Evaluation of Brush Packing Methods on different Semi-Arid Savanna Soil Types and Properties

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ABSTRACT

In Africa, savannas are important biomes used for raising livestock. Encroachment by woody species (so-called “bush encroachment”) disrupts the natural equilibrium between the herbaceous layer and the tree and shrub densities in savanna biomes, thus suppressing palatable grasses and decreasing the carrying capacity for livestock and other herbivores. Bush encroachment threatens sustainable agriculture and initiates land degradation which is threatened by aspects such as overgrazing, climate change and incorrect implementation of fire as management tool. This study forms part of a larger investigation conducted by North-West University (NWU) on brush packing as a restoration technique to increase species diversity and grass biomass production for livestock keeping in semi-arid savanna areas.

Bush encroachment can alter soil properties (or so-called “soil quality indicators”), such as the soil moisture and soil nutrient contents influencing the microclimate. Soil properties will also be altered by the brush packing restoration technique (the technique used to restore bare areas caused by bush encroachment), which will have an influence on the processes leading to land degradation. Sufficient knowledge of brush packing techniques on various soil types and soil properties is vital to combat rangeland degradation and increase soil quality (capacity of soils to maintain biological activity, sustain environmental quality and promote animal and plant productivity). The study sites chosen for this project are situated in the D’Nyala Nature Reserve (conservation land-use type) and Shongoane communally-managed area in the Limpopo province, South Africa. Pattern Sampling was used to collect soil samples of the topsoil from each site for chemical and physical soil analysis, while a hand auger was used to drill holes to determine the soil moisture at different depths using a neutron probe. Methods of soil investigation included: 1) a neutron probe for measuring soil volumetric moisture at 10-centimetre depth intervals; 2) Kopecky rings for measuring soil bulk density; 3) loss-on-ignition testing for determining soil organic matter; 4) a single ring infiltration test for measuring soil infiltration rates; 5) sieve and hydrometer analyses for the estimation of particle size distribution; 6) soil classification by qualitative and quantitative methods (colour, texture and structure); 7) ammonium acetate testing to determine cation exchange capacity and exchangeable cations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{2+}); and 8) extractable phