 1902 when James Stevenson-Hamilton was appointed as warden (Mabunda *et al*., 2003). The Shingwitsi Game Reserve was proclaimed in 1903 and the Sabi Game Reserve expanded by including the area between the Sabie and Olifants rivers under its protection (Mabunda *et al*., 2003). After the National Parks Act was passed in 1926, the Sabi and Shingwitsi game reserves were merged to form the KNP (Carruthers, 1995; cited by Mabunda *et al*., 2003).

KNP, roughly 1 950 000 ha, is situated on the Lowveld in the north-eastern most part of South Africa, bordering Zimbabwe in the north and Mozambique in the east (refer to Figure 2.1). It lies between latitude 22° 25’ to 25° 32’ East and longitude 30° 50’ to 32° 02’ South with a north-south distance of roughly 320 km and a mean east-west distance of approximately 65 km (Joubert, 1986).

2.1.2 Climate

The climate in the Lowveld is correlated with the sub-continent’s regional climate and is influenced by the anticyclonic systems which travel from west to east over southern Africa (Venter and Gertenbach, 1986). The summer season extends from around November to February while the winter season falls between June and August. Summers are wet and characterised by hot temperatures, with an average daily maximum of 34°C and minimum of 21°C (Kennedy and Potgieter, 2003). Winters are dry with mild June and July temperatures averaging at a maximum and minimum of 27°C and 10°C, respectively (Kennedy and Potgieter, 2003). On average, rainfall in KNP increases from north and south, and from east to west. The central and southern parts of the park are located within the lowveld bushveld zone which experiences an annual rainfall of 500-700 mm (Venter *et al*., 2003). Potential evaporation ranges from 1400 mm in the

East to 1700 mm in the West (Heritage *et al*., 2001a). The north falls in the northern arid bushveld zone where annual rainfall ranges between 300 and 500 mm (Venter *et al*., 2003). The potential evaporation for this region of the park varies from 1400 mm (in the east) to 1900 mm (in the west) (Heritage *et al*., 2001b). Heritage *et al*. (2001a) suggest that during summer months, evaporation rates are 60% higher than during winter. The beginning of the rainy season is exemplified by thunderstorms with extreme lightning events. The fact that KNP's climate is divided into distinct dry winter and wet summer periods produces the ideal conditions for fire (Kennedy and Potgieter, 2003). The summer rains provide the moisture required for sustained growth during the dry season and when the next summer cycle arrives, there is ample grass biomass, and hence fuel load available for late winter/ early summer fires.

2.1.3 Geology

KNP is underlain by a variety of igneous, sedimentary and metamorphic geological formations. The geology changes from west to east due to the lithological strikes in a primarily north-south direction (Venter *et al*., 2003). Geologically, the park is divided roughly into the granites (coarse-grained igneous rock) on the west and basalts (fine-grained igneous rock) on the east, as illustrated in Figure 2.1. A narrow north-south stretch of sedimentary rocks separate the granitic and basaltic regions while a rhyolite band runs parallel on the eastern boundary of the park (Venter *et al*., 2003). There is an assortment of geological parent material in the park which is evident from the Lebombo Mountains on the eastern boundary with Mozambique, the sandstone hills northeast of Punda Maria and the granitic rocky terrain in the southwest of the park between Pretoriuskop and Malelane (Mabunda *et al*., 2003)

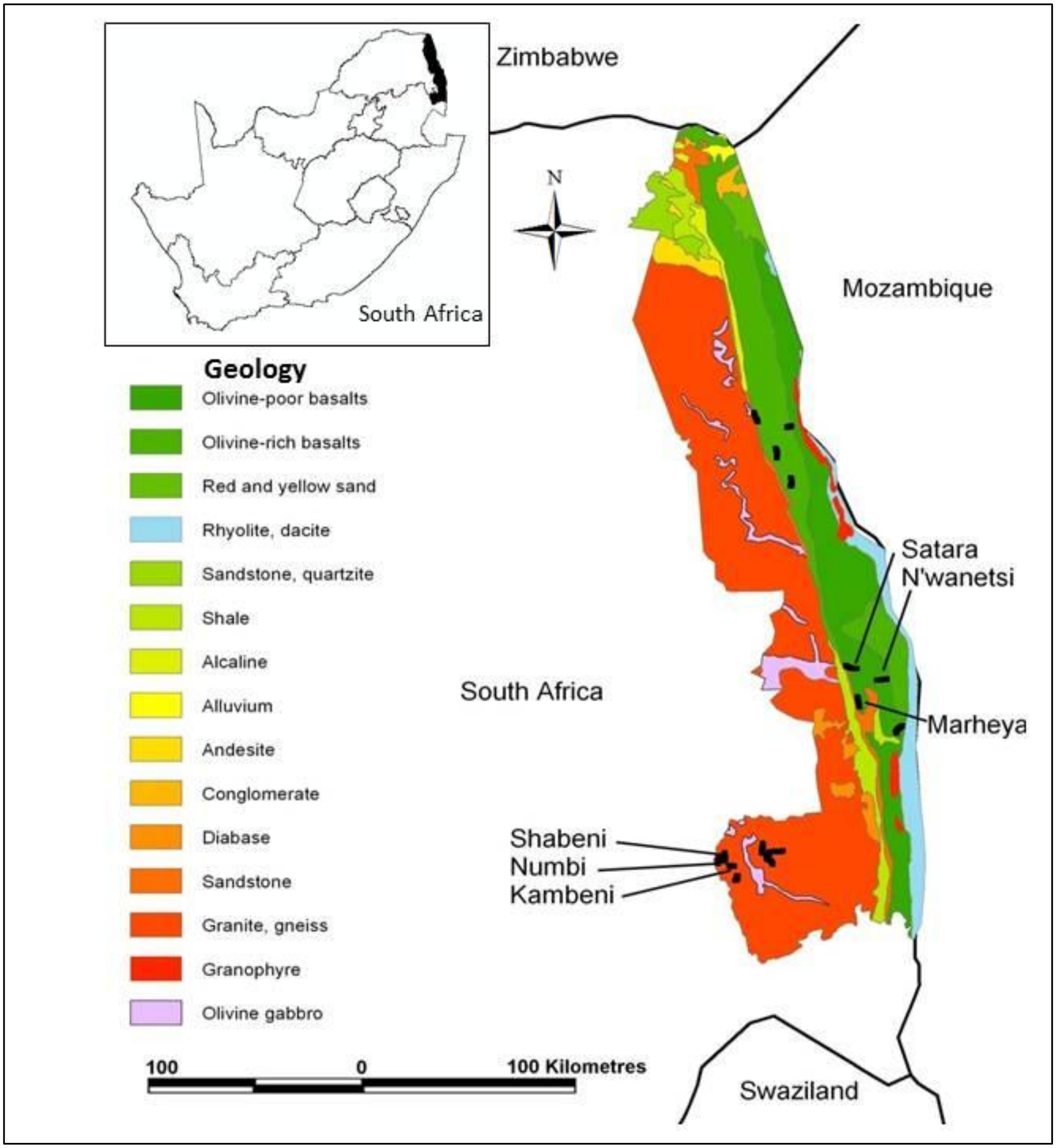


Figure 2.1 A detailed geological map illustrating the location of KNP in the relation to South Africa as well as the EBPs in the park (after Riddell *et al*., 2012)

2.1.4 Soils

The soils in the southern granitic area of the park are characterised by coarse-grained sands and loamy sands. Venter (1986) confirms that soils in this Pretoriuskop region of KNP generally follow the typical catenal sequence from crest to valley bottom as sandy, hydromorphic, duplex and alluvial soils. Crests are described as large and dominated by red apedal sands (Harmse and Van Wyk, 1972; cited by Venter 1986). Crests and upper midslopes are characterised by Huttons, Bainsvlei, Clovelly and Avalon soil forms (Venter, 1990). The hillslope has narrow footslopes distinguished by duplex soils from the Kroonstad and Estcourt soil forms along drainage lines (Venter, 1990). Venter (1990) recognized that due to extended periods of saturation, the lower midslopes often have varying hydromorphic soils. In the central basaltic regions of KNP, the nutrient-rich soils are characterised by fine-grained material such as clays. These basaltic plains which are olivine-poor lavas are dominated by moderately deep to shallow, red and brown, structured and para-duplex soils belonging to the Shortlands and Swartland soil forms (Venter, 1990).

Soil can be defined as a naturally-occurring body of unconsolidated material which supports functional ecosystems. This vital resource delivers very specific services to the ecosystem which varies between soil types. Since the factors which influence soil formation, i.e. parent material, topography, biology, climate and time (Park *et al*., 2001), the soil types typically show strong relationships with the geology, topography and climate. The relationship with time is associated with topographical position and the correlation with biology is rather an indication of the ecosystem services delivered to the ecotope. Venter and Gertenbach (1986) suggest that several plant species can be used as indicator species of specific soil conditions due to the strong correlation between vegetation and soil types (inherited from the geological parent material) in the park. Soil properties such as depth, texture and structure control the fate of rainfall and influences soil water content. These soil properties along with soil nutrients are evidently reflected in the biotic components of the ecosystem (Venter, 1986). The abiotic template of KNP forms an integral and vital role in the ecology of the area (Venter, 1986).

2.1.5 Vegetation

The vegetation of KNP includes nearly 1 968 different plant species in a range of structural features varying from dense forest through to open plains with low shrubs (Venter and Gertenbach, 1986; Mabunda *et al*., 2003). In the south-western section of the park, characterised by undulating terrain and catenas, the vegetation consists of relatively dense woodland species. Typically, tree species such as *Combretum apiculatum* (red bushwillow) and *Terminalia sericea* (silver cluster-leaf) dominate the sandy soils on crests and midslopes while grasses such as *Pogonarthria squarrosa* (herringbone grass) and *Digitaria eriantha* (common finger grass) sparsely cover the crests (Venter and Gertenbach, 1986; Venter, 1990). The footslopes are dominated by tree species such as *Acacia nigrescens* (knob thorn), *Dichrostachys cinerea* (sickle bush) and *Euclea divinorum* (magic guarri) and grass species such as *Themeda trianda* (red grass) and *Panicum maximum* (white buffalo grass) (Venter and Gertenbach, 1986). In the higher rainfall region of Pretoriuskop, where annual rainfall is above 700mm, the vegetation is primarily mesic with dominant tree species such as *Terminalia sericea* and *Dichrostachys cinerea*, and tall grasses such as *Hyperthelia dissoluta* (yellow thatching grass) (Venter and Gertenbach, 1986). The Satara area in the central region of KNP comprises primarily of fine-leaved tree savanna and is dominated by tree species such as *A. nigrescens*, *D. cinerea* and *Sclerocarya birrea caffra* (marula) (Venter *et al*., 2003). The basaltic, nutrient-rich soil in the Satara offers suitable grazing to game by favouring palatable grasses (Venter, 1990). Along footslopes, grass cover is thicker, more palatable and thus more vulnerable to overgrazing by herbivores (Gertenbach, 1983; Venter and Gertenbach, 1986).

Herbivory is considered a key driver in savannas by facilitating heterogeneity in this dynamic system. Herbivore densities fluctuate due to fluctuations in rainfall (Mills *et al*., 1995; cited in Van Wilgen *et al*., 2003). Increased herbivore concentrations increase the grazing pressure on vegetation and have cascading effects on fire intensities due to the reduction in fuel loads. Unlike other fire-prone regions around the world, African savannas are unique due to the presence of both meso- and mega-herbivores such as elephant, rhinoceros, buffalo and hippopotamus (Van Wilgen *et al*., 2003).

2.2 Experimental Burn Plots (EBPs)

The EBPs in KNP form a large, long-term fire-management experiment. The history and development of this experiment is described in further detail in the following subsection. Furthermore, the experimental design and layout is explained as well as the soil and geomorphic template of the burn plots. Selection of particular EBPs where the study is focused are presented and justified.

2.2.1 EBPs history and design

Earlier ideas considered fires to be harmful to the environment and that it would lead to land degradation and ultimately, soil erosion. Thus, KNP management avoided fires by actively supressing and preventing them. Except, after 1957 when it was discovered that fire is an important driver in savanna systems, fires were implemented at a fixed return period (Van Wilgen *et al*., 2000; 2003). KNP management and scientists acknowledged that an understanding of the features of natural fires be developed (Van Wilgen *et al*., 2000). This research experiment was developed in the early 1950s and replicated in four major vegetation landscapes of the KNP (Biggs *et al.*, 2003; Higgins *et al.*, 2007). The experimental design was a randomised block arrangement with four replications of 12 to 14 fire treatments of different combinations of seasons and frequencies of fire in each landscape (Trollope *et al.*, 1998; Biggs *et al*., 2003). As described by Gertenbach (1983), the four major vegetation landscapes that were selected for these EBPs include the Lowveld Sour Bushveld of Pretoriuskop (sandy granitic soils); the Mixed *Combretum spp. / Terminalia sericea* Woodland west of Skukuza (sandy granitic soils); the *Sclerocarya birrea caffra/ Acacia nigrescens* Savanna around Satara (clay basaltic soils); and the *Colophospermum mopane* Shrubveld on Basalt north of Letaba (clay basaltic soils) (see Table 2.1). Figure 2.1 illustrates the distribution of the EBPs in the park and highlights the Pretoriuskop and Satara burn plots that were used for this study. There are a total of 208 burn plots with an average size of roughly 7 ha (370 m x 180 m) each (Trollope *et al.*, 1998). Figure 2.2 illustrates the difference in vegetation density and structure across the two extreme fire treatments, i.e. annual burn and no burn (control) plots.

Table 2.1 The four vegetation types where the EBPs were configured for the fire experiment in the early 1950s (after Van Wilgen *et al*., 2007; Venter and Govender, 2012†)

Vegetation/ veld type	**Region**	**Common tree species**	**Geology**	**Dominant soil types †**	**Mean annual rainfall (mm)**
Sourveld	Pretoriuskop	*Terminalia sericea, Dichrostachys cinerea*	Granite	Clovelly, Hutton, Estcourt, deep red sands	705
Combretum	Skukuza	*Combretum collinum, Combretum zeyheri*	Granite	Clovelly, Hutton, Estcourt, Glenrosa	572
Knobthorn-Marula	Satara	*Acacia nigrescens, Sclerocarya birrea caffra*	Basalt	Shortlands, Swartland, Bonheim, Mispah	507
Mopane	North of Letaba	*Colophospermum mopane*	Basalt	Maya-milkwood, Bonheim, Arcadia	451

Table 2.2 Description of the treatments (frequency and season) each veld type receives

Sourveld	**Combretum**	**Knobthorn-Marula**	**Mopane**
Oct B2	Oct B2	Oct B2	Oct B2
Oct B3	Oct B3	Oct B3	Oct B3
Dec B2	Dec B2	Oct B4	Oct B4
Dec B3	Dec B3	Oct B6	Oct B6
Feb B2	Feb B2	Dec B2	Dec B2
Feb B3	Feb B3	Dec B3	Dec B3
Apr B2	Apr B2	Feb B2	Feb B2
Apr B3	Apr B3	Feb B3	Feb B3
Aug B1	Aug B1	Apr B2	Apr B2
Aug B2	Aug B2	Apr B3	Apr B3
Aug B3	Aug B3	Aug B1	Aug B1
C	C	Aug B2	Aug B2
		Aug B3	Aug B3
		C	C

Frequency:

B1-	Annual burn
B2-	Biennial burn
B3-	Triennial burn
B4-	Quadrennial burn
B6-	Sexennial burn
C-	No burn/ Control

Season:

Oct-	Spring
Dec-	Early summer
Feb-	Late summer
Apr-	Autumn
Aug-	Mid-winter

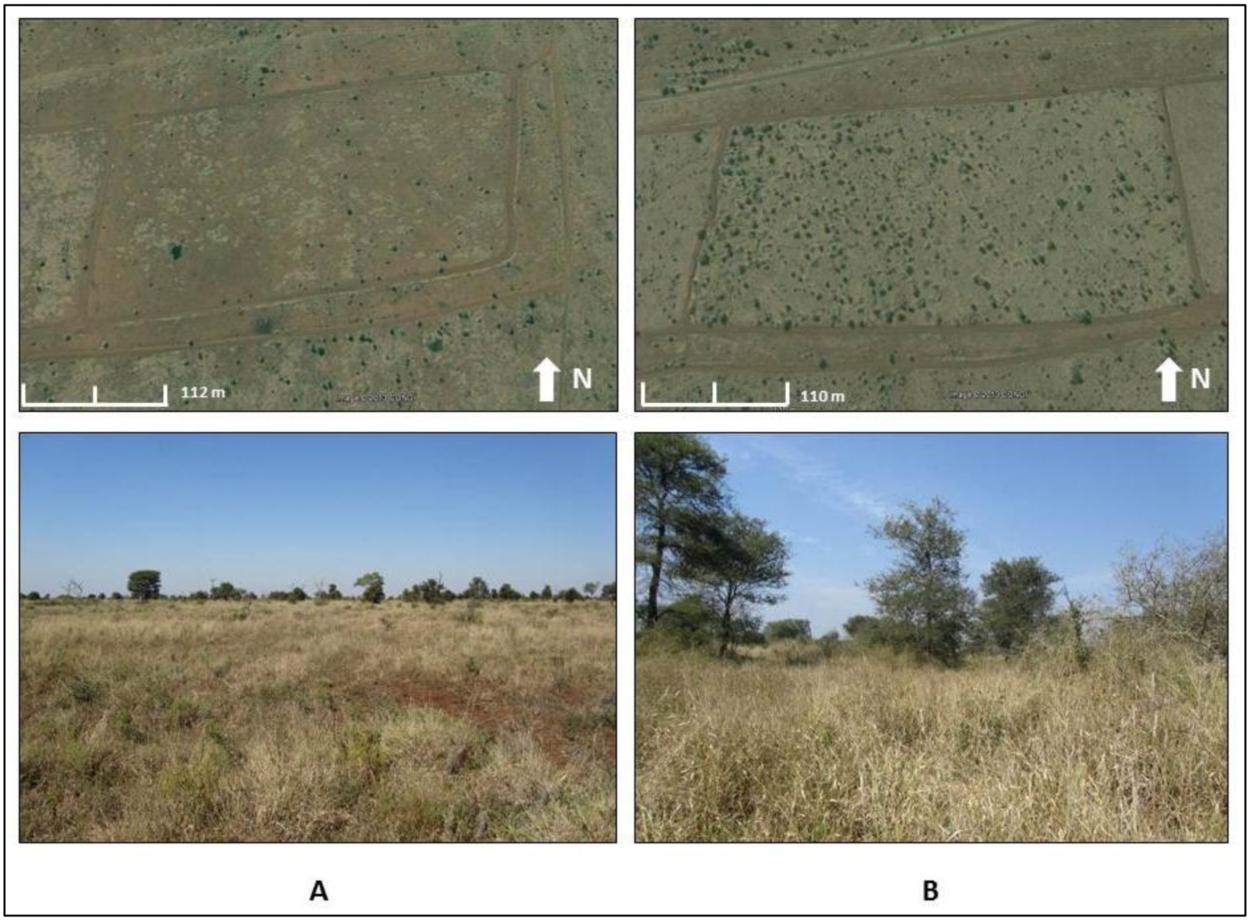


Figure 2.2 Illustrations of how the two extreme burn plots, i.e. annual burn (A) and no burn (B) vary with regards to vegetation density and structure (basaltic N'wanetsi EBPs). Pictures above provide an aerial view whereas the bottom photographs were taken on the plots

2.2.2 EBP soils

Since these EBPs are spread across large areas, soil variation and heterogeneity within the plots and the effects thereof is questioned. The EBPs, especially on the granites, were replicated on the crests (Biggs *et al.*, 2003) in an attempt to reduce the uncertainty regarding soil variation. Venter and Govender (2012) conducted a study in which EBP soils were assessed for similarity between plots, strings and the surrounding environment. A combination of both aerial photography and field surveys were used in order to map the burn plots based on the soil and corresponding vegetation patterns on each plot. They developed a scoring system for identifying similarity or representativeness. This scoring system was based the geomorphic and soil characteristics on each burn plot in relation to the surrounding environment. The following is based on their study:

Scoring for how representative each plot and string is to its surroundings:

1- Not representative at all
2- Slightly representative
3- Moderately representative
4- Well representative
5- Totally representative

Pretoriuskop (sandy granitic soils):
Numbi - 5
Kambeni* (Figure 2.3) - 5
Shabeni - 5
Fayi - 4

Satara (clayey basaltic soils):
Marheya - 4
Satara - 5
N’wanetsi* (Figure 2.4) - 5
Lindanda - 3

** The experimental burn plot strings where this particular study will be focused.*

Experimental burn plot strings were chosen on soils belonging to the two dominant geologies in KNP, i.e. granites and basalts. Besides a geological gradient, EBP strings were selected in order to account for the variable rainfall gradient across the park. On the granites, in the Pretoriuskop section of KNP with a mean annual precipitation of roughly 705 mm, Kambeni was selected as the focus site due to the similarity in soils. On the basalts, in the Satara section of the park which receives a mean annual precipitation of roughly 507 mm, N'wanetsi was chosen, also based on the similarity of the soils. A summary of the different fire treatments on the Kambeni and N'wanetsi EBPs are presented in Appendix A: Table 8.1. Table 8.2 in Appendix: B provides the burning compliance for the prescribed fires on Kambeni and N'wanetsi EBPs.

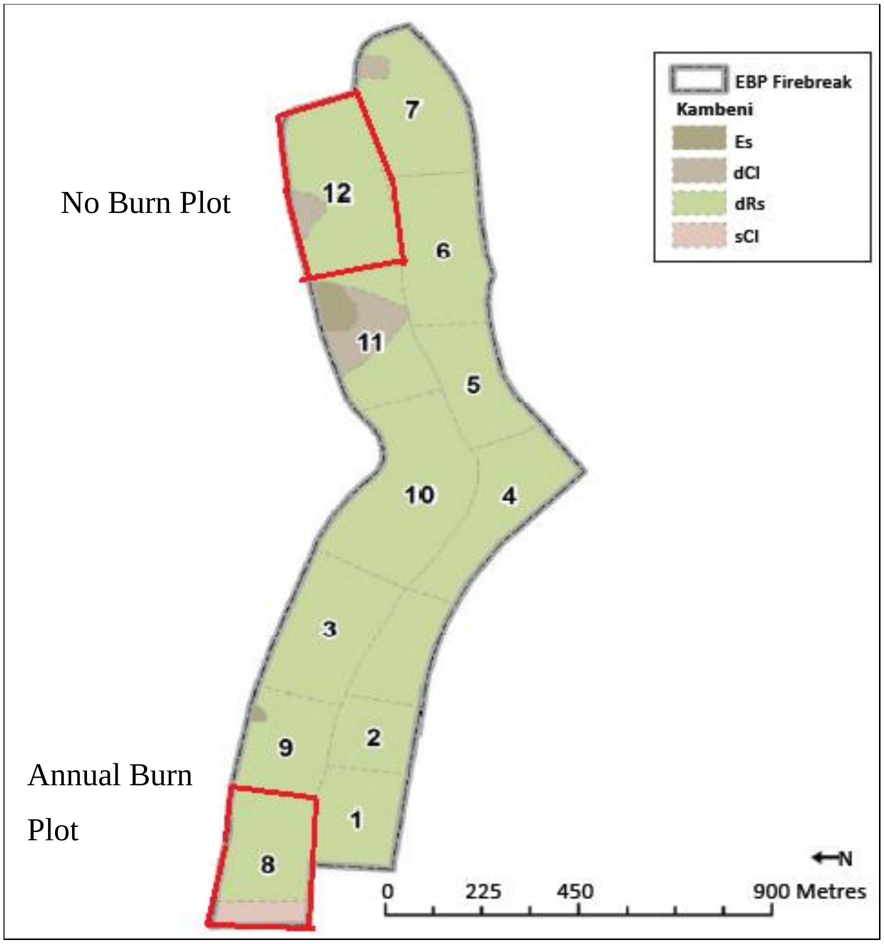


Figure 2.3 The variation in soil types across the Kambeni burn plots (Es- Estcourt, dCl- deep Clovelly, dRs- deep Red Sand, sCl- shallow Clovelly), (after Venter and Govender, 2012)

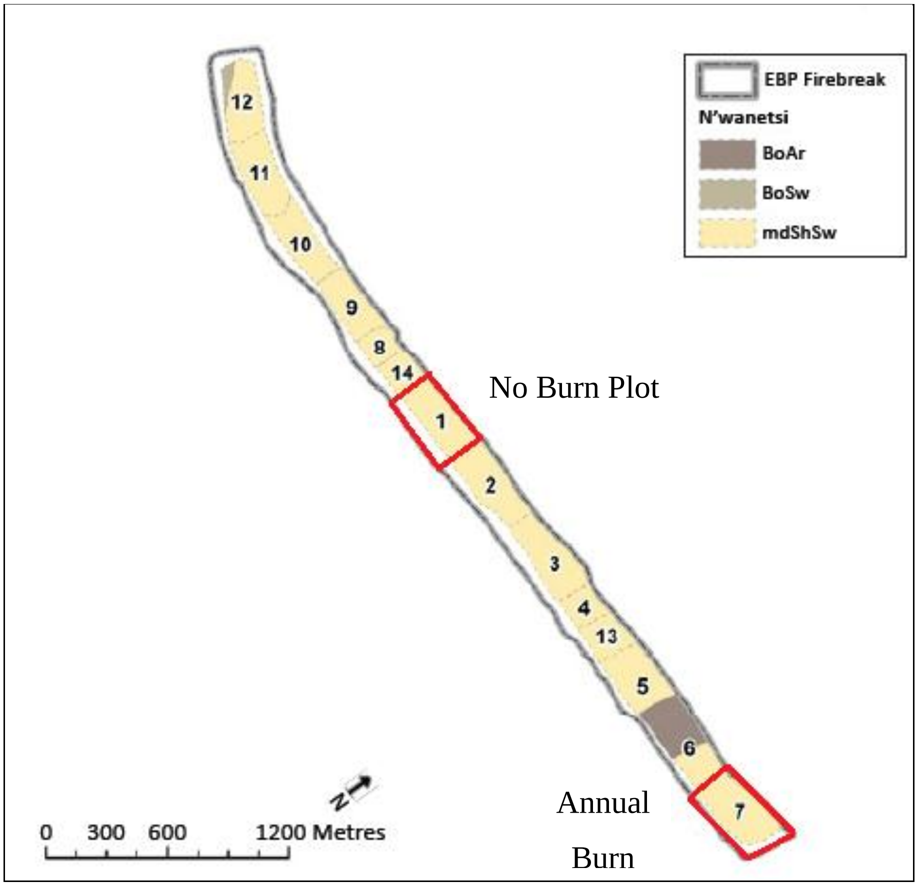


Figure 2.4 The variation in soil types across the N'wanetsi burn plots (BoAr- Bonheim Arcadia, BoSw- Bonheim Swartland, mdShSw-moderately deep Shortlands Swartland), (after Venter and Govender, 2012)

3. METHODOLOGY

In order to address the objectives of determining the effect of long-term fire treatments on soil hydraulic properties in savanna systems, the following chapter details the methodology applied during this study. The period used for data collection extended from October 2012 to May 2013. The sampling design applied in each EBP string is described below.

3.1 EBP Sampling Design

In the sandy, granitic region of Pretoriuskop, data was collected on the Kambeni EBPs between October and November 2012 while on the N'wanetsi EBPs, in the clayey basaltic region of Satara, data was collected during April and May 2013. Data collection was focused on the annual burn plot (burned once a year every August), no burn plot (fire exclusion for more than 50 years) as well as on a plot outside of the EBP string that receives a VFR, so as to account for the effect of a more "natural" fire frequency (roughly 4.5 years) on soil properties. The VFR plot is subjected to fire started by man (rangers who implement prescribed fires and other indiscriminate sources such as tourists, poachers and people walking through the park). Prescribed fires are lit when the area has not burned within a couple of years and fuel load is too high, thereby posing a fire risk. These VFR plots were selected adjacent to the annual burn plots in order to ensure similar landscape positions and representative soils. The plot for the VFR surrounding the Kambeni EBPs was burned in a high intensity fire nearly three months before the site was sampled. Figure 3.1 and Figure 3.2 illustrates all the burn plots on the Kambeni and N'wanetsi strings, respectively, with the annual treatment demarcated in green, the no burn treatment demarcated in red and the VFR site outside of EBPs demarcated with a red "X".

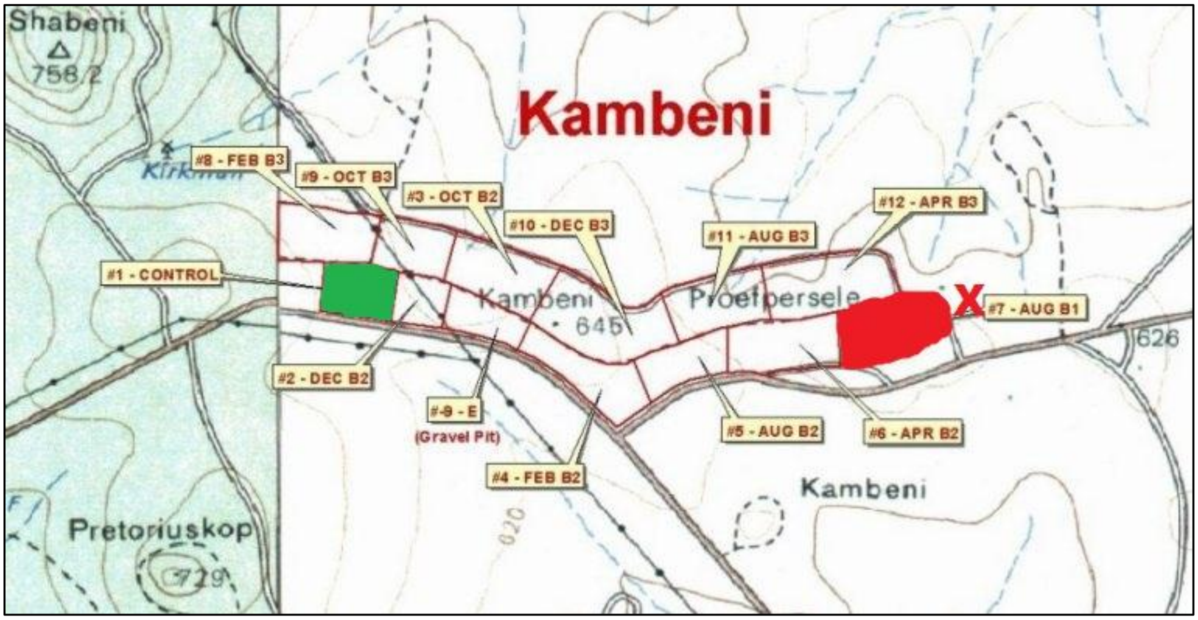


Figure 3.1 The Kambeni EBPs which are subjected to different fire frequencies and seasons (SANParks™ Intranet, 2005)

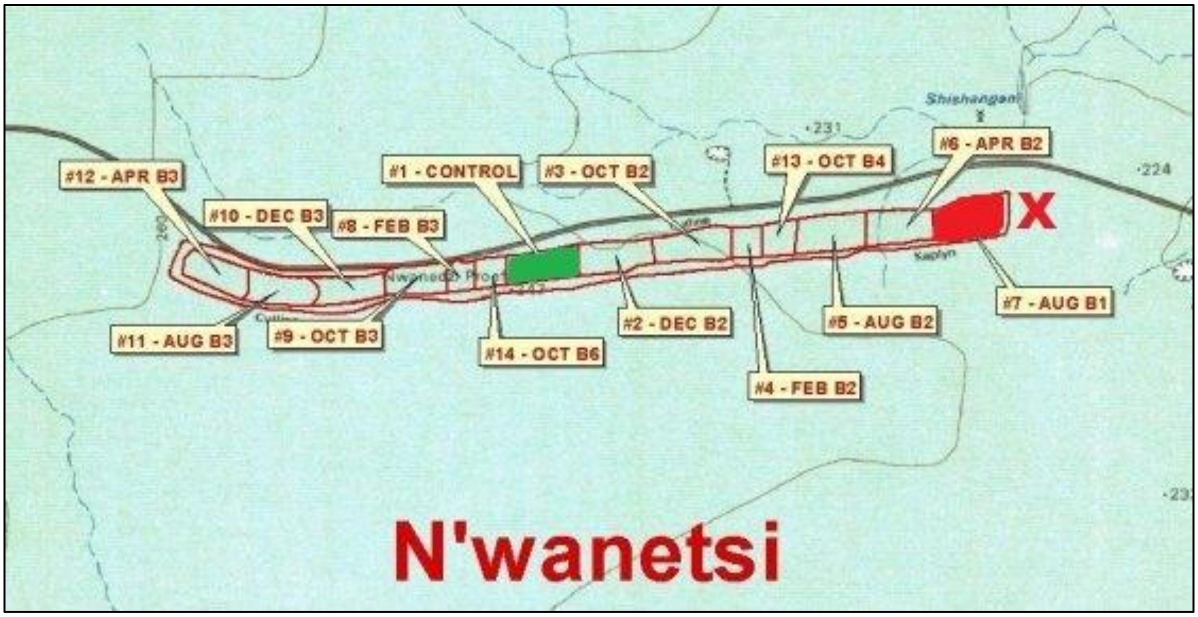


Figure 3.2 The N’wanetsi EBPs which are subjected to various fire frequencies and seasons (SANParks™ Intranet, 2005)

The sampling design used at both Kambeni and N'wanetsi had a stratified-random design (refer to Figure 3.3). Sampling was strictly confined to an area within the burn plot, buffered 20 m away from the edge of the plot in order to account for an identified edge effect resulting from fire-break maintenance (Smit and Asner, 2012). On both the annual and no burn plots, random transects ran diagonally across the plots in order to cover as much of the plot as possible to account for the natural heterogeneity within the plots itself and of savanna systems. Along the transect, 15 random sample points were used to gather soil hydrological data and collect soil samples. Properties such as soil compaction and vegetative data were collected within a 3 m radius in order to establish the effect of the immediate surrounding area on the soil hydrological data.

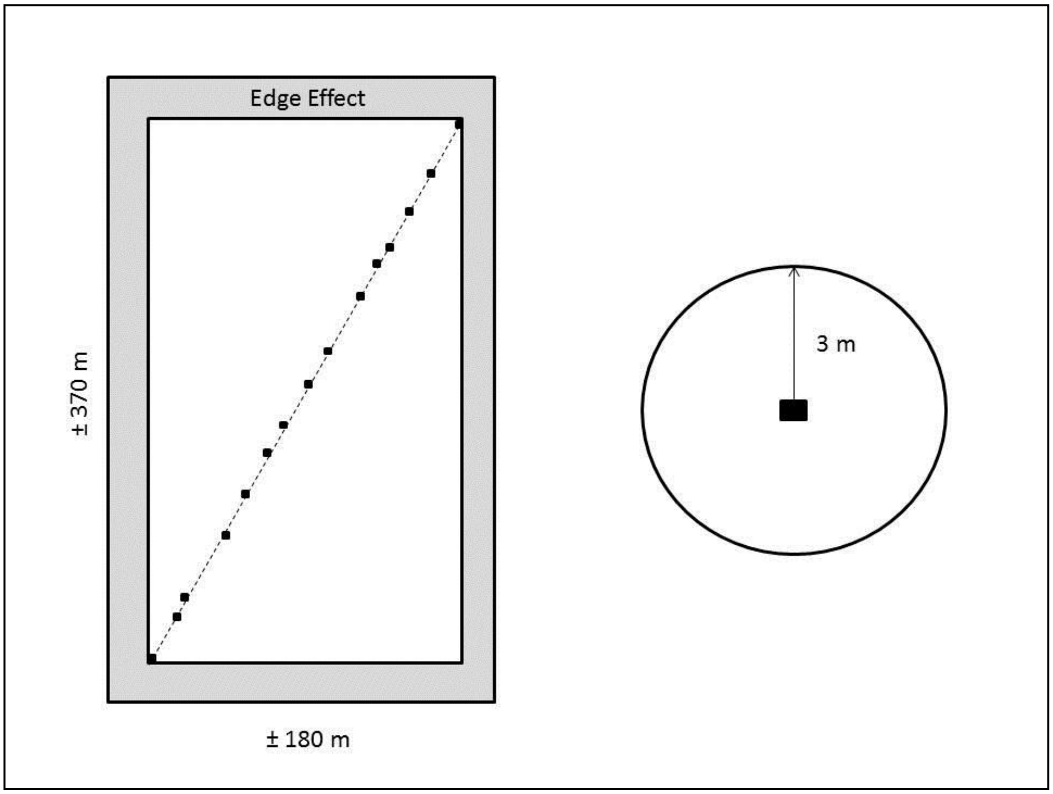


Figure 3.3 A schematic diagram illustrating the layout of the sampling design used on the annual burn, no burn and VFR plots at Kambeni and N'wanetsi

3.2 Methodological Approach

Unless otherwise stated, the following methods were conducted on both Kambeni and N'wanetsi EBPs on the annual burn plot (burns every August), no burn plot (fires actively-suppressed for more than 50 years) as well as on the VFR plot outside of the EBP string (with a mean fire return period of 4.5 years).

3.2.1 Unsaturated hydraulic conductivity (K_{unsat})

At each sample point, unsaturated hydraulic conductivity (K_{unsat}) was measured in order to establish whether the different fire treatments had any effect on the infiltration rate at the soil surface. K_{unsat} was measured at the soil surface using an instrument known as a tension disc infiltrometer (Figure 3.4). Infiltration was measured under two tensions, i.e. 5 mm and 30 mm. Water maintained under tension (suction) infiltrates into the soil and the steady-state infiltration rates are read manually. These infiltration rates are then used to calculate the hydraulic conductivity of unsaturated soil by plotting the steady-state infiltration rates and using the slope of the graph to determine the volumetric hydraulic conductivity. This volume is then converted into a one-dimensional flux based on the method of Ankeny *et al*. (1991) described in the equation:

$$A = \frac{Q_{t\,0.5} - Q_{t\,3}}{Q_{t\,0.5} + Q_{t\,3}} \times \frac{2}{t\,3 - t\,0.5} \tag{3.1}$$

where

A = parameter required in the follow-up equation (3.2) [cm^{-1}],

Q = steady state infiltration rate [$cm^{3}.min^{-1}$],

$t\,0.5$ = tension of 0.5 [cm], and

$t\,3$ = tension of 3 [cm].

Hence, the final hydraulic conductivity is calculated as:

$$K = \frac{AQ_{t\,3}}{(A\pi r^2) + 4r} \tag{3.2}$$

where

K = hydraulic conductivity [cm.min^{-1}], and

r = infiltration radius [cm].

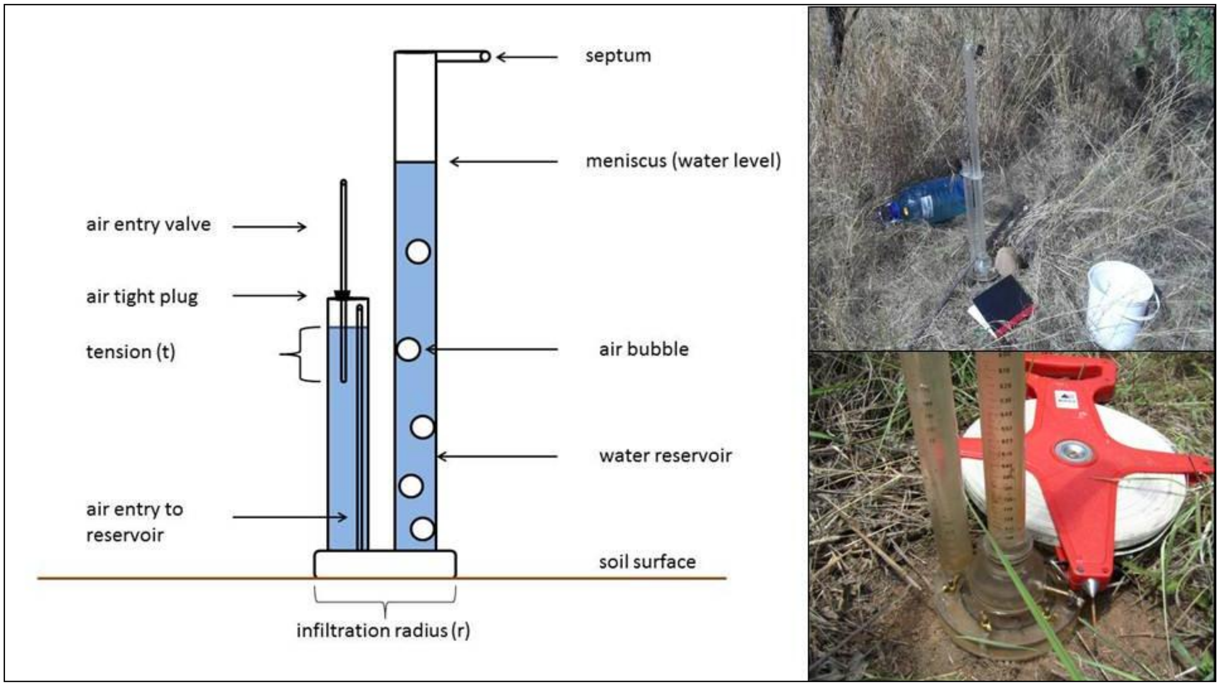


Figure 3.4 The various components of a tension disc infiltrometer and how it is used in the field

By using the capillary rise equation by Bear (1972), it was possible to determine the maximum pore size which would transmit water under a certain tension:

$$r = \frac{2y\ cos\ (\vartheta)}{pgh} \sim \frac{0.15}{h} \tag{3.3}$$

where

r = maximum pore size [cm],

y = surface tension of water [m.t^{-2}],

ϑ = contact angle between water and pore wall (assumed to be 0),

ρ = density of water [m.l^{-3}],

g = gravitational force [l.t^{-2}], and

h = tension head [cm].

3.2.2 Saturated hydraulic conductivity (K_{sat})

Aimed at determining the effect of various fire treatments on hydraulic conductivity within the soil matrix, saturated hydraulic conductivity (K_{sat}) was determined using a Guelph permeameter (Figure 3.5). At each sample point, this instrument was applied in two small holes which were augered at depths of 2-3 cm and 5-7 cm. These sampling depths were selected because literature suggested that fire effects are only prominent within the first few centimetres (pedoderm) of the soil surface (DeBano and Krammes, 1966; Certini, 2005; Mataix-Solera *et al*., 2011). The Guelph permeameter operates by allowing water to flow from the permeameter into the augered hole and to enter the soil. Eventually, the outflow from the permeameter reaches a steady-state once a saturated 'bulb' is formed in the soil (refer to Figure 3.6) (Eijkelkamp Agrisearch Equipment, 2008). Field saturated conductivity (K_{fs}) is measured using the rate of constant outflow, the diameter of the augered hole and the height of the water in the well, explained in the following equations:

$$C^1 = \left(\frac{\frac{h}{r}}{2.074 + 0.093\ \frac{h}{r}} \right)^{0.754} \tag{3.4}$$

where

C^1 = parameter required in the follow-up equation (3.5),

h = height of water in augered hole [cm],

r = radius of augered hole [cm],

Hence, K_{sat} is calculated as:

$$K_{fs} = \frac{C^1 \, Q}{2\pi h^2 + \pi r^2 C^1 + 2\pi \, \frac{h}{\alpha}}$$

(3.5)

where

K_{fs} = one dimensional field saturated hydraulic conductivity [cm.s^{-1}],

Q = three dimensional infiltration rate [cm^3.s^{-1}], and

α = soil texture, based on Elrick *et al.* (1989).

Based on suggestions by Elrick *et al.* (1989) (refer to Table 8.3 in Appendix C), different alpha (α) values were used for the granites (Kambeni) and basalts (N'wanetsi) due to differences in soil textures. Kambeni required an α value of 0.12 (most structured soils with medium and fine sands) and N'wanetsi required an α value of 0.04 (unstructured, fine textured soils).

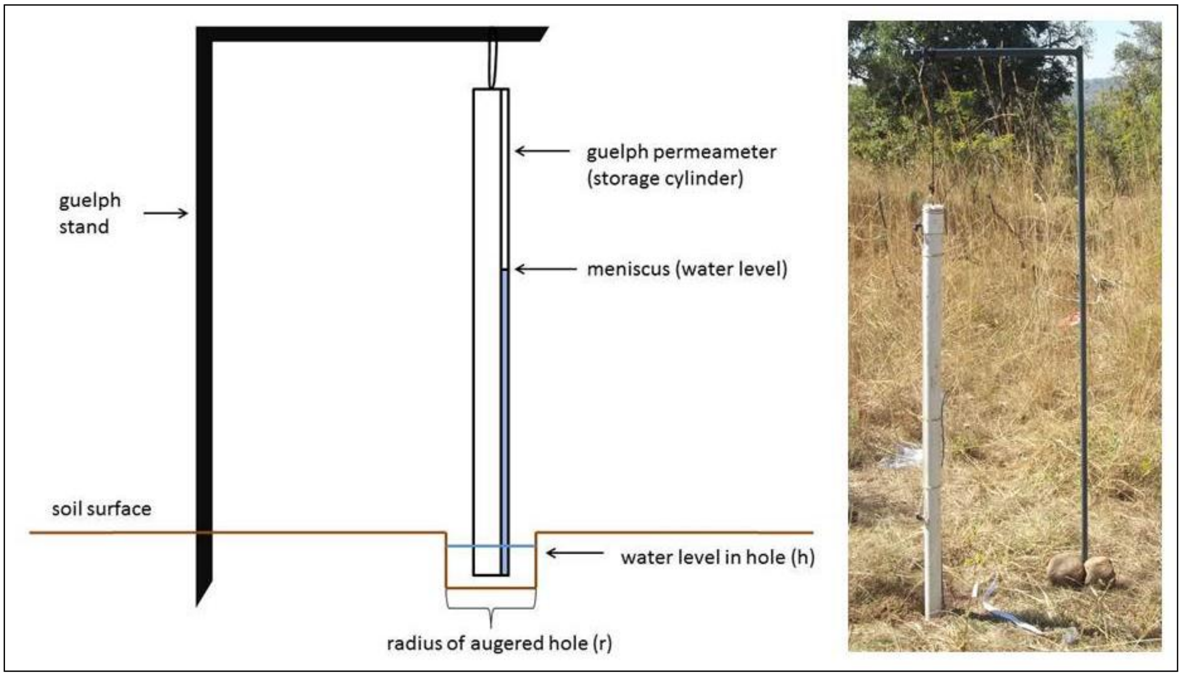


Figure 3.5 An illustration of a Guelph permeameter setup in the field

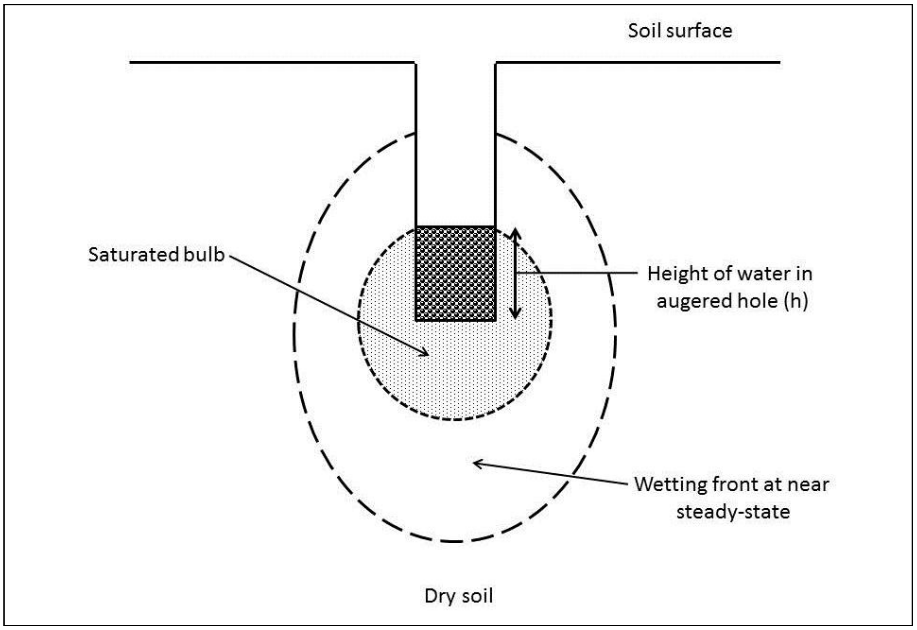


Figure 3.6 An illustration of the saturated bulb which forms at steady-state (after Rodgers & Mulqueen, 2006)

3.2.3 Soil compaction

At each sample point, soil compaction was determined by means of a drop cone penetrometer (Figure 3.7). A 2 kg weight is dropped from a known height and the resulting energy used to penetrate the soil surface is measured using the equation:

$$E = mgh \tag{3.6}$$

where

E = energy [j],
m = mass of penetrometer weight [kg],
g = gravitational constant [$\mathrm{m.s^{-1}}$], and
h = height at which weight is dropped [m].

Soil compaction was measured within a 3 m radius around the point at which the hydraulic tests were performed. A total of ten random measurements were taken and after each strike (release of weight from known height), the depth at which the penetrometer penetrated the soil was measured. At each point, a total of ten strikes were conducted resulting in a total cumulative energy of 307 joules. Therefore, a total of 10 strikes were measured at each of the 10 random points along each of the 15 transect points across the plot. The resistance of the soil to penetration (compaction) is a function of the soil water content, soil type and bulk density. At each EBP site, soil compaction was measured across the different fire treatments at a similar time of year (within the same month) in order to ensure similar water contents. As mentioned before, soils were classed in advance to ensure representativeness and comparability between burn plots (see Venter and Govender, 2012).

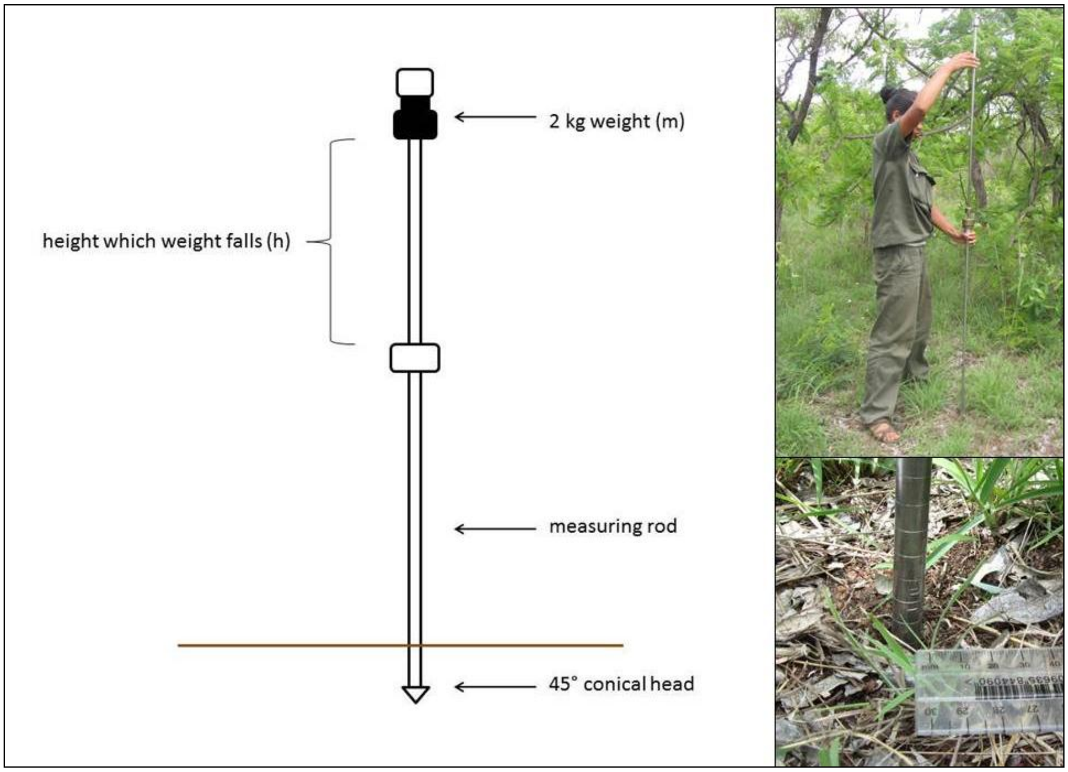


Figure 3.7 The different components of a penetrometer and how it is applied during measurement

Whilst it is acknowledged that herbivores are an important and integral part of the savanna system, it was recognized that herbivory would act as a confounding factor whereby the influence of “fire” versus the influence of “fire and herbivory” would have been difficult to distinguish. Therefore the herbivore exclosures erected on the N’wanetsi EBPs (basalts) in 2005 (Knapp *et al*., 2006) were used in order to exclude the impact of herbivores and identify the influence of fire *only,* on soil compaction.

The herbivore exclosures were constructed with dimensions of 2 m in height and 7 m in diameter with a diamond-shaped mesh (5 cm diameter). These exclosures were constructed in order to exclude all animals ranging from small herbivores such as steenbok to large herbivores such as buffalo and elephant. The herbivore exclosures used were constructed on the annual and no burn plots, only. The distinction between soil surface compaction and deeper subsurface compaction is illustrated through the use of these herbivore exclosures. Soil compaction was determined by measuring penetration resistance of the soil both inside and outside the exclosures on the annual burn plot. In addition, compaction was determined by comparing soil resistance to penetration within the exclosures across the annual and no burn plot; thereby determining the effect of annual fires vs. fire suppression without the additional impact of herbivores. When differences were identified within the top few centimetres (pedoderm) of the soil, it was regarded as surface compaction (sealing). When differences in penetrometer depth were measured in the deeper layers of the soil (> 3 cm), the subsurface soil would be regarded as compacted.

3.2.4 Soil organic matter

Besides playing a major role in soil fertility, soil organic matter influences the way in which water is transported and stored within the soil matrix. Since fire consumes biomass and organic matter, soil samples were collected at each sample point across the different burn plots to determine the effect of contrasting fire frequencies on soil organic matter. A total of 45 soil samples (collected at each of the 15 transect points across the three contrasting fire regimes) were oven-dried at 105 °C for 24 hours and ground, and then sieved using a 2 mm soil sieve. The percentage of total carbon in these soil samples were analysed by Cedara College of Agriculture using a LECO machine (TruMac Series) (refer to Figure 3.8).

Figure 3.8 The Leco TruMac Series used to measure percentage total carbon to infer soil organic matter content (LECO Corporation Website)

3.2.5 Soil water potential

Understanding how water is retained in the soil is critical since it aids post-fire re-establishment of vegetation. Initially, soil water retention capacities were supposed to be measured using the controlled outflow cell method (Lorentz *et al*., 2003) but due to time constraints and other logistical impediments, water potential of the soils were measured using a WP4-t dewpoint potentiameter. The WP4-t measures the combined effect of matric and osmotic potential of the soil sample. These potentials are dependent on the amount of dissolved material in the soil and provide an indication of the adsorptive forces binding water molecules to the soil. The dewpoint potentiameter uses a chilled-mirror technique in order to determine water potential. A soil sample is inserted into the sample chamber and the water potential of the sample is equilibrated with the air within the chamber. The chamber is equipped with a mirror which is monitored for condensation. A thermoelectric cooler controls the temperature of the mirror and photoelectric cell then measures the exact point at which condensation occurs on the mirror surface (WP-4 Dewpoint Potentiameter: Operator's Manual V5, Decagon Devices, Inc. 1998-2007).

At the site where hydraulic tests were run, an undisturbed soil sample was collected using a stainless steel or PVC ring of known volume (i.e. d = 4 cm and h = 5 cm) at a depth of 0 to 5 cm. The soil samples were then taken to a soil laboratory and oven-dried at 70 °C for 48 hours (Wilson *et al*., 2009). The top-most layer of soil was removed and transferred to a special WP4-t plastic cup used for water potential determination. Measured amounts of deionised water (between 0.1-0.2 g) were added in daily increments in order to calculate the gravimetric water contents at which the water potential (matric and osmotic potentials) was measured using the WP4-t (refer to Figure 3.9). These readings would continue until the soil sample was fully saturated (≥ 0 MPa). Unfortunately, the soil structure may have been compromised due to difficulty collecting a small enough, undisturbed subsample to use for water potential measurements. Therefore, it is acknowledged that these results might only have a qualitative interpretation. However the instrument manufacturer, Decagon Devices, assessed the effect of sample disturbance on soil water potential (Decagon Devices, 2011). The study recognized that soil disturbance and changes in bulk density primarily affects the sizes of the large pores, therefore soil disturbance may influence the water content-water potential relationship of the large pore range only. However, these disturbances will have a negligible effect on the water potential of samples in the tightly absorbed and adsorbed ranges; these are the exact ranges in which this study is interested in. These findings coincided with previous studies by Box and Taylor (1962), and Campbell and Gardner (1971).

Figure 3.9 Photograph of a WP4-t dewpoint potentiameter used to measure water potential

3.2.6 Vegetation characteristics

Since this study acknowledges the impact of the immediate surrounding environment on the soil hydrology, certain vegetation characteristics are investigated within a 3 m radius around each sample point. These characteristics were quantified because vegetation influences soil organic matter content, which in turn influences the water-holding capacity of the soil. These independent variables were collected and tested against the hydrological data (dependent variables) to identify any distinct relationships (Section 3.3: Statistical Analyses). The vegetation methods performed are as follows:

i. Grass biomass

Grass biomass was measured by means of a disc-pasture meter (DPM) which has been calibrated for use within the KNP (Trollope and Potgieter, 1986; Zambatis *et al*., 2006). Random biomass readings were repeated ten times within the 3 m radius. Grass biomass was calculated using the equations formulated for use within KNP by Zambatis *et al*. (2006).

If the average DPM height ≤ 26 cm then Equation 3.7 is used and if average height ≥ 26 cm then Equation 3.8 is used:

$$kg.ha^{-1} = \left[31.7176\left(0.3218^{1/x}\right)x^{0.2834}\right]^2 \tag{3.7}$$

$$kg.ha^{-1} = [17.3543\ (0.9893^{x})\ x^{0.5413}]^2 \tag{3.8}$$

where

x = mean DPM height [cm]

ii. Basal cover

At the point where the hydraulic tests were performed, the basal cover was measured as prescribed by Trollope *et al.* (2004). This measurement serves as an indication of the area of bare soil exposed. Ten nearest-distance-to-tuft measurements were collected randomly around the hydraulic test sampling points as well. A formula developed by Hardy and Tainton (1993) was used to calculate basal cover (%) using the nearest-distance-to-tuft measurements:

$$Basal\ Cover\ (\%) = 19.8 + 0.39(\bar{D}) - 11.87(\log_e \bar{D}) + 0.64\left(\bar{d}\right) + 2.93(\log_e \bar{d}) \tag{3.9}$$

where

$\bar{D}$= mean distance from a point to nearest grass tuft [cm], and

$\bar{d}$= mean tuft diameter [cm].

3.3 Statistical Analyses

Statistical analyses are important means of interpreting complex datasets and understanding trends. The data collected during this study was analysed using Statistica v12 (Statsoft, Inc.). The statistical analyses were divided into basic descriptive statistics and more advanced statistical tests. Initially, fundamental statistical tests were performed on the data for comparative analysis to identify differences in the data across the various fire regimes. Frequency distributions were plotted for the K_{unsat}, K_{sat}, penetrometer (soil compaction), soil water potential (water retention capacity), total carbon (organic matter) and DPM (biomass) data obtained on the Kambeni and N'wanetsi EBPs and assessed for normal distributions (refer to figures in Appendix D). If data did not have normal distributions, significant differences in the mean was analysed using a non-parametric Kruskal-Wallis test. If significant differences were found, a post-hoc multiple comparisons test was applied to identify between which fire regimes these differences would lie. However if data distributions were normal, a parametric one-way ANOVA was used to identify significant differences in the variances. When significant differences were found, data were further analysed in order to identify where those differences were by using a post-hoc Tukey Honest Significant Difference (HSD) test. Penetrometer (soil compaction) data collected within and outside the herbivore exclosures on N'wanetsi EBPs were checked for normality and if distributions were not normal, means were analysed using a non-parametric Mann-Whitney U test. If distributions were normal, then a T-test would be used to check for significant differences in soil compaction. For all statistical tests, significant differences were determined by using a confidence interval of 95% ($P < 0.05$).

Since savannas are such dynamic and heterogeneous systems, it is difficult to understand only one process without considering a number of other possible influencing variables. Therefore, this hydrological study took into account the likely influence of ecological factors as well. Subsequently, more sophisticated tests were conducted in order to detect relationships amongst measured variables. A PCA was used to determine how ecological variables (independent data, i.e. grass biomass, basal cover- nearest distance to grass tuft) may influence hydrological processes (dependent data, i.e. K_{unsat}, K_{sat}, etc.). The PCA is a tool which can be used to reduce multidimensional and complex datasets to only a few variables which will still explain most of the information in that dataset. The PCA was applied across the three fire regimes in both the Kambeni and N'wanetsi EBPs. This allowed the identification of which variables were the most influential on how fire affected soil properties on the different geologies with a specific fire regime.

4. RESULTS

4.1 Kambeni EBPs (Granites)

The Kambeni EBPs are situated in the higher rainfall, granitic area of Pretoriuskop (refer to Figure 2.1). These soils are dominated by the Clovelly soil type and deep red sands (Figure 2.3). Data was collected on Kambeni EBPs during the wet season in October - November 2012 (refer to Appendix E: Table 8.4) and was concentrated not only on the annual burn and no burn plots but outside and adjacent to the EBPs too (refer to Figure 3.1). The area outside of the EBPs is referred to as the VFR plot where the landscape is not manipulated by the EBP experiment. It has a more variable fire return period of roughly 4.5 years. Approximately three months before data collection, the VFR area surrounding the burn plots was burnt by a hot fire. A full summary of all the statistical analyses is provided in Appendix F: Tables 8.6 and 8.7.

4.1.1 Unsaturated hydraulic conductivity (K_{unsat})

K_{unsat} data across the fire treatment extremes (annual vs. no burn) and under the variable fire frequency were measured using 5 mm and 30 mm tensions on Kambeni EBPs (Figures 4.1 and 4.2). Under both tensions on the no burn (fire exclusion) plot, the average K_{unsat} was found to be higher than that of the annual burn plot while the VFR plot had the lowest K_{unsat}.

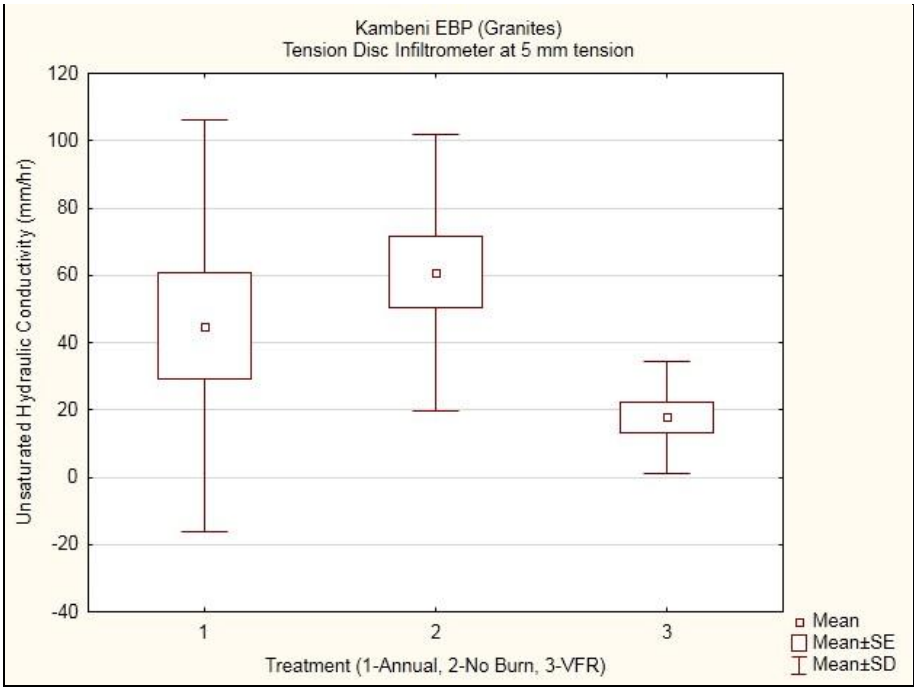


Figure 4.1 Box-whisker plots illustrating the average K_{unsat} (mm/hr) at 5 mm tension across the three different fire treatments on Kambeni EBPs

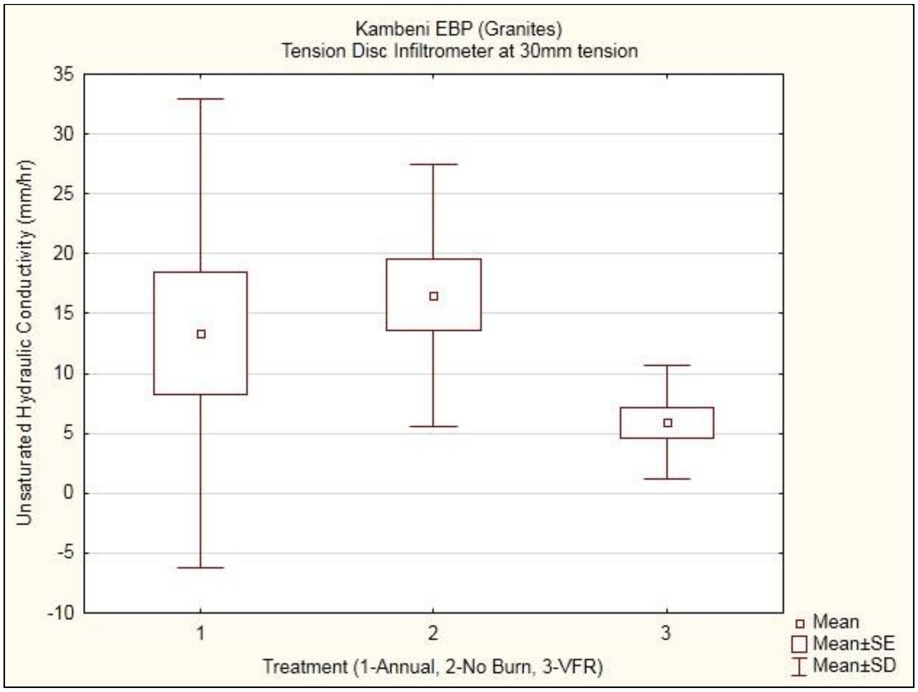


Figure 4.2 Box-whisker plots illustrating the mean K_{unsat} (mm/hr) at 30 mm tension across the three fire treatments

Under both tensions, statistical analyses found these results to be significantly different. A Kruskal-Wallis test under a tension of 5 mm resulted in a significance level of P = 0.005 (H = 10.830) while under 30 mm tension P = 0.01 (H = 9.183). A post-hoc pairwise multiple comparisons test was performed in order to identify across which fire frequencies these significant differences were.

For 5 mm tension, the multiple comparisons test found that the significance actually lies between the VFR and no burn plots (P = 0.003) (Table 4.1). A similar trend was observed under 30 mm tension where a significant difference in K_{unsat} was found between the VFR and no burn plot (P = 0.007) (Table 4.1). It was hypothesised that the plot with the most frequent fires, i.e. annual burn plot, would result in the slowest infiltration rates. However, these results do not confirm this as the VFR plot with a mean fire return period of 4.5 years has significantly slower infiltration rates. This is most probably due to the VFR plot burning roughly three months before the site was sampled. The amount of time after a fire is likely to play a significant role in how soils respond to hydrological processes such as infiltration, in the short term. Therefore, it is speculated that it is not necessarily fire frequencies affecting soil infiltration rates but rather the time following a fire.

Interestingly in Figures 4.1 and 4.2, the variation (i.e. standard deviation) observed in the data is greatest on the annual burn plot which may be explained in the way or patterns in which fire burns in savanna systems. Generally on the annual fire treatment, fires are cooler and tend to burn more heterogeneously resulting in a patchy fire mosaic. This is due to less biomass available to burn and reduced fuel continuity after only one season's growth (Govender *et al*., 2006). The least amount of variation in the data is observed on the VFR plot which was exposed to a high intensity fire just three months prior to sampling and it is believed to have resulted in soil being burned in a more homogenous manner.

Table 4.1 The significance values (p-values) for the Kruskal-Wallis pairwise multiple comparisons test on the K_{unsat} data collected at Kambeni EBPs

Under 5 mm tension			
	Annual	No Burn	VFR
Annual		0.249	0.339
No Burn	0.249		**0.003**
VFR	0.339	**0.003**	
Under 30 mm tension			
Annual		0.272	0.498
No Burn	0.272		**0.007**
VFR	0.498	**0.007**	

Using Equation 3.3, it was calculated that K_{unsat} is much slower under a tension of 30 mm than 5 mm (Table 4.2) because all pores with a radius smaller than 3 mm will be able to transmit water under a tension of 5 mm whereas under a tension of 30 mm, only pores with a radius smaller than 0.5 mm will be able to conduct water.

Table 4.2 The maximum pore size able to transmit water under tensions of 5 mm and 30 mm

Tension	5 mm	30 mm
Maximum Pore Size (mm)	3	0.5

4.1.2 Saturated hydraulic conductivity (K_{sat})

Across the three different fire regimes at Kambeni, K_{sat} were measured at two different soil depths i.e. 2-3 cm and 5-7 cm, Figures 4.3 and 4.4 respectively. At both soil depths, results indicated that the slowest K_{sat} was on the VFR plot, similarly observed in the K_{unsat} measurements. However, the Kruskal-Wallis test revealed that there was no significant difference in K_{sat} at both depths. The Kruskal-Wallis test for data collected at 2-3 cm depth indicated a significance level of P = 0.47 (H = 1.512) while at a depth of 5-7 cm, P = 0.633 (H = 0.914).

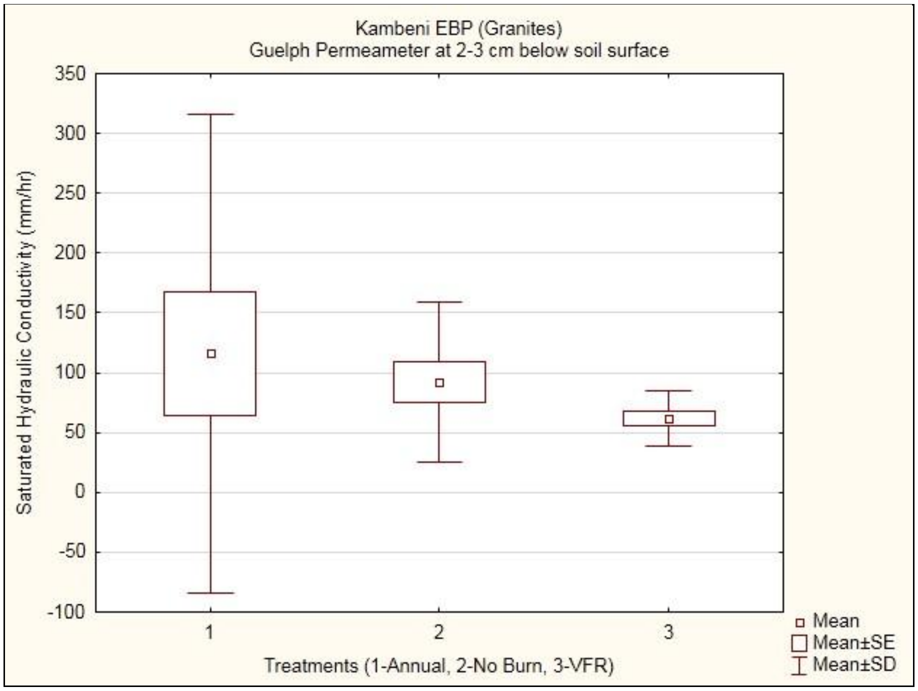


Figure 4.3 K_{sat} (mm/hr) at 2-3 cm below soil surface across contrasting fire treatments on Kambeni EBP

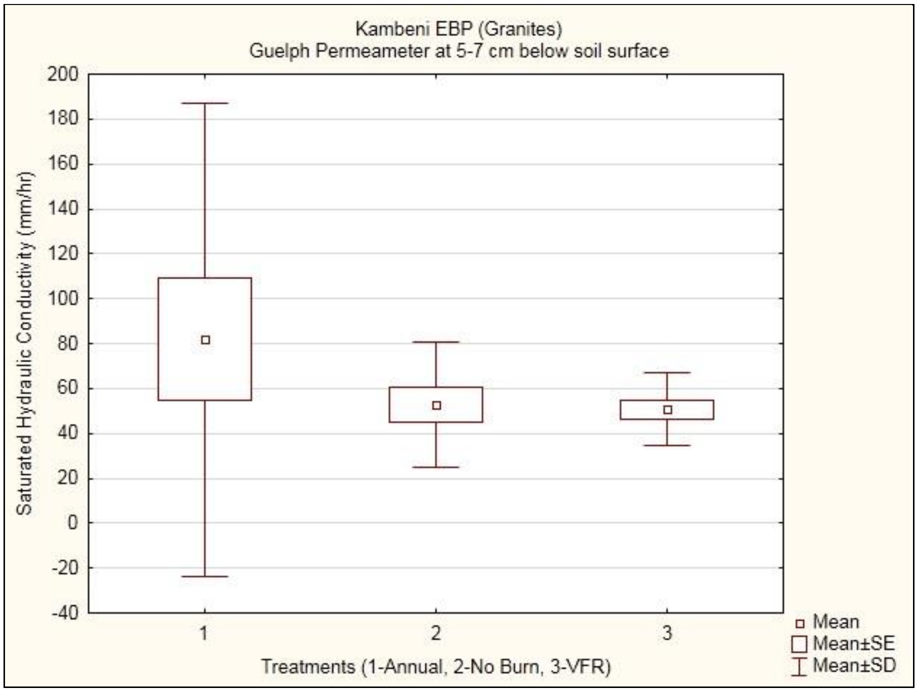


Figure 4.4 Mean K_{sat} (mm/hr) at 5-7 cm below soil surface across the various fire treatments on Kambeni EBP

Based on the hydraulic conductivity data collected at the soil surface and at the two shallow depths below the soil surface, it appears as though it is only the unsaturated conductivities at the soil surface which is significantly affected by fire. This is likely since fires in savanna systems travel so rapidly across the soil, that there is not enough time to allow substantial transfer of heat between the fire and soil. However, this may only be applicable for situations where there is low aboveground fuel and where fires are less intense.

Akin to the K_{unsat} measurements, the different fire regimes affected the variability in the data differently. The annual burn plot has the greatest variability which is possibly linked to the variability in fire intensities as the savanna fires burn heterogeneously across the soil and resulting in some areas being burned more intensely than others.

4.1.3 Soil compaction

Soil compaction was measured across the three fire frequencies at Kambeni EBP. The data illustrated in Figure 4.5 suggests that the first few centimetres of soil on the annual burn plot, is more compacted than the VFR and no burn plots. These tests analysed the first three penetrometer strikes to account for the pedoderm (< 4 cm) to identify shallow surface compaction, and the final tenth strike to account for deeper layers of the A-horizon to distinguish whether the subsurface soil is also compacted (± 10 cm). The Kruskal-Wallis test determined the differences in the mean penetration depth of the initial three strikes, which are roughly at a depth of 2-6 cm and the final strike at a depth of ± 10 cm. All strikes were found to be significantly different between the fire treatments, i.e. 1st strike P-value = 0.000, 2nd strike P-value = 0.000, 3rd strike P-value = 0.000 and the 10th strike P-value = 0.000 (refer to Table 4.3).

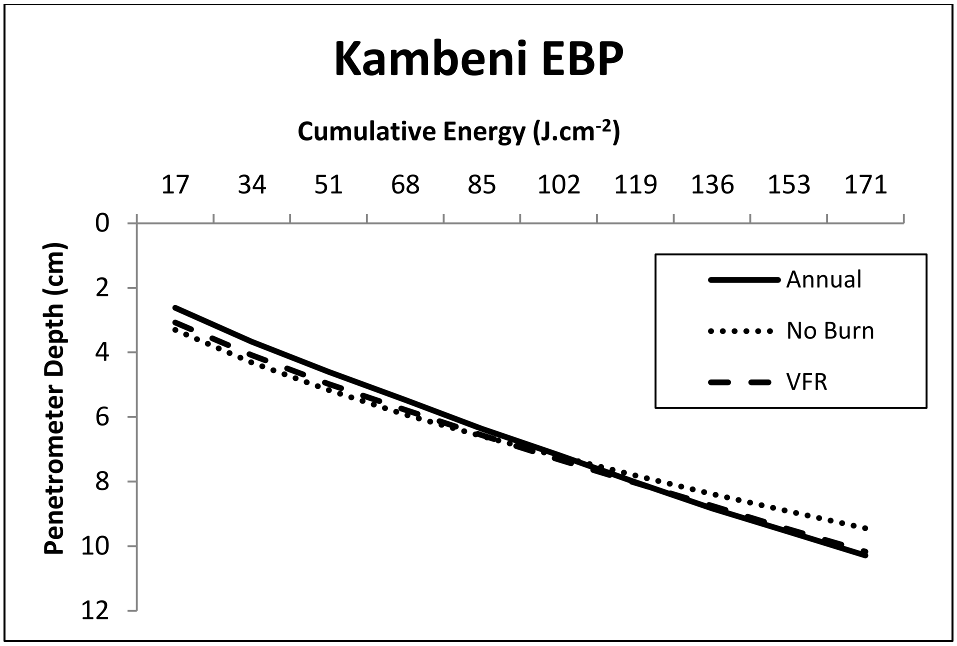


Figure 4.5 Soil compaction measured using a drop-cone penetrometer

Since significant differences were found, data were further analysed in order to identify where those differences lay by using a post-hoc multiple comparisons test (Table 4.3). Based on the initial three strikes, the post-hoc analysis indicated that the shallow soil surface layer is more compacted on the annual burn plot than compared to the other fire frequencies. This finding coincides with studies by Snyman (2002, 2003) which were conducted in semi-arid grasslands in South Africa, whereby it was also found that fire resulted in compacted soils. Fire burns and removes vegetation, reduces cover and increases soil surface exposure to natural elements such as direct rain, wind and heat. The bare soil is then vulnerable to mechanical processes such as raindrop impact and splash which result in soil compaction (DeBano, 2000). However, it is difficult to conclude whether these differences in soil compaction are due to different fire regimes or due to varying herbivore densities across the plots. After a fire, the annual burn plot has a higher density of herbivores due to the improvement in grazing quality as well as the added advantage of better visibility for herbivores spotting predators (Owen-Smith, 1982). Due to herbivore exclosures erected on the N'wanetsi EBPs by a previous project (Knapp *et al.*, 2006), there was an opportunity to tease out the effects of fire and fire/ herbivores on soil compaction (refer to Section 4.2.3).

Table 4.3 Kruskal-Wallis and multiple comparisons results for the soil compaction data collected at Kambeni EBPs

Kruskal-Wallis (KW) results and post-hoc multiple comparisons test (p-values)			
	Annual	No Burn	VFR
1St Penetrometer Strike (KW: H (2) = 49.855; P= 0.000)			
Annual		**0.000**	**0.000**
No Burn	**0.000**		0.1
VFR	**0.000**	0.1	
2nd Penetrometer Strike (KW: H (2) = 37.705; P= 0.000)			
Annual		**0.000**	**0.001**
No Burn	**0.000**		0.061
VFR	**0.001**	0.061	
3rd Penetrometer Strike (KW: H (2) = 24.407; P= 0.000)			
Annual		**0.000**	**0.009**
No Burn	**0.000**		0.190
VFR	**0.009**	0.190	
10th Penetrometer Strike (KW: H (2) = 19.77; P= 0.000)			
Annual		**0.000**	1
No Burn	**0.000**		**0.002**
VFR	1	**0.002**	

Based on the deeper tenth strike, post-hoc analysis indicated that compaction is significantly more on the no burn plot than the burned plots. This result is the inverse of the soil surface compaction, i.e. the no burn plot was not as compacted as the burned plots. It is believed that the deeper soil layer on the no burn plot is not necessarily more compacted but rather, more structured. The deeper structured soil may be due to higher organic matter (compared to the burned plots) acting as a cementing agent binding soil aggregates (DeBano, 1990). Snyman (2002) noted that decreased soil organic matter content leads to poorly-structured soils.

4.1.4 Soil organic matter

Soil organic matter not only drives soil fertility but also affects how water moves through the soil matrix due to its hydrophilic properties. The organic matter, i.e. total carbon was measured in soil samples collected across the various fire frequencies. As hypothesized, the soils on the annual burn plot had the lowest total carbon (Table 4.4). The results of the Kruskal-Wallis test suggested that these differences in organic matter across the different fire frequencies were not statistically significant (H (2) = 1.260, P = 0.533). It is plausible that fires on these burn plots in the Pretoriuskop region of the park do not significantly alter the soil organic content because these fires are fast-moving surface fires and do not have the time required to penetrate deep into the soil. Certini (2005) established that at sites with high biomass, intense but fast-moving fires do not allow for deep heat penetration into the soil. Fast-moving fires are typical phenomena in the semi-arid savannas of KNP, thus not allowing enough contact time with the soil surface to facilitate the transfer of heat into the soil.

Table 4.4 The percentage of total carbon (organic matter) measured in the soils sampled across the different fire frequencies at Kambeni EBPs

	Annual	No Burn	VFR
Total Carbon (%)	1.023	1.365	1.262

4.1.5 Soil water potential

The water potentials measured from the soil surfaces collected across the three contrasting fire frequencies provide a qualitative interpretation of how fire may influence the water retention (or water-holding) capacities of the soils. At similar water contents, the no burn plot has the lowest water potential (Figure 4.6). This is particularly true for water contents ranging 3-12 %. Statistically, it was found that mean water potentials at low water contents did not differ significantly between different frequencies (H (2) = 0.902; P= 0.637). Using statistical analyses to test the significance of the results is believed to be too sensitive since these water potential ranges are marginal and fire variability across the plots are high. Indeed there will be overlap of water potential measurements, however these qualitative results still alludes to useful interpretations.

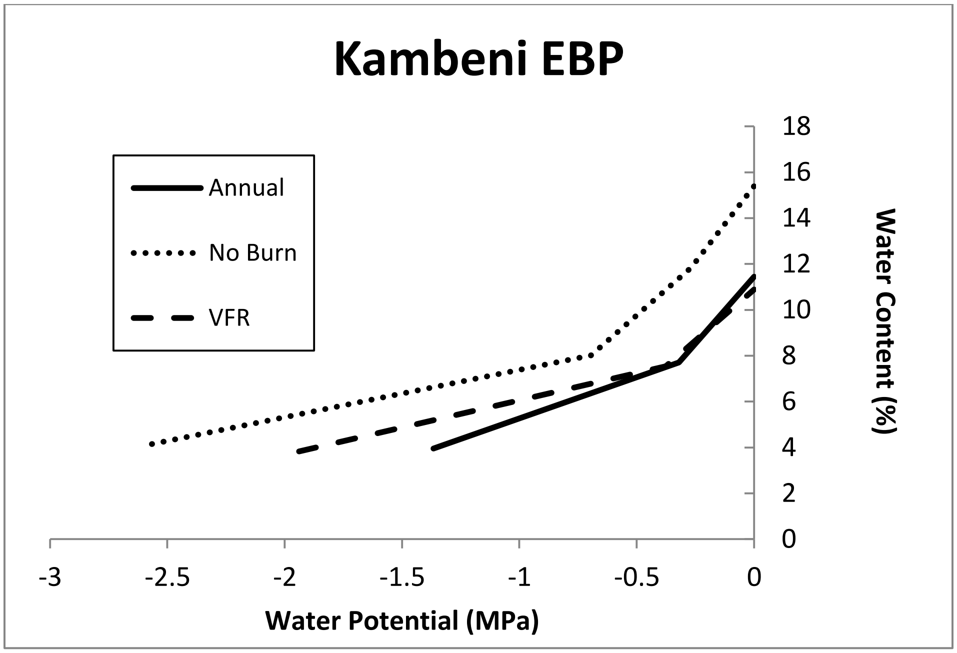


Figure 4.6 A graph providing a qualitative illustration of the water potentials across the different burn plots on Kambeni string

Although not statistically significant, these results suggest that on the no burn plot, water is held more tightly in the soil matrix and is less able to move freely. It is likely that this linked to higher biomass (Table 4.5) and bioactivity on this plot due to decades of fire exclusion. Laboratory observations found that some of the samples collected from the soil surface of the VFR were hydrophobic. This would explain and contribute to the slowest infiltration rates measured on this VFR plot which burned roughly three months prior to sampling (see Section 4.1.1).

4.1.6 Vegetation characteristics

i. Grass biomass

Grass biomass was compared across the three fire regimes on Kambeni EBP using a DPM (Table 4.5). As expected, the fire-suppressed no burn plot had the highest biomass (2199 $kg.ha^{-1}$). A Kruskal-Wallis test found biomass to be significantly different across all the plots (H (2) = 157.162, P = 0.000) (Figure 4.7). Thereafter, a post-hoc pairwise multiple comparisons test identified that the grass biomass differed between all three fire frequencies (Table 4.6). It is likely that the greater grass biomass observed on the no burn plot is linked to the low water potential of the soil measured on the no burn plot due to the presence of hydrophilic organic matter which accumulated after > 50 years of fire suppression. Interestingly, the VFR plot which had burned more recently than the annual burn plot had a higher fuel load than the annual plot.

Table 4.5 The grass biomass measured across the varying fire frequencies at Kambeni EBPs

	Annual	No Burn	VFR
Grass Biomass ($kg.ha^{-1}$)	984	2199	1193

Table 4.6 Post-hoc results for the grass biomass data collected at Kambeni EBPs

Post-hoc multiple comparisons test (p-values) (KW: H (2) = 157.162; P= 0.000)			
	Annual	No Burn	VFR
Annual		**0.000**	**0.006**
No Burn	**0.000**		**0.000**
VFR	**0.006**	**0.000**	

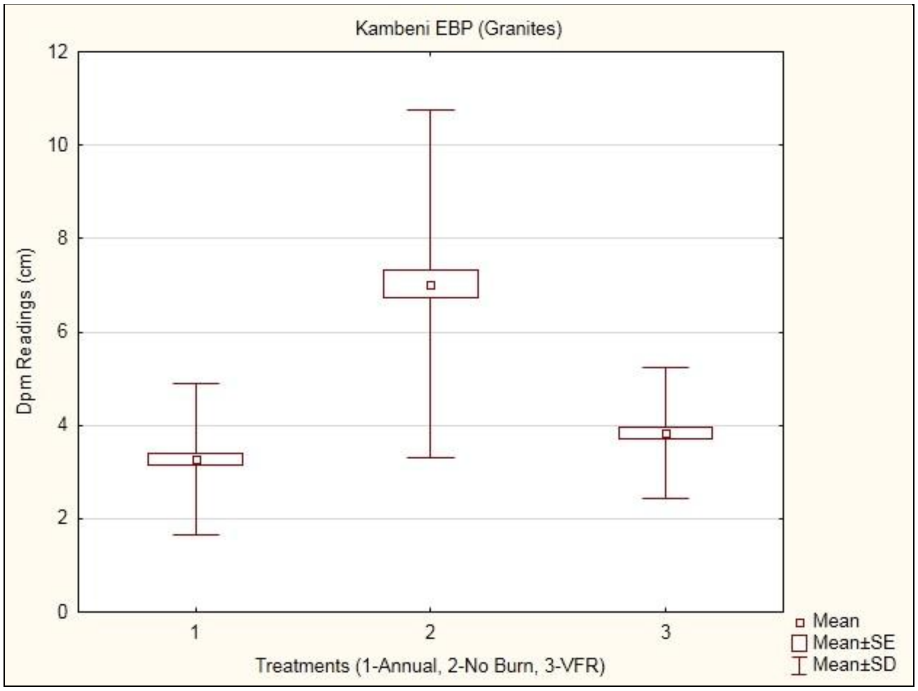


Figure 4.7 A boxplot illustrating the different means in DPM readings across the different plots

ii. Basal cover

Unlike initially predicted, the no burn plot had the lowest percentage basal cover (Figure 4.8). Lower basal cover calculated for the no burn plot on Kambeni implies that the area of bare soil exposed is greatest on this plot, which is untrue. Based on field observation, this pattern would be the opposite of what was calculated, i.e. there is a higher percentage basal cover on the no burn plot. Since the fate of raindrops are influenced by vegetation, an increased amount of bare soil results in a larger area for raindrops to land and infiltrate whilst also, providing a larger evaporative surface area whereby water can be lost to the atmosphere.

Two possible reasons for this confusing finding are provided. Firstly, this is due to the fact that fire exclusion for > 50 years has disturbed the co-existence between trees and grasses, favouring trees rather than grasses on these plots. Some studies conducted in semi-arid savannas found that grasses benefit from fires because trees are greatly impacted and grasses can recover and re-establish more quickly due to less competition with trees and simpler life-history strategies (Higgins *et al*., 2000; Smit *et al*., 2010). Thus, since fire has been suppressed for many decades, it is possible that grasses may not be able to compete with trees for resources. The second possible explanation is that the formula provided by Hardy and Tainton (1993) (Equation 3.9) to calculate basal cover may not be applicable to this particular environment. Hardy and Tainton (1993) developed their formula based on a study conducted in the grasslands of South Africa whereas the Kambeni EBPs are a fire-manipulated area situated in a lower rainfall region dominated by woody vegetation such as *Dichrostachys cinerea* and *Terminalia sericea*. Thus, the proportions of trees and grasses would differ between the two biomes.

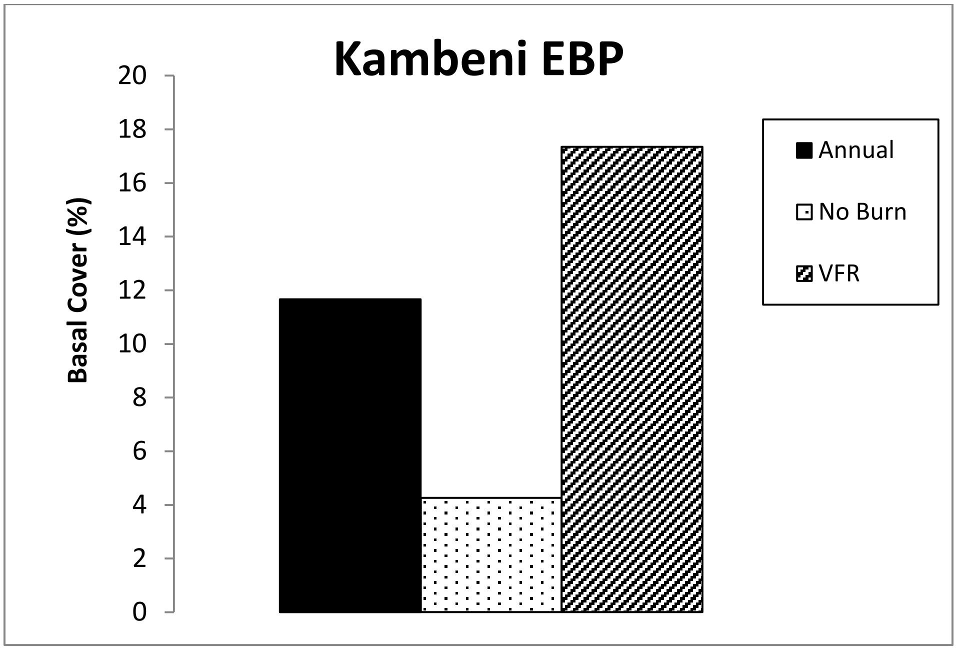


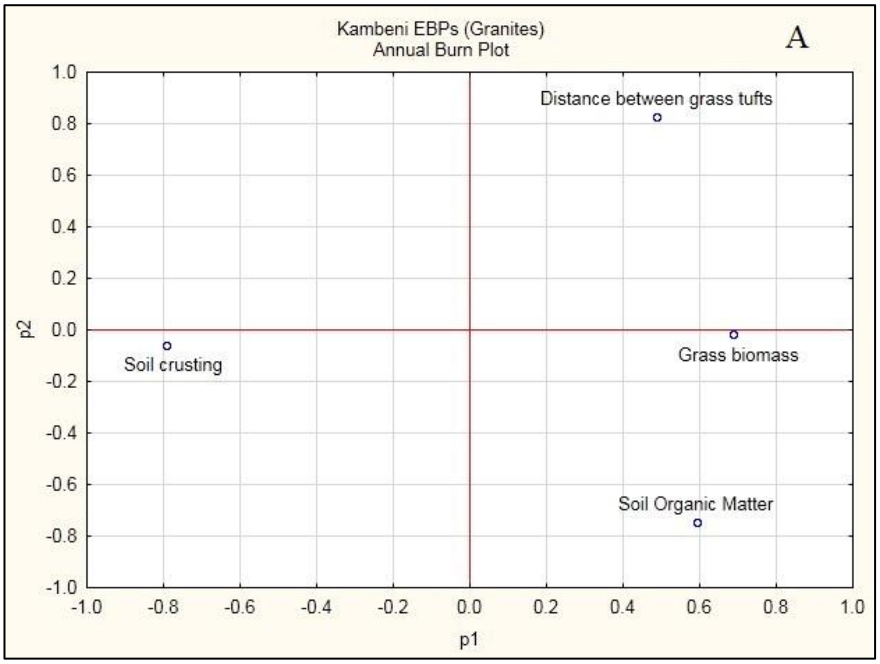
Figure 4.8 Bar graph illustrating the difference in basal cover across the different fire regimes

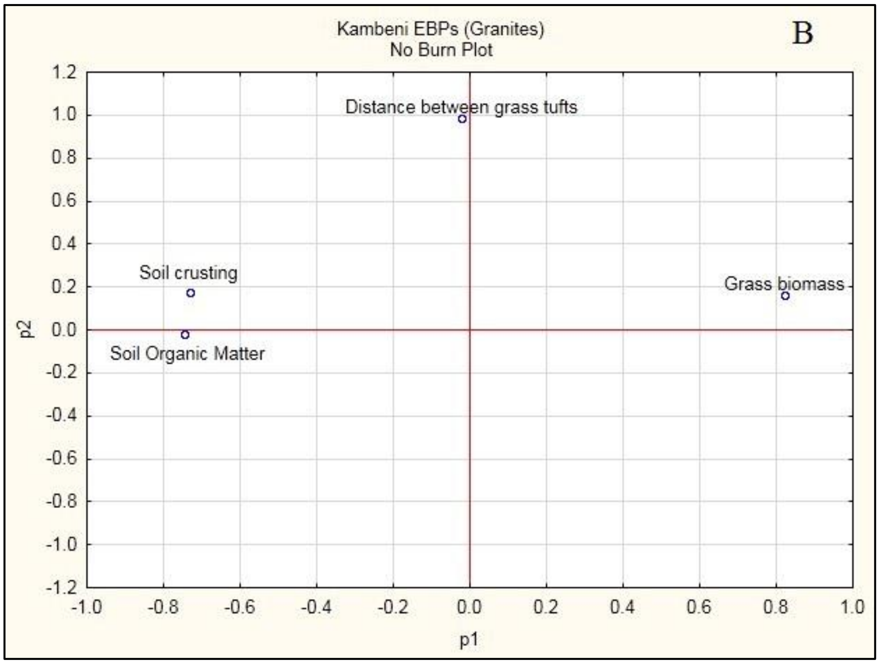
4.1.7 Principle components analysis (PCA)

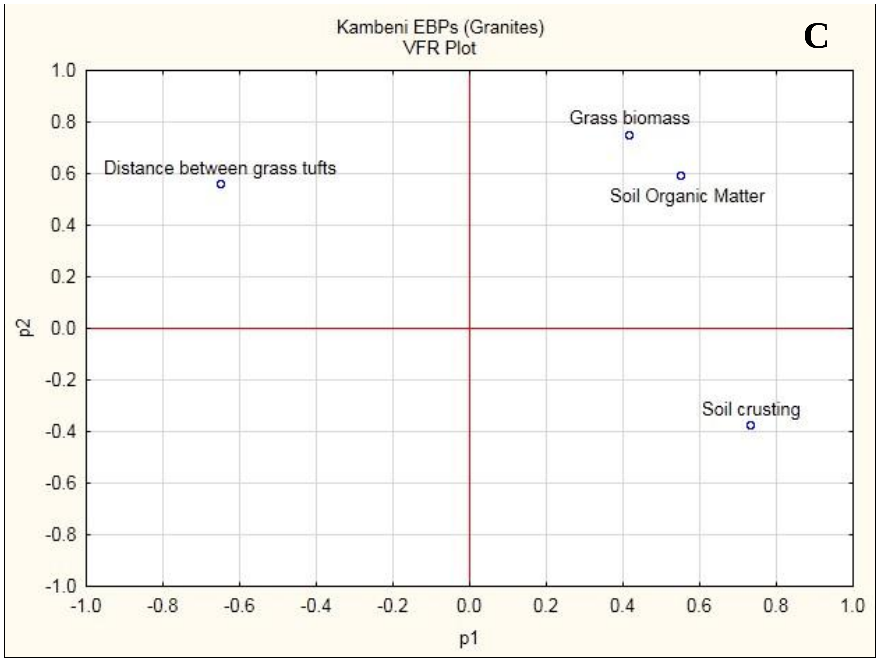
The PCA results for Kambeni EBPs are displayed in Figure 4.9. The PCA was used to reduce and model the complex dataset in order to determine which variables were the most influential on how fire affected soil infiltration properties under different fire regimes. In Figure 4.9, P1 and P2 represents the two “principles” on which the model was formulated, based on the trends in the data. The first principle, P1, is the primary principle which explains majority of the information stemming from the data while P2 represents the second principle. Influential variables are determined by first assessing the P1 axis, examining which variable scores the highest on a scale from 0.0 - 1.0. Thereafter, the same is determined for P2.

On the annual burn plot (Figure 4.9.A), the two principle components used explains up to 73 % of the variability (trends) in the dataset. Although grass biomass and soil organic matter plays a greater role on P1, it has a negative influence on P2. However, distance between grass tufts (basal cover) is influential on both principles. Therefore, most of the information or trends observed by the data can be explained by the distance between grass tufts. This implies that in a sandy, coarse-grained area with frequent (annual) fires, the distance between grass tufts is the most influential variable on soil infiltration. The distance between grass tufts is related to the amount of bare soil exposed to the elements (rainfall, sun and wind) and influences the area of the soil surface opened to allow raindrops to land and infiltrate. Furthermore, this alludes to the extent of bare soil vulnerable to evaporation from the soil surface due to direct sun exposure. In Figure 4.9.B, grass biomass plays an important role in the variability of the dataset on the no burn plot. Furthermore, the two principle components account for a total of 60 % of the variability. Thus in a coarse-grained environment where fire is suppressed, grass biomass is the most important driver influencing how water infiltrates through the soil surface since above-ground biomass affects the degree of bare soil exposed to raindrop infiltration as well as offer protection from soil evaporation. On the VFR plot, Figure 4.9.C, the majority of the information is explained by soil organic matter and grass biomass. These two principle components account for a total variation of 70 %. Therefore, in a sandy, coarse-grained area with a variable fire return interval of roughly 4.5 years, soil organic matter and grass biomass are most influential variables driving soil infiltration. The influence of soil organic matter on water infiltration may be twofold. Firstly, organic matter contains significant amounts of fine material which could constrain infiltration at low water contents and secondly, soil organic matter aids soil aggregation which supports infiltration by creating preferential pathways.

Figure 4.9 PCA loading plots derived from data collected for each plot on Kambeni EBPs.
(A- Annual; B- No Burn; C- VFR)






Kambeni EBPs (Granites)
VFR Plot
C
Grass biomass
Distance between grass tufts
Soil Organic Matter
Soil crusting
p2
p1
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

4.2 N’wanetsi EBPs (Basalts)

N’wanetsi EBPs are situated on the basalts in the central region of KNP, near Satara (refer to Figure 2.1). The dominant soil types on these burn plots are Shortlands and Swartland (refer to Figure 2.4). Data was collected on N’wanetsi towards the end of the wet season in May 2013 (refer to Appendix F: Table 8.5). Similar to Kambeni, the study included an area outside of the EBP string that accounted for the effect of a more “variable” fire frequency (VFR) on soil properties. Therefore, data collections were concentrated on the annual burn and no burn plots as well as outside of the experimental burn plots (refer to Figure 3.2). A summary of all the statistical analyses used is provided in Appendix F: Tables 8.8 and 8.9.

4.2.1 Unsaturated hydraulic conductivity (K_{unsat})

K_{unsat} data across the fire treatment extremes (annual vs. no burn) and under the VFR were measured under 5 mm and 30 mm tensions on N’wanetsi EBPs. Under both tensions, i.e. 5 mm (Figure 4.10) and 30 mm (Figure 4.11), data suggests a similar K_{unsat} across the three fire treatments. Data suggests that there is no significant difference in K_{unsat}, under 5 mm suction, across the three fire regimes (H (2) = 1.463, P = 0.481). Similarly under 30 mm suction, there is no significant difference in K_{unsat} across the different fire regimes (H (2) = 2.468, P = 0.291).

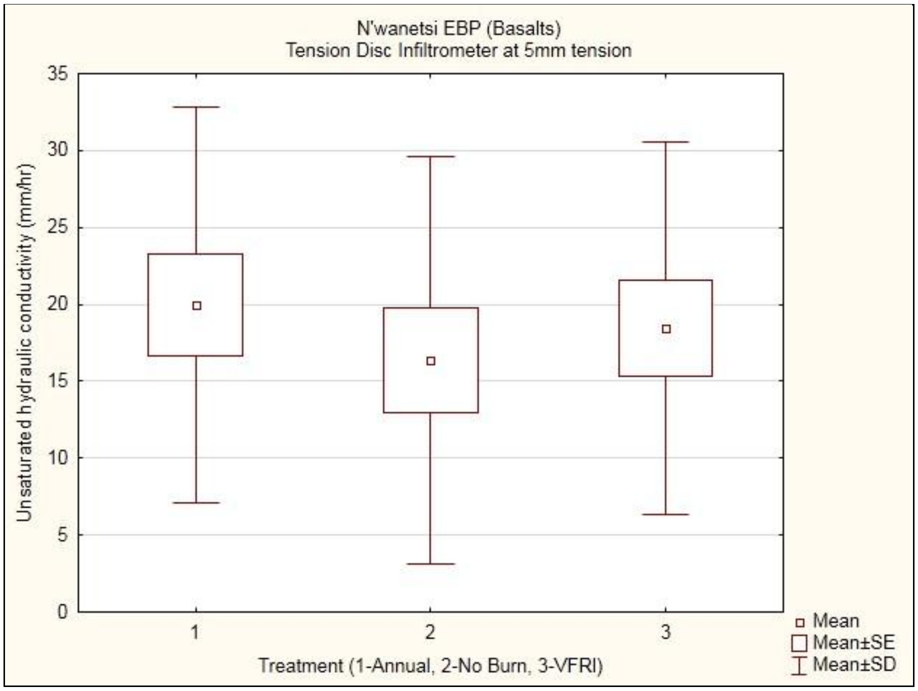


Figure 4.10 Box-whisker plots illustrating the K_{unsat} (mm/hr) measured under different fire treatments at N'wanetsi burn plots under a tension of 5 mm

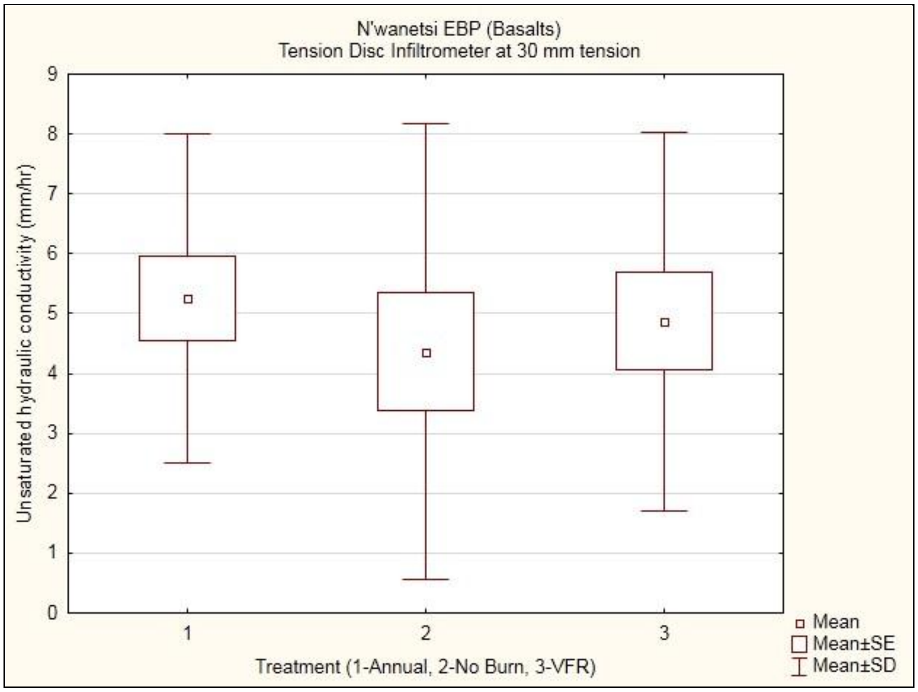


Figure 4.11 Box-whisker plots illustrating the mean K_{unsat} (mm/hr) measured at N'wanetsi burn plots under a suction head of 30 mm

Results indicated that there was no significant difference in K_{unsat} across the three different fire regimes. For the last couple of years (± seven years), this annual plot has not been fully burned due to insufficient fuel loads which would not support the prescribed fires. However, when the plot did burn, it only burned in a very patchy manner (N. Govender *pers. comm.*). The low biomass measurements as well as the low basal cover, measured on the annual burn plot, would lead to such fire behaviour.

Even though the VFR plot outside the EBPs burned more recently than the annual burn plot, both had burned more than 1.5 years before this study. Based on the theory suggested previously that fire effects are most pronounced immediately after a fire and that these effects dissipate over time, it seems logical why all three plots had similar infiltration rates.

4.2.2 Saturated hydraulic conductivity (K_{sat})

At a depth of 2-3 cm below the soil surface, there was no significant difference in K_{sat} across the different fire treatments (H (2) = 5.791, P = 0.055) (refer to Figure 4.12). The variability in the data is quite distinct between the annual plot and other plots. Furthermore, there was also no significant difference in K_{sat} 5-7 cm below the soil surface (H (2) = 4.431, P = 0.109) (refer to Figure 4.13). The difference in the variability in the data across the treatments is very interesting. The variability is greater on the VFR plot than on the other two plots, especially the annual plot. It is speculated that this variance is due to the homogenous vegetation cover on the annual and no burn plots. In addition to the heterogeneous vegetation cover on the VFR plot, the fires which burn across this area will naturally induce variability.

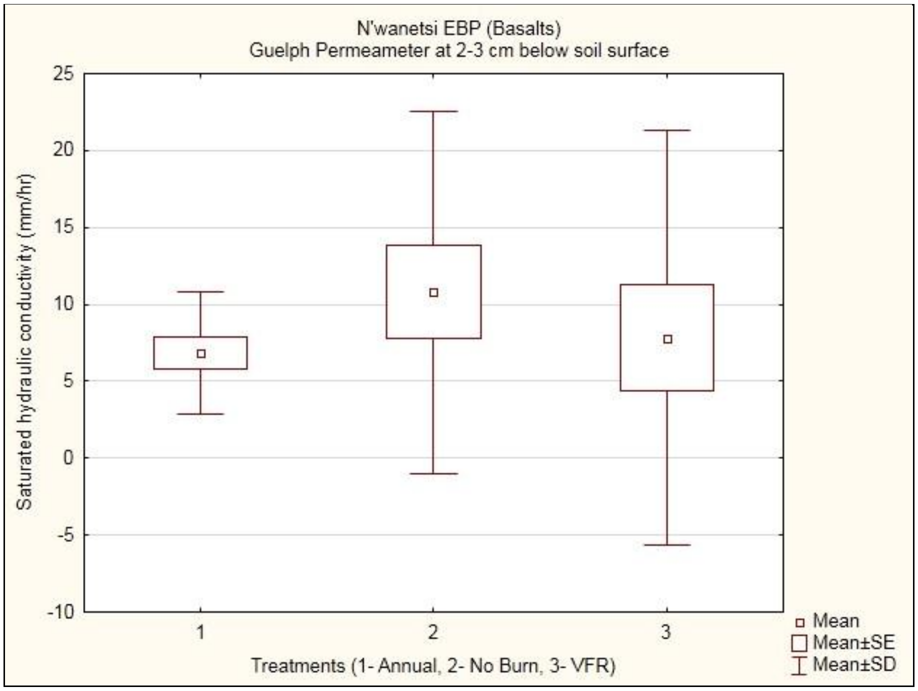


Figure 4.12 Box-whisker plots describing K_{sat} (mm/hr) at a depth of 2-3 cm below soil surface across various fire treatments on N'wanetsi EBP

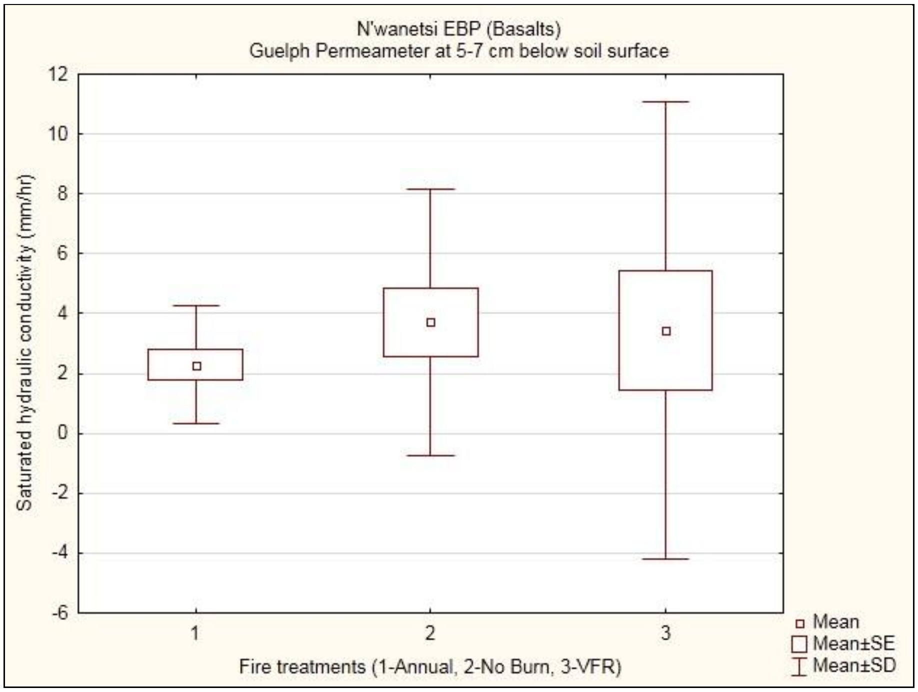


Figure 4.13 Box-whisker plots describing the K_{sat} (mm/hr) measured at N'wanetsi at a depth of 5-7 cm below the soil surface

4.2.3 Soil compaction

Results indicate that the annual burn plot is the most compacted (Figure 4.14). The mean penetrometer depth for the initial three strikes were compared across the different burn plots to account for the pedoderm (< 3 cm) and to identify shallow surface compaction while the final tenth strike was analysed to account for deeper layers of the A-horizon and to distinguish whether the subsurface soil was also compacted (± 5 cm). The Kruskal-Wallis tests revealed that the mean penetrometer depths for all three initial strikes as well as the tenth (final) strike were significantly different across the varying fire frequencies and no burn plot (Table 4.7). Post-hoc multiple comparisons tests where used to identify where these differences lied. The multiple comparisons tests established that the difference was significant between the annual and the no burn plots as well as between the annual and VFR plots (Table 4.7).

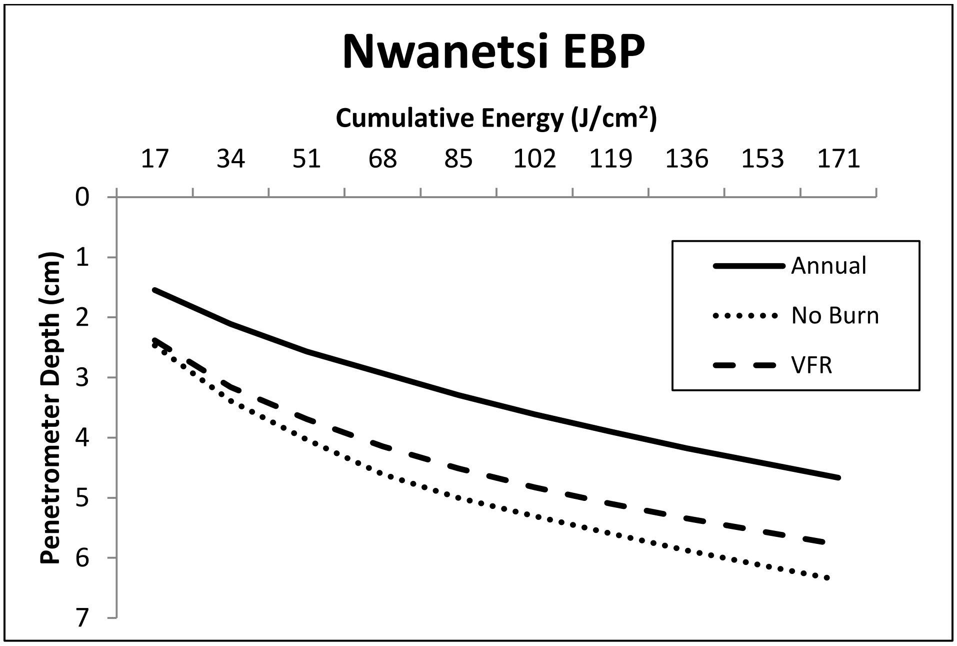


Figure 4.14 Penetrometer measurements collected on the N'wanetsi EBP indicating the compaction of the soil across the different fire treatments

Table 4.7 Kruskal-Wallis and multiple comparisons test results illustrating significant differences in soil compaction between the different fire treatments on N'wanetsi EBPs

Soil compaction: Kruskal-Wallis (KW) results and multiple comparisons P-values			
	Annual	No Burn	VFR
1st Penetrometer Strike (KW: H (2) = 75.598; P= 0.000)			
Annual		**0.000**	**0.000**
No Burn	**0.000**		1
VFR	**0.000**	1	
2nd Penetrometer Strike (KW: H (2) = 87.989; P= 0.000)			
Annual		**0.000**	**0.000**
No Burn	**0.000**		0.517
VFR	**0.000**	0.517	
3rd Penetrometer Strike (KW: H (2) = 89.02; P= 0.000)			
Annual		**0.000**	**0.000**
No Burn	**0.000**		0.2
VFR	**0.000**	0.2	
10th Penetrometer Strike (KW: H (2) = 56.688; P= 0.000)			
Annual		**0.000**	**0.000**
No Burn	**0.000**		0.304
VFR	**0.000**	0.304	

The findings illustrated in Figure 4.14 and Table 4.7 suggests that the soil on the annual burn plot is more compacted than the VFR and no burn plots. This coincides with the results obtained on the Kambeni EBPs (granites) as well as previous studies by Riddell *et al.* (2012) and by Snyman (2002, 2003) which were also conducted in semi-arid landscapes in South Africa. It is understood that a greater area of soil surfaces is exposed to the elements once a fire burns and denudes an area of vegetation cover. Thus, the bare soil surfaces become susceptible to compaction due to soil processes such as raindrop impact and splash (DeBano, 2000).

Literature (e.g. Cerda *et al.*, 1995; DeBano, 2000; Ice *et al.,* 2004; Mills and Fey, 2003; Snyman, 2003) suggested that fire would lead to a more compacted soil surface. However, it was later discovered that for the last seven years the annual burn plot did not burn as frequently as it should have due to low biomass which could not support the fires (N. Govender *pers. comm*.). This discovery creates concern regarding the absence of fire yet the exposure to a high density of herbivores on the annual burn plot. Herbivores often congregate on the plots after the prescribed fire in August due to improved grazing quality and better visibility against predators (Owen-Smith, 1982). In addition, this plot is in close proximity to a watering hole and would provide further motivation for animals to congregate on this plot. The herbivore exclosures erected on the annual and no burn plots were used to determine the effect of herbivores on soil compaction.

The penetrometer data collected inside and outside the herbivore exclosures on N'wanetsi EBPs did not have a normal distribution thus a non-parametric, Mann-Whitney U test was used in order to test for any significant differences in mean penetrometer depths. The results from penetrometer readings collected both outside and inside herbivore exclosures on the annual and no burn plots revealed that soil is more compacted outside the herbivore exclosures (U = 137.5, P = 0.000 and U = 149, P = 0.000, respectively) (refer to Figure 4.15). Similar results were found for the deeper tenth strike. These results imply that the effect of herbivore trampling on subsurface compaction has a greater impact than the effect of fire considering that subsurface compaction was even found on the no burn plot. The effects were observed to a minimum soil depth of 4.5 cm.

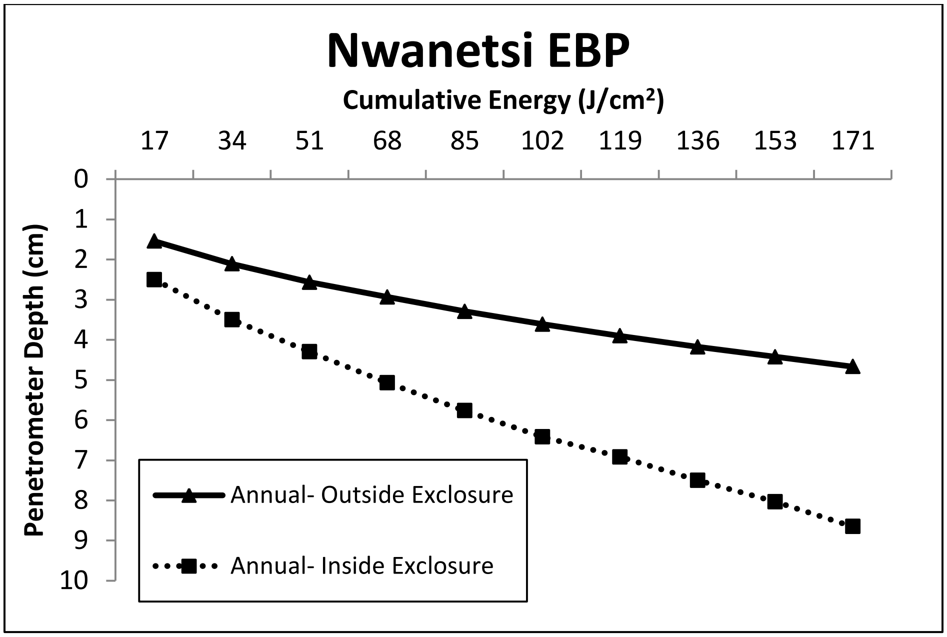


Figure 4.15 Penetrometer measurements collected on the N'wanetsi annual burn plot indicating the compaction of the soil outside and inside herbivore exclosures

In order to determine, solely, what the effect of fire on soil compaction is, penetrometer readings collected in the herbivore exclosures across the annual and no burn fire treatments were compared. Since data was not normally distributed, a non-parametric Mann-Whitney U test was applied to test for significant differences in mean soil compaction across the different fire frequencies (without the influence of herbivores). Results indicated that even when herbivores are excluded from the system (Figure 4.16), fire still impacts soil surface compaction where the annual plot had a more compacted and sealed soil surface than the no burn plot (U = 28, P = 0.000). These marked differences were observed beyond the soil surface. Thus in the absence of herbivores, fires lead to disturbed soil surfaces which are sealed and compacted due to processes such as raindrop impact and splash resulting from reduced protection by vegetation cover (DeBano, 2000).

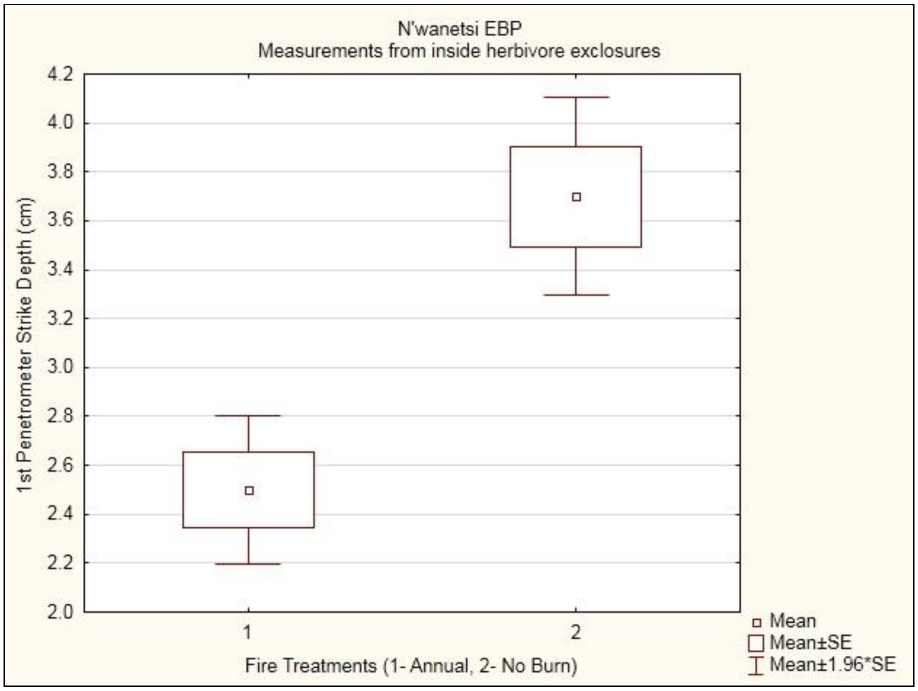


Figure 4.16 A graph illustrating the average depth of soil penetration after one strike inside the herbivore exclosures across the fire and no fire treatments

4.2.4 Soil organic matter

Soil organic matter affects water distribution and storage in the soil matrix and since fire consumes organic matter, total carbon was measured in soil samples collected across the various fire frequencies. Results presented in Table 4.8 indicate that the soils on the annual burn plot had the lowest total carbon. The Kruskal-Wallis results suggested that these differences in organic matter across the different fire frequencies were statistically significant (H (2) = 29.337, P = 0.000). A post-hoc multiple comparisons test revealed that soil organic matter differed significantly lower on the no burn plot (Table 4.9). As a result of decades of fire exclusion, the above-ground biomass is greatest on the no burn plot and likely contributing to the increased soil organic matter measured on this fire-suppressed plot.

Table 4.8 The percentage of total carbon (organic matter) measured in the soils sampled across the different fire frequencies at N’wanetsi EBPs

	Annual	No Burn	VFR
Total Carbon (%)	2.105	3.561	2.24

Table 4.9 Post-hoc results for the total carbon data collected at N’wanetsi EBPs

Post-hoc multiple comparisons test (p-values) (KW: H (2) = 29.337; P= 0.000)			
	Annual	No Burn	VFR
Annual		**0.000**	1.000
No Burn	**0.000**		**0.000**
VFR	1.000	**0.000**	

4.2.5 Soil water potential

At similar water contents, the no burn plot has the lowest water potential (Figure 4.17). This is particularly true for water contents ranging 2-10 %. The Kruskal-Wallis found that soil water potentials did not differ significantly between different fire frequencies (H (2) = 1.800; P= 0.407).

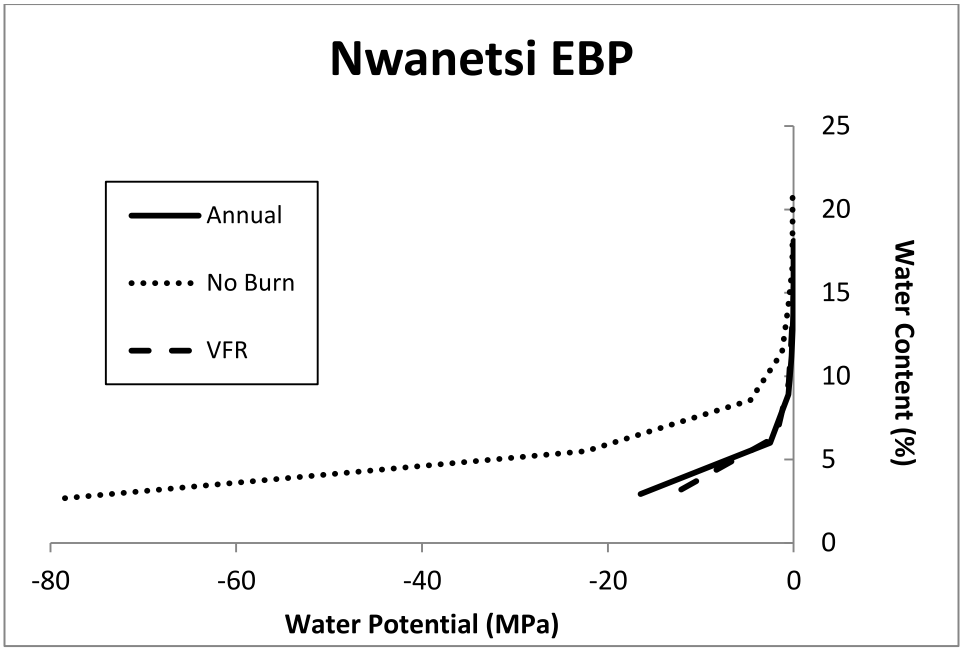


Figure 4.17 A graph providing a qualitative illustration of the water potentials across the different burn plots on the basaltic N'wanetsi EBPs

These results coincide with the Kambeni results which also suggested that on the no burn plot, water is held tightly in the soil matrix and is less able to move freely. It is speculated that due to many years of fire suppression on the no burn plot, there is a greater concentration of biomass and consequently more organic matter on this plot in relation to the other plots exposed to fires. Soil organic matter is known to be hydrophilic due to the strong attraction between water molecules and the charged polar sites on organic matter (Schaetzl and Anderson, 2005).

4.2.6 Vegetation characteristics

i. Grass biomass

Results indicated that the fire-suppressed no burn plot had a higher grass biomass than the other two fire treatments (H (2) = 176.041, P = 0.000) (Table 4.10). Since significant differences in the means were found, a post-hoc pairwise multiple comparisons test was performed in order to identify where these significant differences were. All the plots were significantly different to one another (Table 4.11). It is interesting to note that the lowest biomass was measured on the annual plot which was highlighted as being responsible for the unsuccessful fires which were prescribed for the past seven years.

Table 4.10 The grass biomass measured across the different fire frequencies at N'wanetsi EBPs

	Annual	No Burn	VFR
Grass Biomass (kg.ha^{-1})	1734	4119	2990

Table 4.11 Post-hoc results for the total carbon data collected at N'wanetsi EBPs

Post-hoc multiple comparisons test (p-values) (KW: H (2) = 176.041; P= 0.000)			
	Annual	No Burn	VFR
Annual		**0.000**	**0.000**
No Burn	**0.000**		**0.000**
VFR	**0.000**	**0.000**	

ii. Basal cover

As expected, basal cover is lower on the annual plot than the no burn plot (Figure 4.18). However, basal cover is lowest on the VFR plot which may be due to the VFR plot burning more frequently than the annual plot since the annual plot has been unable to support a prescribed fire for roughly the last 7 years (since 2006). It is interesting that in basaltic regions of KNP, the formula (Equation 3.9) provided by Hardy and Tainton (1993) is applicable unlike on the Kambeni EBPs in the granites. Since Hardy and Tainton (1993) conducted their study in a South African grassland, it is likely that their formula would be suitable to the *Sclerocarya birrea caffra/ Acacia nigrescens* Savanna in Satara due to the lower proportion of trees in the landscape whereas the granites are classified as the Lowveld Sour Bushveld which had more woody vegetation than the Satara section (Smit *et al*., 2010).

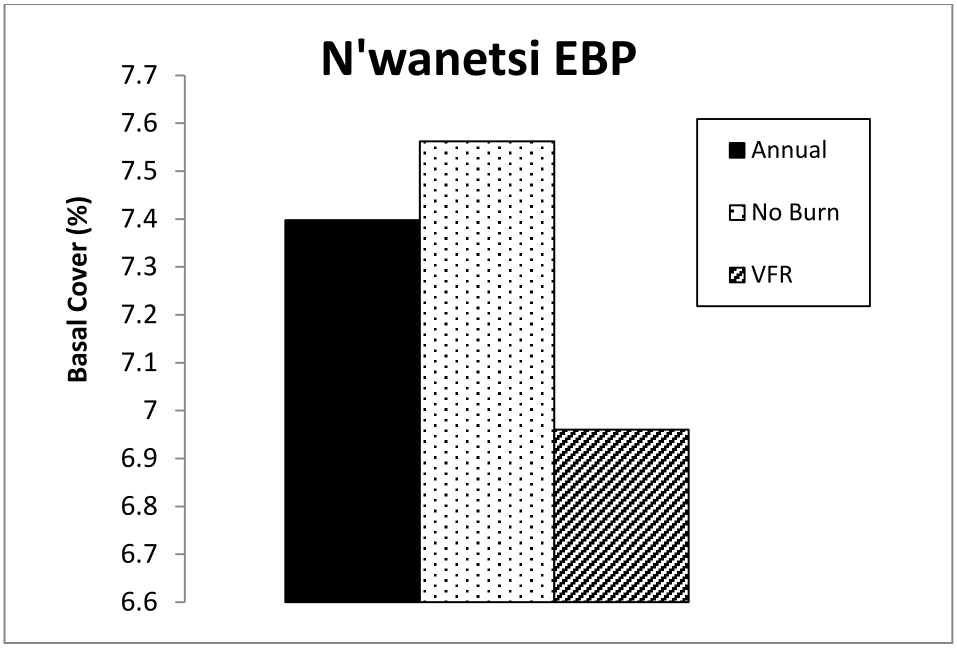


Figure 4.18 The difference in basal cover across the different fire regimes

4.2.7 Principle components analysis (PCA)

The results of the PCA for N’wanetsi EBPs are displayed in Figure 4.19. The loading plot in Figure 4.19.A illustrates how on a fine-grained soil with frequent fires, soil infiltration is influenced by soil organic matter. The two principle components used explains up to 73 % of the variability in the dataset. Similarly in Figure 4.19.B, soil organic matter plays an important role in how water infiltrates through the soil on the no burn plot. Approximately 77 % of the variability is explained by the two components. On clayey soils with a mean fire return interval of 4.5 years, soil infiltration is primarily influenced by soil organic matter (Figure 4.19.C). The two principle components used in the analysis accounts for a total variation of 76 %.

Irrespective of the fire regime on the basalts, soil organic matter is the most influential variable affecting the soil hydrology. It is believed that the effects of the organic matter are coupled with the effect of the high clay content on the basalts, both regarded as hydrophilic due to the significant amount of fine material. Therefore, in conjunction with low permeability in clayey soils, soil organic matter may limit infiltration.

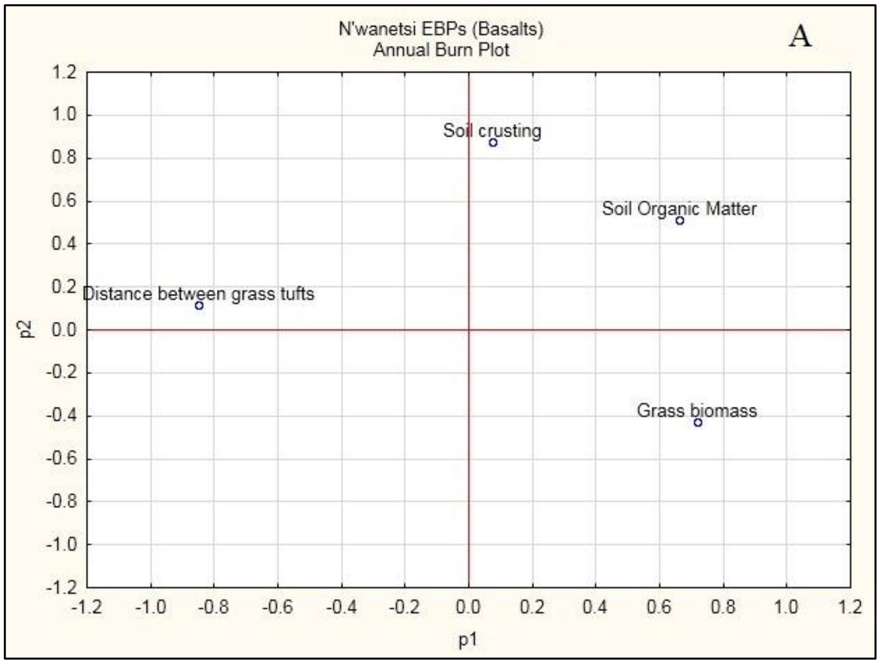
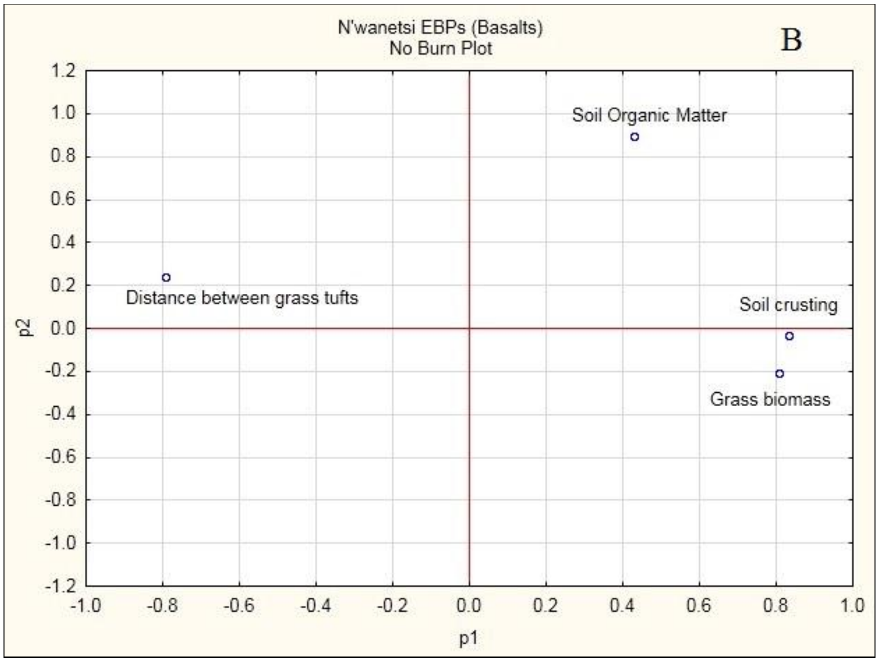
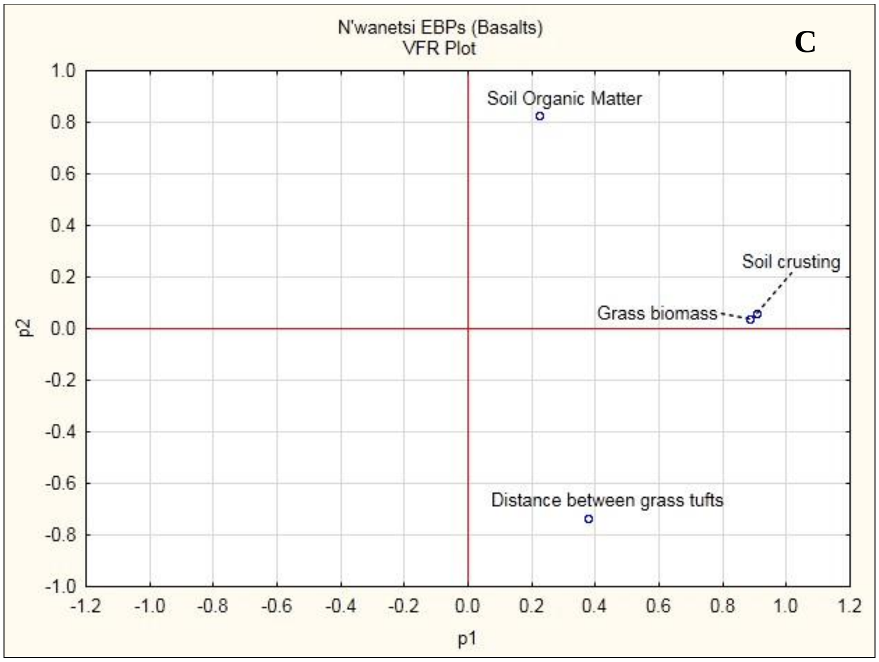


Figure 4.19 PCA loading plots derived from data collected for each plot on N'wanetsi EBPs
(A- Annual; B- No Burn; C- VFR)




N'wanetsi EBPs (Basalts)
VFR Plot
C
Soil Organic Matter
Soil crusting
Grass biomass
Distance between grass tufts
p2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
p1

5. DISCUSSION AND SYNTHESIS

Since fire is a critical driver in savanna ecosystem dynamics, it is vital that their influence on savanna hydrology is understood. Thus, the EBPs provided an ideal opportunity to investigate the effect of long-term fire frequencies on soil hydrology.

A review of the literature suggested that fires affected soil by decreasing infiltration rates due to a change in the hydrological functioning of the soil (Martin and Moody, 2001; Thonicke *et al*., 2001). Therefore, it was initially hypothesized that high fire frequencies would result in decreased infiltration rates. However, results gathered on the granitic EBPs revealed that soil infiltration rates were actually slowest on the recently burned VFR plot at Kambeni. It is believed that this is attributed to the time following the fire and not the long-term fire regime. Fire effects appear most pronounced shortly after a fire and dissipates with time. Field observations showed that while soil surfaces are covered by ash, water infiltrates rapidly into the soil surface. Yet when these ash particles disappear, either blown away by wind or percolates through the soil profile, the charred soil surface beneath the ash layer is hydrophobic and inhibits infiltration. Similarly, DeBano *et al.* (2005) suggests that water will infiltrate through this wettable ash layer until the water-repellent, charred soil surface is reached where soil infiltration is constrained. Once water infiltrates beyond the ash layer (or the ash layer has disappeared), the ability of the soil to allow infiltration may not be sufficient and thus forces water to run across the hydrophobic soil leading to soil erosion. In a semi-arid savanna such as KNP where short, high-intensity rainfall events are typical, the ability of the soil to allow infiltration is critical to prevent substantial topsoil erosion. If rainfall intensity exceeds the rate of soil infiltration, run-off is inevitable.

The findings stemming from the K_{unsat} data infers that soil infiltration rates improve after a few years following a fire. The K_{unsat} rates measured on the annual burn plot was similar to the no burn plot where fire has been actively suppressed for decades. Therefore, even though the annual plot last burned 1.5 years before, the infiltration rates were not substantially slower than the unburned plot indicating that the effects of the fire 1.5 years prior were no longer current. This theory held true for both the EBPs on granites and basalt soils. There was no significant difference in infiltration rates between the three fire regimes considering that the annual and VFR plots burned seven years and 1.5 years prior, respectively. Thus, it appears as though the soil has recovered here as well since infiltration rates are similar to the plot where fire has been suppressed for the past few decades. It is acknowledged that burned soils will recover or return to its natural equilibrium at different rates depending on factors such as pre-fire soil moisture content, fuel load, fire duration and fire intensity. It is suggested that soils recover due to surface runoff process which allow for the removal and redistribution of hydrophobic soil particles and ash. Jacobs *et al*. (2007) suggested that due to the low infiltration capacity, even minor rainfall events may trigger surface runoff which promotes the redistribution of sediment, organic material and nutrients. The mechanism for the recovery of burned soils in a post-fire environment is recommended for future research. A similar study by Strydom *et al.* (2014) conducted on similar soils found no significant differences in K_{unsat} between unburned soils and soils which burned only nine months prior; suggesting a faster improvement in soil infiltration rates at that particular site.

Unlike originally hypothesized, there was no significant difference in K_{sat} between the different fire regimes at neither 2-3 cm nor 5-7 cm below the soil surface on either geology. Amongst others, studies by Certini (2005), DeBano *et al.* (2005) and Mataix-Solera *et al.* (2011) suggested that the effects of fire on soil properties is most pronounced in the pedoderm where the greatest change in temperature occurs but could be measured up to depths of 10 cm. Considering that these studies were conducted in Europe and North America, it is likely that these differences are due to differences in the types of fires experienced in semi-arid African savannas. Typical savanna fires are less intense (Govender *et al*., 2006) and rapid-moving compared to the intense fires which burn across pine forests in Europe and North America where the majority of these studies were conducted. Therefore, it is believed that the fires burning across these burn plots may not be intense enough to penetrate beyond the soil surface and/or that these fires burn too rapidly across the surface to allow enough contact time for heat transference. In addition, grasses which are the dominant fuel for savanna fires (constitutes 70-98 % of the total fuel) (Shea *et al*., 1996), combusts rapidly due to their fine structure. This may contribute to the low heat transference in savanna fires.

The K_{unsat} and K_{sat} measured across the two geologies found that both these hydraulic properties were slowest on the basaltic EBPs. This would be expected considering the higher proportion of clays and finer particles in basaltic soil. The differences in variation in the K_{unsat} and K_{sat} data measured on Kambeni (granites) and K_{sat} data measured on N'wanetsi (basalts) were particularly intriguing. When compared to the other plots on Kambeni, there is not as much variation in the hydraulic conductivities measured on the recently burned VFR plot. This means that the hot fire which burned across the VFR area outside of the EBPs likely homogenized the soil properties across the plot. This is contrary to the typical behaviour of savanna fires which characteristically burn in a heterogeneous manner due to the inherent heterogeneity of the landscape (Trollope and Potgieter, 1985). These fires result in a patchy mosaic of varying degrees of fire intensities across the landscape. However, the homogeneity in the K_{sat} data measured on the annual burn plot on the N'wanetsi string is believed to be site-specific and attributed to the lack of mixed vegetation across the plot; hence no heterogeneous burning. Unlike the VFR and no burn plots where grass biomass was significantly greater, the lack of heterogeneity resulting from no patches of different vegetation types would lead to a more homogenized substrate. Grass tufts and their roots are known to create preferential pathways for water infiltration through the soil. Furthermore, these results coincides with Riddell *et al.* (2012) which found similar results and also proposed that these reduced variation in K_{sat} on the annual burn plot is due to the development of a more homogenized soil surface structure.

Since similar studies (e.g. Snyman, 2003; Mills and Fey, 2004; Riddell *et al.*, 2012) which were conducted in semi-arid areas in South Africa found that fire induced soil compaction, it was hypothesized that the soils on the annual burn plots would be the most compacted. This was shown on both the Kambeni and N'wanetsi strings, where the soils were more compacted on the annual plot compared to the other fire and no fire treatments. Initially, it was difficult to determine whether these differences in soil compaction were due to the effect of fire on the soils or as a result of the high density of herbivores which concentrate on the annual plots in search of improved grazing quality and/or improved visibility against predators after a fire. The herbivore exclosures erected on the annual and no burn plots on N'wanetsi provided the ideal opportunity to investigate the effect of herbivores on soil compaction. It was found that the effects of the herbivores were greater than the effects of fire on soil compaction. Herbivores usually concentrate around recently burned areas for improved grazing and generally avoid denser vegetation, preferring open areas for better visibility against predators (Owen-Smith, 1982). Russell *et al*. (2001) found similar results when cattle lead to compacted soil surfaces but did not reduce infiltration rates. Furthermore, an investigation into the effects of fire alone revealed that with the exclusion of herbivores, fire may still lead to shallow soil compaction and sealing due to fire burning vegetation, denuding an area and leaving it exposed to processes such as raindrop impact and splash (DeBano, 2000). The impact of raindrops and splash is assumed to be particularly significant on the N'wanetsi EBPs due to the high clay content present at these sites which may be affected by the dispersion of clay and blocking of pores at the soil surface; similar results were found by Mills and Fey (2004).

Unlike the initial hypothesis that the soil organic matter content would be significantly lower on the frequently-burned annual plot on both strings, this was found to be valid for the basaltic N'wanetsi strings only. It is believed that the fire intensities on these burn plots are not sufficient enough to impact soil properties beyond the soil surface. Scholes and Walker (1993) proposed that under varying fire frequencies, the increase or decrease in soil organic matter is controlled by the intensity of the fire as well as the changes in primary production affected by the fire. With regards to the low organic matter content measured on the N'wanetsi annual burn plot, it is believed that the significantly reduced above-ground biomass is the agent leading to significantly less soil organic matter. The role of soil organic matter is twofold; it drives soil fertility as well as influence water movement and storage via the water-holding capacity of the soil, which will now be discussed next.

The hypothesis that soil water potential would be lowest on the no burn plot because the water-holding capacity of these soils would be high was found to be valid. The water-holding capacity of these soils on the fire-suppressed no burn plots on both geological EBP strings are likely linked to increased biomass and organic matter content as a consequence of decades of fire exclusion. The reduced water potential and subsequent water-holding ability of the soils on the annually-burned plots will result in water percolating much faster through the soil due to less adsorptive forces by hydrophilic organic matter acting on the water molecules and retaining the water (Schaetzl and Anderson, 2005). Furthermore, the soil water potential measured on the basalts was notably lower than the coarse-grained granitic burn plots. This finding is attributed to greater soil organic matter content measured on the basalts as well as the increased proportion of clays and finer particles inherent in basaltic soils. Stoof *et al.* (2010) noted that water-holding capacity, an indication of the amount of water which can be stored in the soil, and soil infiltration controls the fate of precipitation. Thus, the ability of the soil to retain moisture is a critical driver controlling the movement of soil water through the landscape. Since post-fire regeneration of burned vegetation is reliant on water, the capacity of the soil to retain moisture is particularly vital owing to the fact that most savanna fires occur after the dry season (Kennedy and Potgieter, 2003) when the veld is water-stressed. Thus, the re-establishment of plants is dependent on water retention capacities at low water contents. Indirectly, the ability of the soils to store water in the catchment controls the distribution of herbivores in the landscape as their movements are guided by palatable forage.

Vegetation characteristics such as grass biomass and basal cover were assessed in order to determine how they may influence soil hydraulic properties in a fire-prone savanna system. As hypothesized, the highest grass biomass was found on the fire-suppressed no burn plots on both EBP strings in the granitic and basaltic regions of KNP; as would be expected after many years of fire exclusion. Furthermore, basal cover was greatest on the fire-suppressed no burn plot on the basaltic N'wanetsi EBPs. These findings are likely due to decades of fire exclusion resulting in the accumulation of vegetation on the no burn plots. This increase in vegetation may control the distribution of water through the catchment.

The influence of independent variables, such as grass biomass, distance between grass tufts (basal cover), soil crusting (compaction) and soil organic matter, on soil hydraulic conductivities under contrasting fire regimes were evaluated. According to this study, soil hydraulic properties on the granitic burn plots on Kambeni are mostly controlled by vegetation characteristics. These characteristics such as grass biomass and basal cover influences the fate of raindrops by controlling whether they infiltrate into the soil and secondly by controlling the extent of bare soil subjected to soil evaporation. These suggest that ecological factors play a major role in hydrological processes such as infiltration, permeability and the fate of raindrops. In contrast, the soil hydraulic properties on the N'wanetsi EBPs were primarily controlled by soil organic matter, irrespective of the fire frequency. It is believed that the hydraulic effect of the organic matter content in the soil is coupled with the hydraulic effect of the high clay content on these basaltic plots which are characterised by moderately deep Shortlands-Swartland soil. Both organic matter and clays are known to be hydrophilic influencing how it stores and conducts water.

6. CONCLUSIONS

Fire effects are complex owing to many interrelated factors which all play a role in influencing each other. Soil hydrology is affected by both direct and indirect fire effects. Fire may either directly impact the soil by altering soil chemistry and inducing hydrophobicity or indirectly by changing environmental conditions at the soil surface. Therefore investigating and understanding the impact of fires in semi-arid savannas is vital considering that fire is a major driver in savanna ecosystem dynamics. This is of particular importance in KNP where fire is also applied as a management tool to control and manipulate vegetation structure and composition. Furthermore, the fact that information relating to the impact of fire on soil hydrology in semi-arid African savannas is scarce, it provides additional incentive for research of this nature.

The effect of fire frequencies on soil hydraulic properties is negligible considering that it is actually the time following a fire which plays a significant role on soil hydrology in a savanna ecosystem. The effects of fire on soil infiltration rates were most prominent after a recent fire whereas plots where fires had burned more than two years prior had similar infiltration rates as unburned plots. These effects were primarily observed at the soil surface suggesting that savanna fires may lack the high intensities required and/or due to its rapid burning behaviour, does not have sufficient contact time to transfer heat beyond the soil surface. Furthermore data suggested that after two years following the fire, soil infiltration rates improved suggesting that soils are capable of recovery relatively soon. Re-sampling soil hydraulic properties on the VFR plot at Kambeni after two years will serve as further confirmation that soil infiltration rates will improve and increase again to pre-fire conditions.

The frequently-burned plots on the coarse-grained soils on Kambeni were the most compacted. On the clayey soils in the central basaltic region of KNP, it was high concentrations of herbivores which lead to soil compaction to depths of at least 4.5 cm. With the exclusion of herbivores, fires resulted in compacted soil surfaces due to bare soil exposed to processes such as raindrop impact and splash. Even though soils were compacted by both fire (indirectly) and herbivores (directly), this did not impact soil hydraulic properties significantly. In this case, the influence of soil compaction by fires and herbivores on soil hydrology is considered negligible. With the water-holding capacities of the soil influenced by above-ground biomass and organic matter, the effect of fire frequencies on the ability of the soils to retain moisture at low water contents is critical to understand seeing as it is one of the most important properties in a post-fire environment.

In light of climate change and problems associated with bush encroachment, it is critical for scientists and managers to understand how fires impact soils and their hydraulic properties, especially in a fire-manipulated landscape such as KNP. Considering that KNP management policies are designed for large-scale areas, these results would need to be extrapolated and confirmed at a catchment scale. The findings gathered in this study provide the initial platform from which further large-scale studies may be initiated to compliment, support and improve these results.

Recommendations

This study has yielded some very interesting findings and has improved the understanding of fire effects on soil hydrology in savanna systems. This study provides valuable insight into how factors such as fire, soil, water, vegetation and herbivores interact in the semi-arid savanna landscape. However, as with any research, outcomes are not absolute and there are aspects of uncertainty which have been identified during the study, possibly influencing interpretations.

Since soils are so diverse and may change over short distances due to its heterogeneity, the primary concern involves the experimental design of the EBPs. On the granites, the EBP strings were positioned on hillslope crests in order to minimise soil variation (Biggs *et al*., 2003) and the study by Venter and Govender (2012) concluded that the majority of the plots are representative of the surrounding landscapes except for a few outliers. Even though the plots where this research was focused on both the granites and basalts were identified as suitable plots for comparative studies, it is still recommended that a particle size analysis be used to determine the soil texture across these plots. This will reduce the uncertainty regarding whether differences in soil hydraulic properties are truly due to the burning regime or due to different soil textures.

Unfortunately before the EBP experiment was initiated, pre-conditions of the veld are unknown. Had such baseline data been available, it would have been interesting to identify how the soil hydraulic properties could have been altered after more than 50 years of fire treatments. Furthermore, there have been many cases where scheduled burning did not occur owing to insufficient fuel load due to herbivory or droughts, or too much moisture in the veld thus preventing the ideal conditions to support the prescribed fire.

Furthermore, it is urged that this initial study be taken forward by investigating the effect of fire intensities on soil hydrology as well and not just focus on fire frequency. Patterns identified in this study along with suggestions by many other studies (e.g. Scholes and Walker; 1993; DeBano and Neary, 2005; Mataix-Solera *et al.*, 2011) proposed that the intensities of fire play a major role in how the soil is affected, and especially how deep and how long these effects may linger. To facilitate this research, it is recommended that the impact of ash on soil infiltration rates also be assessed. Cerda and Robichaud (2009) recognized that there are many post-fire studies which usually neglect the temporary effect of ash aiding soil infiltration.

It is recommended that the impact of herbivores on soil compaction in the granitic areas of KNP also be investigated in order to compliment the findings stemming from the herbivore exclosures in the basalts. It is possible that the extent of soil compaction by herbivores might be different between the two geologies considering that the grain sizes of the sediment differs, there is more finer-material on the basaltic soils, and that herbivore densities are generally greater on the basalts.

It was noted that in the basaltic region of KNP, the formula used to calculate basal cover (Hardy and Tainton, 1993) was applicable and provided realistic results while it miscalculated trends on the Kambeni EBPs in the granites. Since Hardy and Tainton (1993) conducted their study in a South African grassland, it is likely that their formula would rather be suitable to the *Sclerocarya birrea caffra/ Acacia nigrescens* Savanna in Satara due to the high proportion of grasses which is similar to the grasslands Hardy and Tainton (1993) used. Meanwhile, the Kambeni EBPs in the higher rainfall, granitic region of KNP are classified as the Lowveld Sour Bushveld which has more woody vegetation than the Satara section. It is recommended that this formula only be used in similar landscapes as the original study site or that an alternative method of evaluating basal cover and consequently the area of bare soil be applied.

Once our understanding has been enriched as to the effects of both fire frequency and fire intensity, it would be ideal to up-scale this type of study to larger areas. Stoof *et al.* (2011) recognized the scarcity in pyro-hydrology research at catchment scales and attempted to investigate this fire-water relationship by burning an entire catchment. Their study highlights the need for catchment-scale fire experiments considering that the fire effects observed at plot scale may be diluted by the heterogeneity and variation inherent in larger areas such as catchments. Thus, by increasing the scale of this study, results will be more applicable to management policies since these policies are designed for implementation at a large scale.

Since fire is implemented as a management tool, KNP management could benefit from this study by improving fire policies and making better informed decisions. In order to ensure that catchment hydrological properties are not adversely affected by unsuitable burning regimes which may result in increased water repellency, decreased infiltration rates and decreased water retention capacities, it is advised that management actively ensures that the veld does not burn as often as every two years. Soil properties require a minimum of two years to return to pre-fire conditions on both the granitic and basaltic regions of the park. Since management utilises a Strategic Adaptive Management (SAM) approach with clear objectives which undergoes regular reviews, policies should be modified in order to take these findings into account when making fire management decisions. A co-operative relationship between science and management is necessary to ensure a steady transfer of knowledge between the two sectors to facilitate SAM.

While it is acknowledged that these results stem from plot-scale investigations, these findings have improved our fire-hydrology understanding and provides a preview into processes that may translate at the catchment scale. Whereas prior to this study, the effects of fire on soil hydrology in semi-arid savanna systems were previously unknown.

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8. APPENDICES

Appendix A: Description of the various fire treatments at Kambeni and N’wanetsi EBP strings

Table 8.1 The different fire treatments associated with the Kambeni and N’wanetsi EBPs

Plot number	**Fire Treatment**	
	Kambeni	**N’wanetsi**
1	Control	Control
2	December B2	December B2
3	October B2	October B2
4	February B2	February B2
5	August B2	August B2
6	April B2	April B2
7	August B1	August B1
8	February B3	February B3
9	October B3	October B3
10	December B3	December B3
11	August B3	August B3
12	April B3	April B3
13		October B4
14		October B6

Frequency:

B1-	Annual burn
B2-	Biennial burn
B3-	Triennial burn
B4-	Quadrennial burn
B6-	Sexennial burn
C-	No burn/ Control

Season:		**Intensity:**
Oct-	Spring	Hot
Dec-	Early summer	Cool
Feb-	Late summer	Cool
Apr-	Autumn	Warm
Aug-	Mid-winter	Hot

Appendix B: Kambeni and N’wanetsi burn history

Table 8.2 The burning schedule for the Kambeni and N’wanetsi EBPs since its commencement in the early 1950s

	August Annual Burn Plot	
Year	**Kambeni (Granites)**	**N'wanetsi (Basalts)**
1954	Scheduled burn	
1955	Scheduled burn	
1956	Scheduled burn	Scheduled burn
1957	Scheduled burn	Scheduled burn
1958	Scheduled burn	***Did not burn***
1959	Scheduled burn	Scheduled burn
1960	Scheduled burn	Scheduled burn
1961	Scheduled burn	Scheduled burn
1962	Scheduled burn	Scheduled burn
1963	Scheduled burn	***Did not burn***
1964	Scheduled burn	***Did not burn***
1965	Scheduled burn	***Did not burn***
1966	Scheduled burn	Scheduled burn
1967	Scheduled burn	Scheduled burn
1968	Scheduled burn	***Did not burn***
1969	Scheduled burn	Scheduled burn
1970	Scheduled burn	***Did not burn***
1971	Scheduled burn	Scheduled burn
1972	Scheduled burn	Scheduled burn
1973	Scheduled burn	***Did not burn***
1974	Scheduled burn	Scheduled burn
1975	Scheduled burn	Scheduled burn
1976	Scheduled burn	Scheduled burn
1977	Scheduled burn	Scheduled burn
1978	Scheduled burn	Scheduled burn
1979	Scheduled burn	Scheduled burn
1980	Scheduled burn	Scheduled burn
1981	Scheduled burn	Scheduled burn

1982	Scheduled burn	Scheduled burn
1983	***Did not burn***	***Did not burn***
1984	Scheduled burn	Scheduled burn
1985	Scheduled burn	Scheduled burn
1986	Scheduled burn	***Did not burn***
1987	***Did not burn***	***Did not burn***
1988	Scheduled burn	Scheduled burn
1989	Scheduled burn	***Did not burn***
1990	Scheduled burn	Scheduled burn
1991	Scheduled burn	Scheduled burn
1992	***Did not burn***	***Did not burn***
1993	Scheduled burn	***Did not burn***
1994	***Did not burn***	***Did not burn***
1995	Scheduled burn	***Did not burn***
1996	Scheduled burn	Scheduled burn
1997	Scheduled burn	Scheduled burn
1998	Scheduled burn	***Did not burn***
1999	Scheduled burn	Scheduled burn
2000	Scheduled burn	Scheduled burn
2001	Scheduled burn	Scheduled burn
2002	Scheduled burn	Scheduled burn
2003	Scheduled burn	***Did not burn***
2004	Scheduled burn	***Did not burn***
2005	Scheduled burn	Scheduled burn
2006	Scheduled burn	Scheduled burn
2007	Scheduled burn	***Did not burn***
2008	Scheduled burn	***Did not burn***
2009	Scheduled burn	***Did not burn***
2010	Scheduled burn	***Did not burn***
2011	Scheduled burn	***Did not burn***
2012	***Unfavourable weather conditions***	***Did not burn***

Appendix C: Alpha values required for K_{sat} calculations

Table 8.3 The alpha (α) values used based on soil texture and structure (Elrick *et al*., 1989; Elrick and Reynolds, 1992; Reynolds, 1993c)

α^* (cm^{-1})	**Soil Texture/ Structure Category**
0.01	Compacted and structureless clays (clay liners)
0.04	Unstructured fine-textured soil (clays)
0.12	Most structured soils with medium and fine sands (first choice for most soils)
0.36	Coarse sands and highly structured soils with large cracks and macropores
0	The Gardner Solution (Reynolds and Elrick, 1985). Pressure and gravity contributions negligible

Appendix D: Frequency distribution plots used to assess for normal distributions

Below are the frequency distribution plots used to check whether data was normally-distributed or not, allowing for the correct statistical tests to be used. Note that some distributions illustrated in Figures 8.3 and 8.9 are normal. However in order to maintain consistency and to ensure that penetrometer data on both geologies are analysed comparatively, non-parametric tests were used.

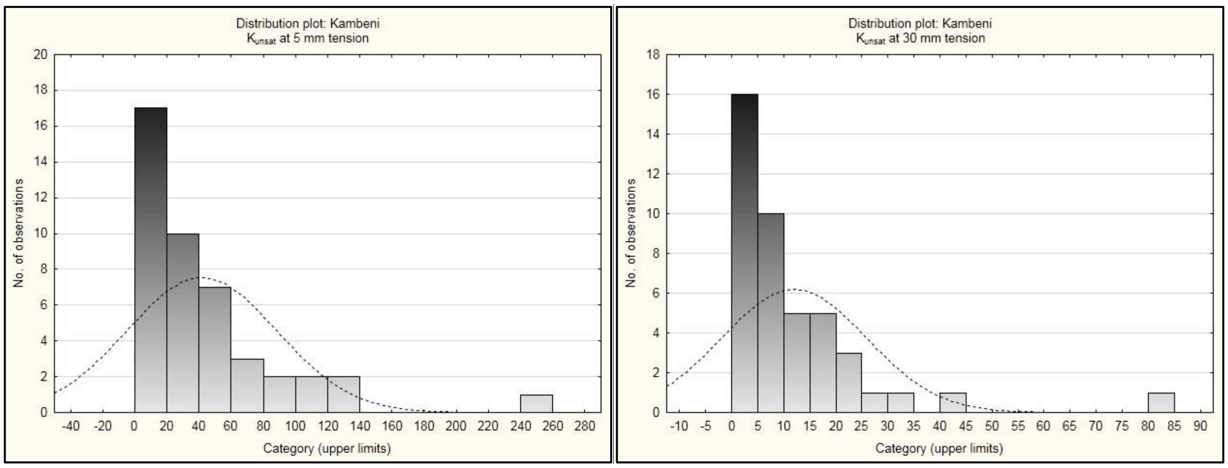

Figure 8.1 Distribution plots for the K_{unsat} data collected at Kambeni EBPs

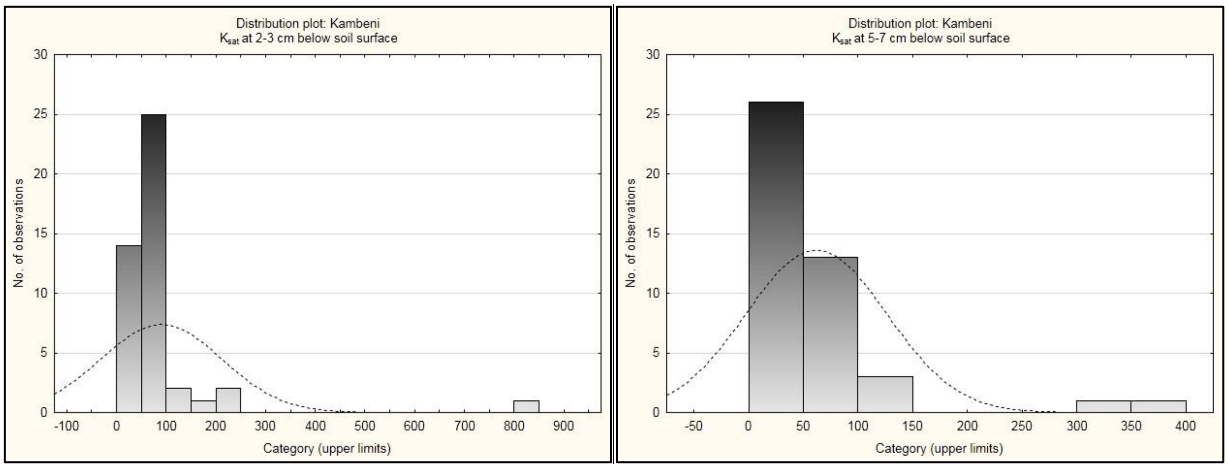

Figure 8.2 Distribution plots for the K_{sat} data collected at Kambeni EBPs

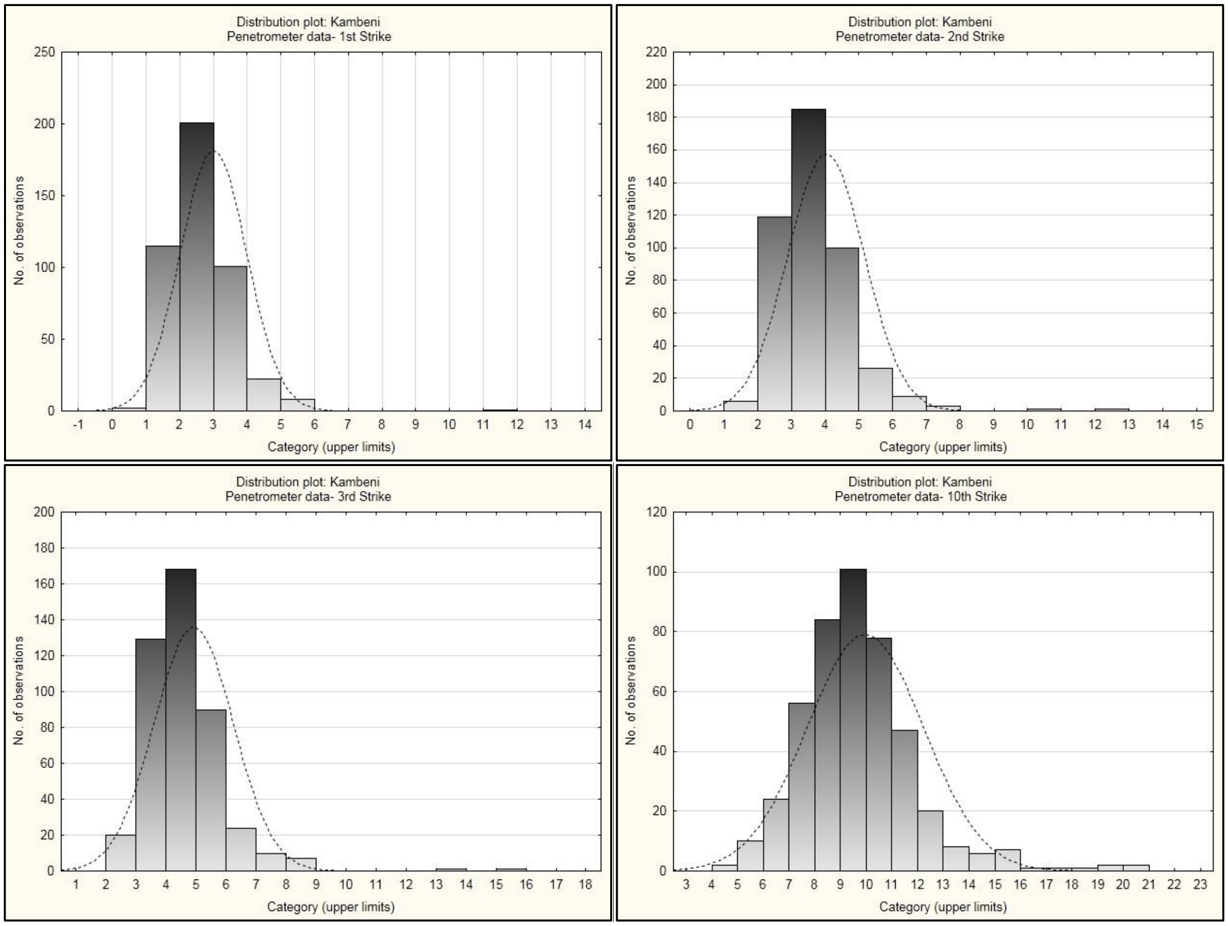

Figure 8.3 Distribution plots testing for normality in penetrometer data collected at Kambeni

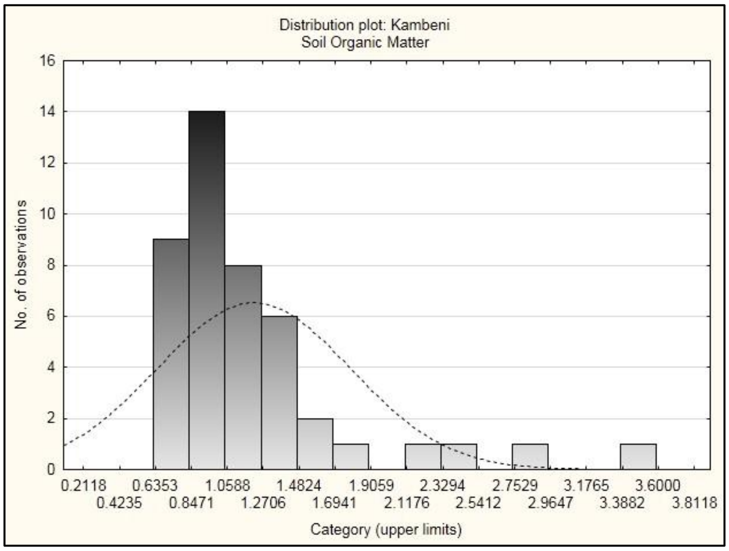

Figure 8.4 Checking for normality in soil organic matter data collected at Kambeni using distribution plots

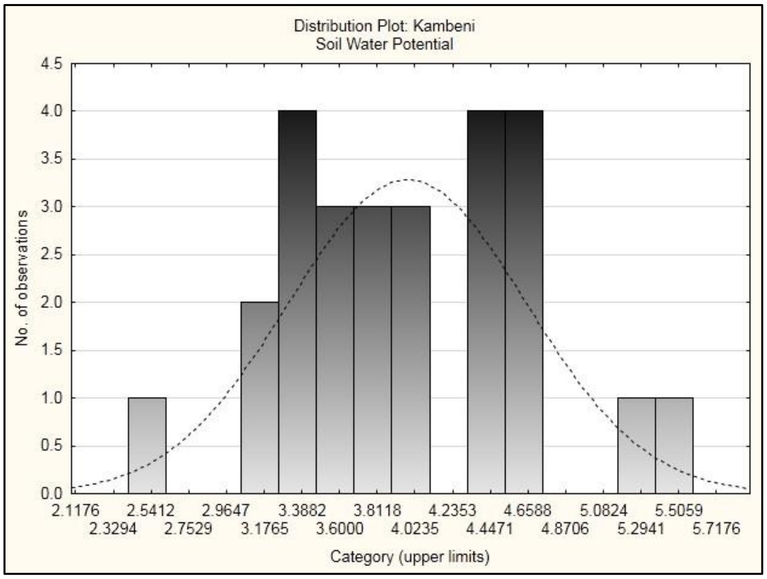

Figure 8.5 Checking for normality in Kambeni water potential data using distribution plots

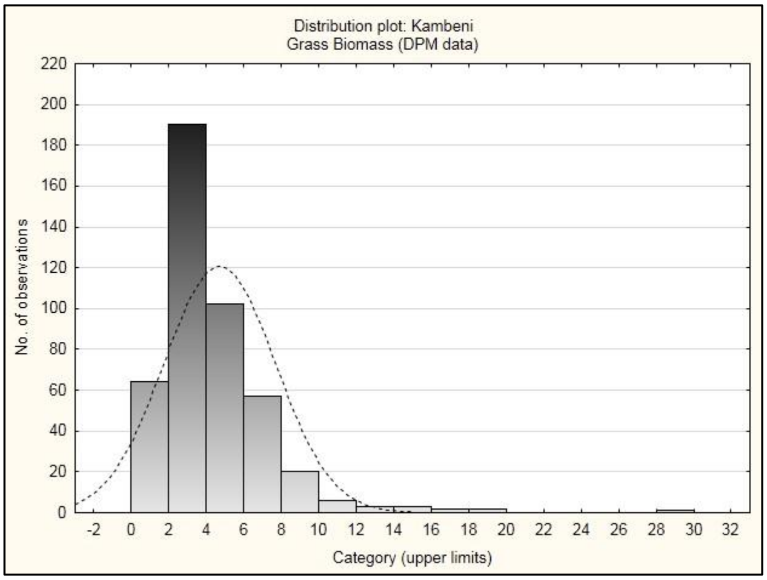

Figure 8.6 Checking for normality in DPM data collected at Kambeni using distribution plots

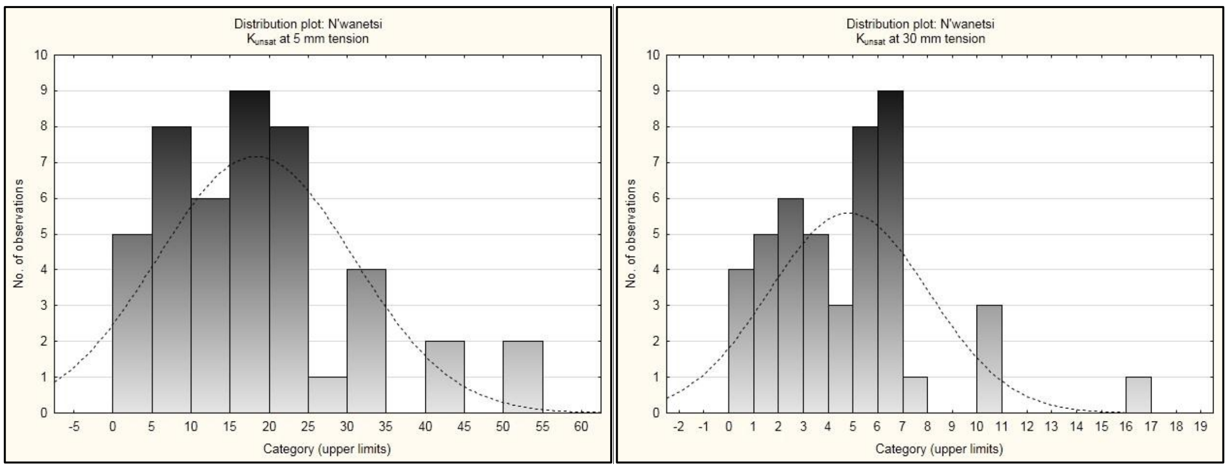

Figure 8.7 Distribution plots for the K_{unsat} data collected at N’wanetsi EBPs

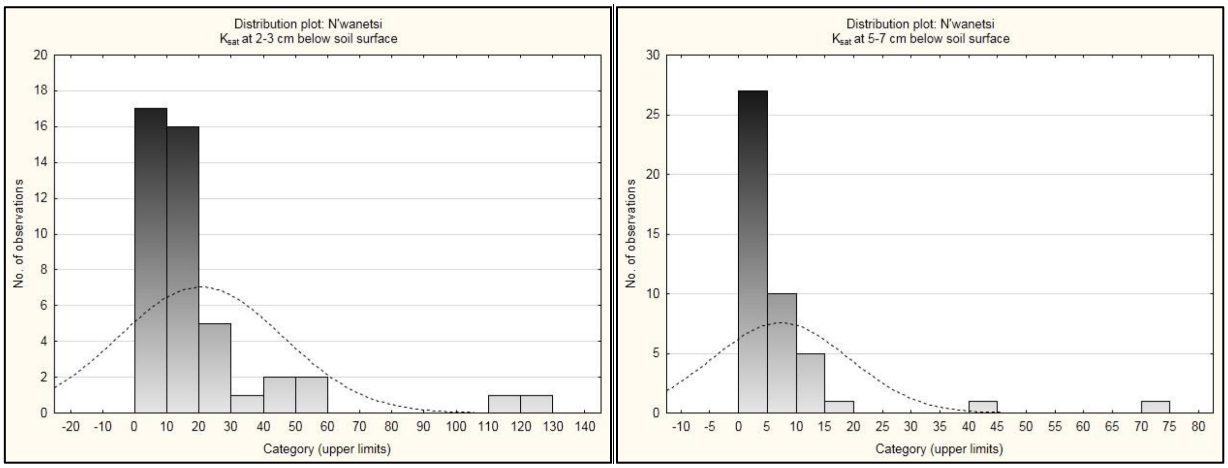

Figure 8.8 Distribution plots for the K_{sat} data collected at N’wanetsi EBPs

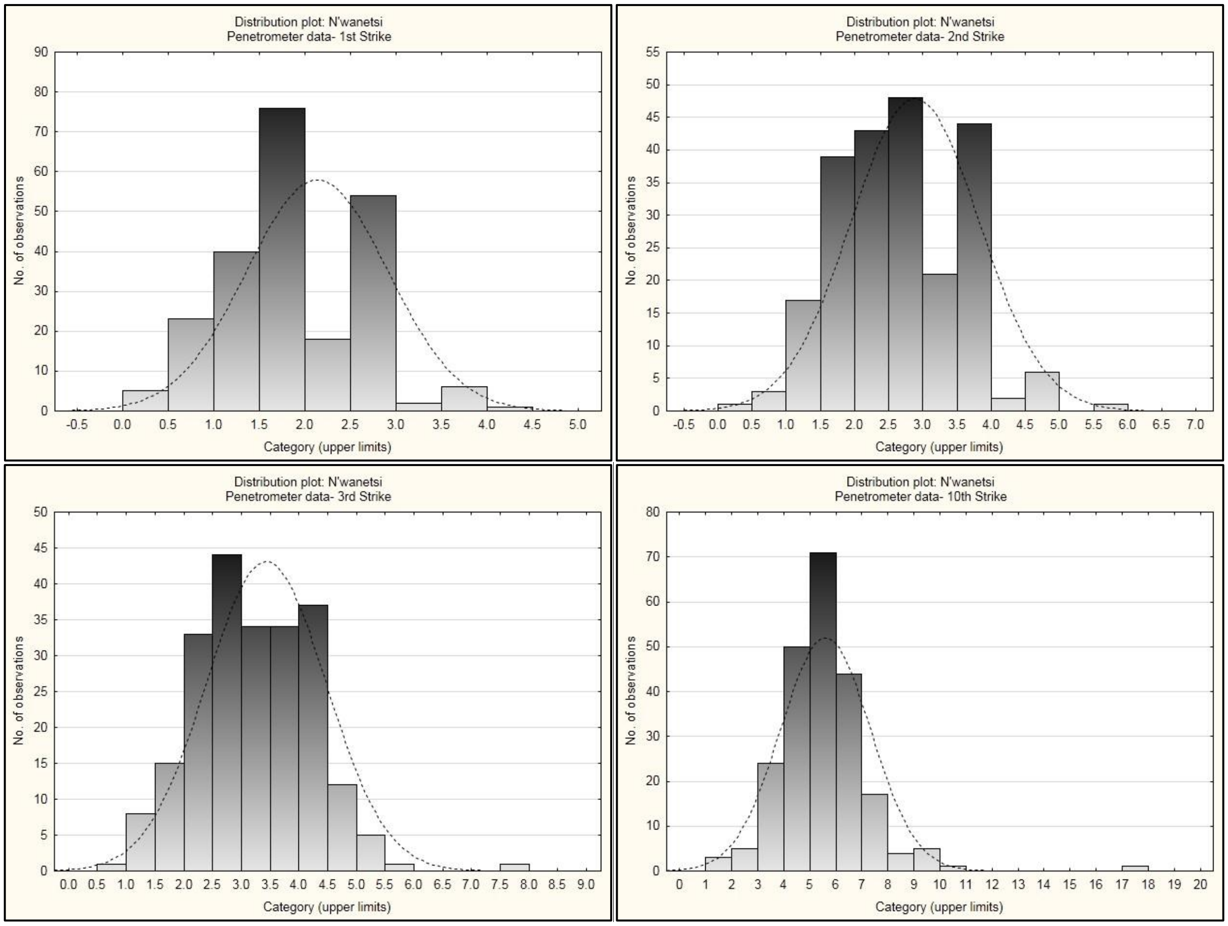

Figure 8.9 Distribution plots testing for normality in penetrometer data collected at N’wanetsi

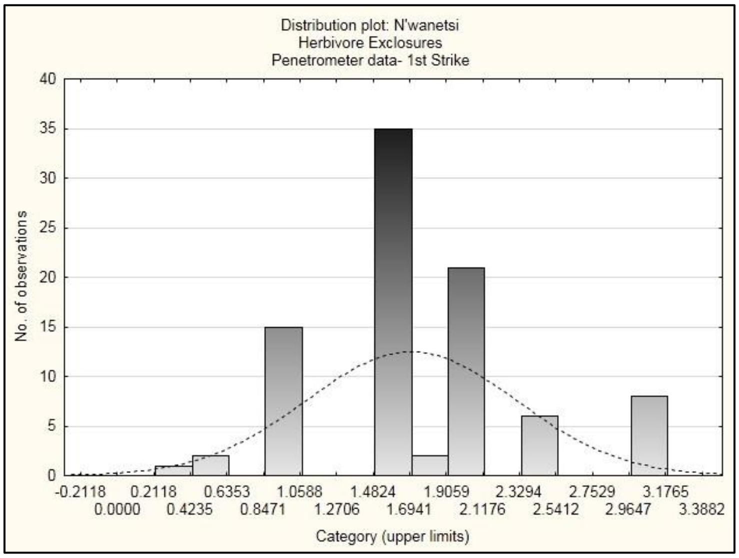

Figure 8.10 Distribution plots testing for normality in penetrometer data collected at both inside and outside the herbivore exclosures on N’wanetsi annual burn plot

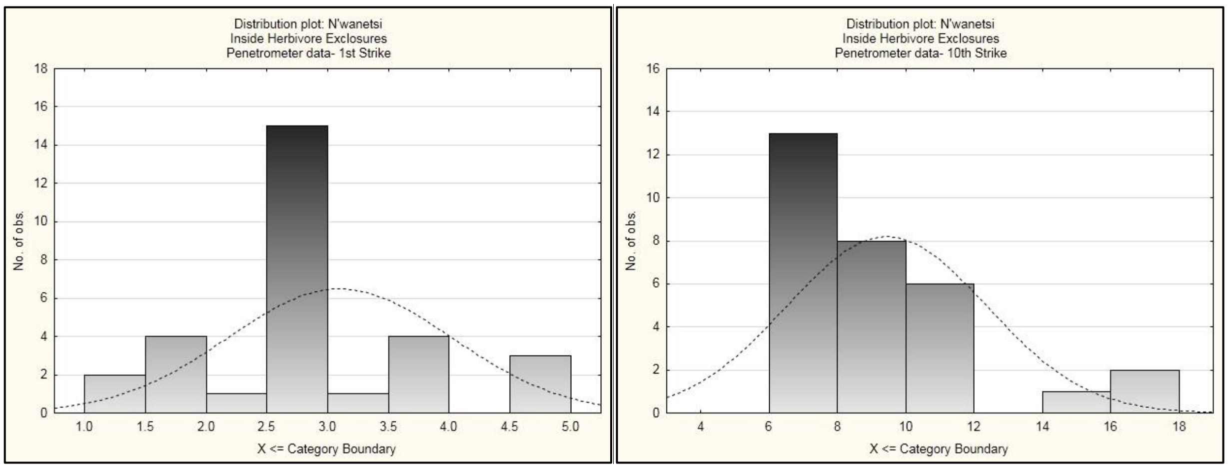

Figure 8.11 Distribution plots testing for normality in penetrometer data collected inside the herbivore exclosures on N'wanetsi annual and no burn plots

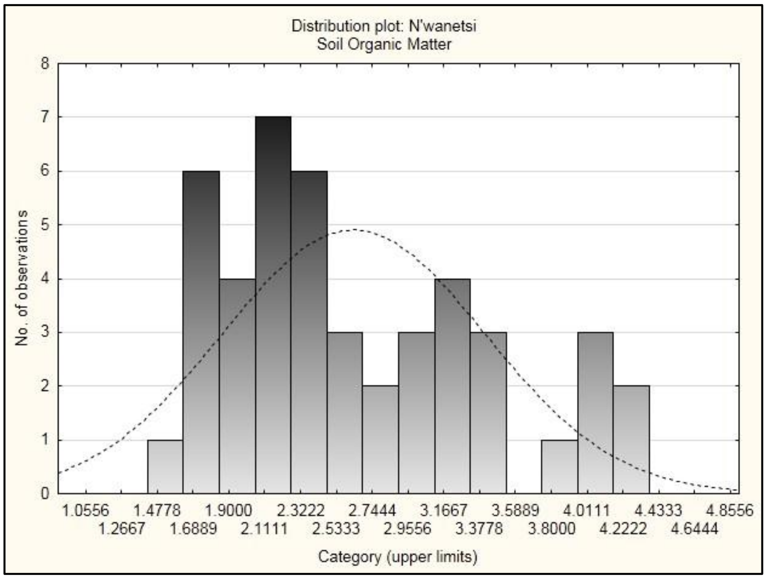

Figure 8.12 Checking for normality in soil organic matter data collected at N'wanetsi EBPs using distribution plots

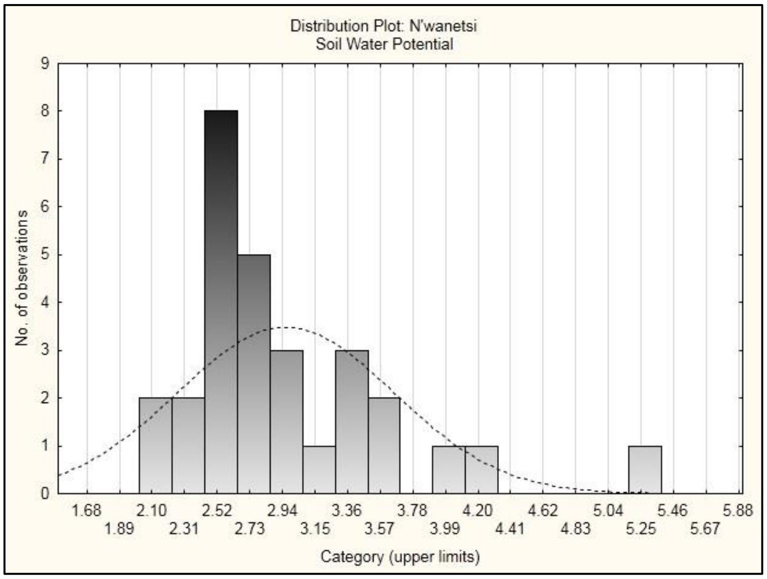

Figure 8.13 Distribution plots for soil water potential data collected at N'wanetsi EBPs

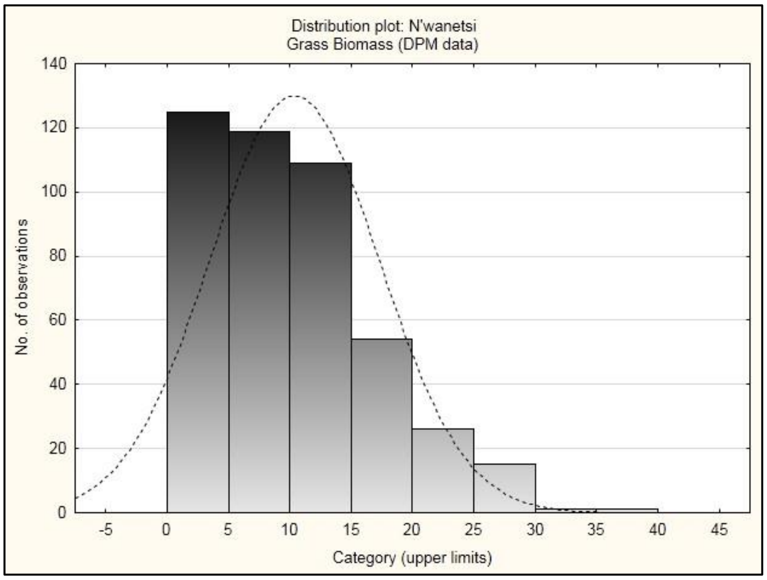

Figure 8.14 Checking for normality in DPM data collected at N'wanetsi EBPs

Appendix E: Results for each test conducted at Kambeni and N'wanetsi EBPs

Table 8.4 Measurements obtained at each sample point at Kambeni EBPs

Fire Frequency		Sample Point	K_{unsat} (mm/hr)		K_{sat} (mm/hr)		Soil Compaction- 1^{st} Strike penetrometer depth (cm)	Organic Matter- Total carbon (%)	Soil Water Potential (MPa) Day 1	Grass Biomass- DPM height (cm)	Basal Cover- Distance to tuft (cm)	GPS Co-ordinates	
			0.5 cm	3 cm	2-3 cm	5-7 cm						Latitude	Longitude
KAMBENI (Granites)	Annual Burn	**1**	15.5	4.2	32.1	37.3	2.8	1.1		2.4	3.8	25° 09' 17.045" S	31° 16' 12.222" E
		2	62.3	16.4	42.9	310.6	2.8	1.2	-1.5	3.0	3.2	25° 09' 16.721" S	31° 16' 12.515" E
		3	70.0	17.7	828.7	358.2	3	0.7	-1.8	2.1	3.1	25° 09' 16.506" S	31° 16' 12.815" E
		4	3.9	1.8	166.6	29.5	2.6	0.8		3.2	4.7	25° 09' 16.439" S	31° 16' 13.320" E
		5	20.8	4.0	19.3	8.1	2.3	1.0	-0.8	2.7	5.0	25° 09' 15.990" S	31° 16' 13.602" E
		6	8.1	2.7	59.0	37.6	2.3	1.1	-3.8	3.1	3.3	25° 09' 15.546" S	31° 16' 13.836" E
		7	242.2	81.0	48.4	20.5	2.1	1.5	-1.3	4.3	3.5	25° 09' 15.162" S	31° 16' 13.416" E
		8	29.9	11.0	37.0	54.5	3.3	1.0	-0.3	4.6	4.8	25° 09' 14.784" S	31° 16' 14.093" E
		9	102.6	20.0	81.4	27.6	2.4	1.2	-1.2	4.4	4.0	25° 09' 14.424" S	31° 16' 14.255" E
		10	22.5	7.9	76.5	41.0	2.3	0.9		3.1	6.0	25° 09' 13.865" S	31° 16' 14.574" E
		11	0.7	0.3	61.9	62.3	2.3	1.0		4.7	4.0	25° 09' 13.320" S	31° 16' 15.000" E
		12	41.4	12.0	66.0	41.3	2.1	1.1	-0.6	2.0	4.0	25° 09' 13.271" S	31° 16' 15.677" E
		13	12.4	4.5	46.3	31.4	2.1	1.0	-0.9	4.0	6.1	25° 09' 13.170" S	31° 16' 16.211" E
		14	21.0	8.2	82.4	55.4	2.3	1.0		2.8	2.9	25° 09' 12.924" S	31° 16' 16.530" E
		15	20.3	8.7	96.6	111.1	3.4	0.8		3.1	3.3	25° 09' 12.870" S	31° 16' 17.118" E
	No Burn	**1**	46.3	16.1	237.6	106.5	4.4	2.4		4.3	8.7	25° 09' 09.366" S	31° 15' 05.748" E
		2	134.2	40.7	240.4	105.3	3.2	1.6		7.2	10.6	25° 09' 09.096" S	31° 15' 05.814" E
		3	35.9	13.7	69.3	28.2	3.6	1.0		7.6	11.9	25° 09' 08.544" S	31° 15' 05.579" E
		4	93.4	22.3	90.2		3.5	1.0		6.1	11.0	25° 09' 08.052" S	31° 15' 05.448" E
		5	14.5	6.0	39.5	37.7	3.5	1.4	-2.7	10.6	7.7	25° 09' 07.601" S	31° 15' 05.315" E
		6	31.8	10.2	58.3	28.9	3.2	1.5	-2.8	9.1	7.9	25° 09' 07.211" S	31° 15' 04.716" E
		7	86.9		105.1	33.3	3.0	3.4	-6.4	5.5	7.8	25° 09' 07.145" S	31° 15' 04.919" E
		8	3.6	1.7	26.7	35.3	3.0	0.7	-3.9	8.4	7.9	25° 09' 06.126" S	31° 15' 04.067" E
		9	21.2	8.3	131.3	79.7	2.9	0.9	-0.9	6.8	8.2	25° 09' 06.120" S	31° 15' 03.719" E
		10	105.3	30.0	22.8	75.6	2.9	0.9	-1.2	6.7	5.9	25° 09' 06.540" S	31° 15' 03.186" E
		11	51.7	17.1	89.2	32.9	3.0	0.9	-1.8	7.4	6.3	25° 09' 06.966" S	31° 15' 02.705" E

		12	66.8	22.8	78.4	43.1	2.8	1.0		7.9	6.9	25° 09' 07.049" S	31° 15' 02.423" E
		13	49.7	9.7	35.9	26.5	3.5	1.1	-1.7	6.0	7.7	25° 09' 07.415" S	31° 15' 02.423" E
		14	131.8	27.3	94.7	45.7	3.8	1.4	-1.7	5.8	3.7	25° 09' 07.782" S	31° 15' 02.340" E
		15	38.6	6.0	68.2	60.1	3.6	1.4		6.4	5.2	25° 09' 08.141" S	31° 15' 02.411" E
KAMBENI (Granites)	VFR	**1**	14.2	5.2	67.9	33.9	3.7	2.8	-4.8	5.0	4.5	25° 09' 16.253" S	31° 16' 24.912" E
		2	0.7	0.3	48.8	45.9	3.2			4.0	3.4	25° 09' 15.888" S	31° 16' 25.205" E
		3	8.2	3.1	14.1	76.6	3.8	1.6		5.3	4.6	25° 09' 15.629" S	31° 16' 25.428" E
		4	1.8	0.8	58.3	22.0	3.3	0.8	-1.3	4.0	5.4	25° 09' 15.222" S	31° 16' 25.716" E
		5			98.4	44.6	2.1	0.7		3.6	4.9	25° 09' 15.012" S	31° 16' 26.165" E
		6	49.9	9.9	56.7	50.1	2.8	1.3		3.3	3.9	25° 09' 14.706" S	31° 16' 26.550" E
		7	11	3.9	66.8	45.4	2.1	0.7	-0.8	4.3	6.9	25° 09' 14.483" S	31° 16' 27.101" E
		8	23.6	8.5	70.4	43.9	3.2	1.8	-1.1	2.7	7.3	25° 09' 14.285" S	31° 16' 27.515" E
		9	7.9	3.3	38.1	38.5	3.4	1.2		4.3	5.8	25° 09' 14.106" S	31° 16' 27.875" E
		10	9.6	4.2	74.4	88.3	2.9	0.9	-2.3	3.5	7.0	25° 09' 14.028" S	31° 16' 28.464" E
		11	48.5	16.1	94.1	44.1	2.8	1.0		4.7	7.2	25° 09' 13.692" S	31° 16' 28.469" E
		12	9.7	4.2	63.1	60.3	3.5	1.2	-1.0	3.7	3.3	25° 09' 13.212" S	31° 16' 28.301" E
		13	12.1	4.9	58.8	54.6	3.6	2.3	-3.6	2.5	3.8	25° 09' 12.917" S	31° 16' 28.924" E
		14	42.8	14.8	32.4	50.2	3.3	0.7		3.0	3.6	25° 09' 12.504" S	31° 16' 27.713" E
		15	9.2	3.8	89.8	60.5	2.8	0.8	-0.6	3.9	2.2	25° 09' 11.940" S	31° 16' 27.546" E

Table 8.5 Measurements obtained at each sample point at N'wanetsi EBPs

Fire Frequency		Sample Point	K_{unsat} (mm/hr)		K_{sat} (mm/hr)		Soil Compaction- 1st Strike penetrometer depth (cm)	Organic Matter- Total carbon (%)	Soil Water Potential (MPa) Day 1	Grass Biomass- DPM height (cm)	Basal Cover- Distance to tuft (cm)	GPS Co-ordinates	
			0.5 cm	3 cm	2-3 cm	5-7 cm						Latitude	Longitude
N'WANETSI (Basalts)	Annual Burn	**1**	3.4	1.1	4.1	0.8	1.4	1.5	-10.8	1.5	12.2	24° 26' 48.2" S	31° 53' 15.1" E
		2	32.2	7.8	4.1	1.8	1.6	1.8	-6.1	2.1	8.9	24° 26' 47.9" S	31° 53' 15.3" E
		3	6.9	2.0	5.0	1.5	1.5	2.0	-20.6	5.9	4.4	24° 26' 47.5" S	31° 53' 15.5" E
		4	10.6	3.7	2.8	0.9	1.6	2.3		5.6	3.5	24° 26' 47.4" S	31° 53' 15.8" E
		5	6.7	1.8	5.9	4.7	1.4	2.6	-17.2	4.3	5.1	24° 26' 46.9" S	31° 53' 16.3" E
		6	24.0	7.0	6.5	5.2	2.3	3.1		4.6	7.2	24° 26' 46.6" S	31° 53' 16.7" E
		7	23.2	5.9	5.5	0.8	1.4	2.1	-19.4	4.2	7.7	24° 26' 46.1" S	31° 53' 12.4" E
		8	51.7	10.3	6.9	1.1	1.5	1.9	-15.6	3.1	5.4	24° 26' 45.7" S	31° 53' 17.4" E
		9	23.0	5.8	11.4	0.8	1.1	2.4	-22.2	13.2	5.3	24° 26' 45.4" S	31° 53' 17.8" E
		10	3.3	0.8	4.3	1.7	1.6	2.2	-21.0	5.3	6.4	24° 26' 45.1" S	31° 53' 18.4" E
		11	23.0	6.8	17.3	1.8	1.7	1.7		9.8	6.3	24° 26' 44.8" S	31° 53' 18.8" E
		12	21.6	6.5	6.7	6.5	1.3	2.3	-13.0	5.1	3.8	24° 26' 44.5" S	31° 53' 19.2" E
		13	21.3	5.7	11.5	4.7	1.4	2.1	-19.1	4.9	5.6	24° 26' 44.3" S	31° 53' 19.7" E
		14	18.3	6.6	8.2	0.5	1.7	1.9	-19.3	5.5	7.1	24° 26' 44.0" S	31° 53' 20.1" E
		15	30.5	6.9	1.8	1.6	1.8	1.8	-13.5	7.1	4.3	24° 26' 43.7" S	31° 53' 20.2" E
	No Burn	**1**	6.0	1.1	1.6	7.4	1.7	3.2	-94.8	11.3	5.0	24° 26' 58.1" S	31° 51' 49.2" E
		2	1.1	0.5	2.9	1.8	2.1	3.2	-48.7	13.6	8.6	24° 26' 57.8" S	31° 51' 49.3" E
		3	31.4	5.9	7.1	1.3	1.7	3.5	-96.2	12.3	10.6	24° 26' 57.4" S	31° 51' 49.3" E
		4	5.3	1.8	7.0	1.5	2.6	3.5	-65.5	18.9	5.4	24° 26' 57.5" S	31° 51' 49.6" E
		5	11.8	3.4	4.5	1.0	2.7	4.0		21.5	2.5	24° 26' 57.0" S	31° 51' 50.1" E
		6	16.2	4.6	7.3	1.3	2.4	3.0		17.9	5.5	24° 26' 56.8" S	31° 51' 50.4" E
		7	9.0	2.6	3.9	3.0	3.2	3.1		14.9	4.7	24° 26' 56.9" S	31° 51' 50.7" E
		8	8.4	2.0	10.2	18.6	2.6	3.1	-113.2	15.3	3.5	24° 26' 56.7" S	31° 51' 50.9" E
		9	20.8	5.5	15.4	1.8	2.7	4.2		17.8	4.2	24° 26' 56.5" S	31° 51' 51.2" E
		10	51.6	16.5	47.5	3.5	2.3	4.3	-70.1	13.8	6.2	24° 26' 56.3" S	31° 51' 51.7" E
		11	14.3	3.8	4.5	2.8	2.9	4.1	-60.6	16.1	3.2	24° 26' 56.2" S	31° 51' 51.8" E
		12	18.8	4.6	17.2	1.1	2.8	3.8		13.7	5.9	24° 26' 56.1" S	31° 51' 52.1" E
		13	10.0	3.5	5.5	3.0	2.7	4.0		14.7	7.2	24° 26' 55.8" S	31° 51' 52.8" E
		14	8.5	2.9	4.2	4.3	1.9	3.2		14.2	5.9	24° 26' 55.7" S	31° 51' 53.2" E

		15	32.1	6.8	23.0	3.1	2.7	3.4		17.6	7.5	24° 26' 55.7" S	31° 51' 53.3" E
N'WANETSI (Basalts)	VFR	**1**	0.2	0.1	4.5	2.3	2.6	2.5		9.4	3.7	24° 26' 46.4" S	31° 53' 29.9" E
		2	42.7	10.2	3.6	3.4	2.0	2.7	-11.8	10.3	5.4	24° 26' 46.3" S	31° 53' 30.4" E
		3	12.8	2.0	0.7	0.2	2.8	2.1	-17.1	15.9	9.4	24° 26' 46.0" S	31° 53' 30.6" E
		4	18.5	5.4	9.9	2.5	2.1	2.0		8.1	8.7	24° 26' 45.8" S	31° 53' 30.9" E
		5	18.3	4.8	1.8	0.4	2.0	2.4	-18.1	8.8	7.1	24° 26' 45.5" S	31° 53' 31.2" E
		6	16.2	3.5	1.4	2.4	2.1	2.1		7.5	7.9	24° 26' 45.4" S	31° 53' 31.3" E
		7	25.6	6.8	3.9	1.1	2.7	1.8	-10.3	8.2	8.7	24° 26' 45.1" S	31° 53' 31.3" E
		8	43.3	10.9	4.0	3.8	2.0	2.4		5.7	5.9	24° 26' 44.6" S	31° 53' 31.3" E
		9	5.2	1.6	1.2	0.7	2.6	2.8	-19.8	9.6	8.9	24° 26' 44.3" S	31° 53' 31.2" E
		10	19.2	6.3	52.0	30.8	2.1	1.7	-16.6	8.8	5.7	24° 26' 44" S	31° 53' 31.1" E
		11	22.1	6.7	8.6	1.2	2.9	2.5		14.3	6.4	24° 26' 43.5" S	31° 53' 31.2" E
		12	17.7	5.6	0.9	0.3	2.2	1.8	-4.4	11.1	6.4	24° 26' 43.3" S	31° 53' 31.4" E
		13	11.9	2.6	1.6	0.6	2.6	2.4	-6.0	11.3	6.2	24° 26' 42.8" S	31° 53' 31.6" E
		14	18.6	5.4	0.6	0.7	2.6	2.4	-6.5	12.1	7.4	24° 26' 42.5" S	31° 53' 31.6" E
		15	4.8	0.8	22.3	1.4	2.4	2.2	-10.4	11.4	7.9	24° 26' 42.1" S	31° 53' 31.7" E

Appendix F: Results for each statistical test conducted at Kambeni and N’wanetsi EBPs

Table 8.6 Statistical results for each variable measured at the Kambeni EBPs

Variable		Distribution	Statistical Test	Test Value	P-value	Significance	Post-hoc Test	Post-hoc Details
K_{unsat}	5 mm	Not normal	Kruskal-Wallis	10.830	0.005	Yes	Multiple Comparisons	Table 4.1
	30 mm	Not normal	Kruskal-Wallis	9.183	0.010	Yes	Multiple Comparisons	Table 4.1
K_{sat}	2-3 cm	Not normal	Kruskal-Wallis	1.512	0.470	No	Not required	
	5-7 cm	Not normal	Kruskal-Wallis	0.914	0.633	No	Not required	
Soil Compaction	1st Strike	Not normal	Kruskal-Wallis	49.055	0.000	Yes	Multiple Comparisons	Table 4.3
	2nd Strike	Not normal	Kruskal-Wallis	37.705	0.000	Yes	Multiple Comparisons	Table 4.3
	3rd Strike	Not normal	Kruskal-Wallis	24.407	0.000	Yes	Multiple Comparisons	Table 4.3
	10th Strike	Not normal	Kruskal-Wallis	19.770	0.000	Yes	Multiple Comparisons	Table 4.3
Soil Organic Matter		Not normal	Kruskal-Wallis	1.260	0.533	No	Not required	
Soil Water Potential		Not normal	Kruskal-Wallis	0.902	0.637	No	Not required	
Grass Biomass		Not normal	Kruskal-Wallis	157.102	0.000	Yes	Multiple Comparisons	Table 4.6

Table 8.7 Principle Components Analysis results for the Kambeni EBPs

Kambeni		R^2X	Eigenvalues	Q^2	Significance	Iterations	Total Variability (%)
Annual	Principle Component 1	0.423	1.690	-0.100	Yes	8	73
	Principle Component 2	0.312	1.246	0.138	No	4	
No Burn	Principle Component 1	0.441	1.765	0.030	Yes	6	60
	Principle Component 2	0.257	1.027	-0.094	No	7	
VFR	Principle Component 1	0.358	1.431	-0.002	Yes	50	70
	Principle Component 2	0.342	1.368	0.087	No	8	

Table 8.8 Statistical results for each variable measured at the N’wanetsi EBPs

Variable		Distribution	Statistical Test	Test Value	P-value	Significance	Post-hoc Test	Post-hoc Details
K_{unsat}	5 mm	Not normal	Kruskal-Wallis	1.463	0.481	No	Not required	
	30 mm	Not normal	Kruskal-Wallis	2.468	0.291	No	Not required	
K_{sat}	2-3 cm	Not normal	Kruskal-Wallis	5.791	0.055	No	Not required	
	5-7 cm	Not normal	Kruskal-Wallis	4.431	0.109	No	Not required	
Soil Compaction	1st Strike	Not normal	Kruskal-Wallis	75.598	0.000	Yes	Multiple Comparisons	Table 4.7
	2nd Strike	Not normal	Kruskal-Wallis	87.989	0.000	Yes	Multiple Comparisons	Table 4.7
	3rd Strike	Not normal	Kruskal-Wallis	89.020	0.000	Yes	Multiple Comparisons	Table 4.7
	10th Strike	Not normal	Kruskal-Wallis	56.688	0.000	Yes	Multiple Comparisons	Table 4.7
Inside vs. Outside Herbivore Exclosures (Annual Plot)		Not normal	Mann-Whitney U	137.500	0.000	Yes	Not necessary	
Inside Herbivore Exclosures (Annual and No Burn Plot)		Not normal	Mann-Whitney U	28	0.000	Yes	Not necessary	
Soil Organic Matter		Not normal	Kruskal-Wallis	29.337	0.000	Yes	Multiple Comparisons	Table 4.9
Soil Water Potential		Not normal	Kruskal-Wallis	1.800	0.407	No	Not required	
Grass Biomass		Not normal	Kruskal-Wallis	176.041	0.000	Yes	Multiple Comparisons	Table 4.11

Table 8.9 Principle Components Analysis results for the N’wanetsi EBPs

N’wanetsi		R^2X	Eigenvalues	Q^2	Significance	Iterations	Total Variability (%)
Annual	Principle Component 1	0.420	1.680	-0.100	Yes	12	73
	Principle Component 2	0.301	1.231	0.126	No	7	
No Burn	Principle Component 1	0.540	2.159	0.272	Yes	5	77
	Principle Component 2	0.226	0.9034	0.069	No	5	
VFR	Principle Component 1	0.450	1.801	-0.023	Yes	5	76
	Principle Component 2	0.308	1.230	0.192	No	8	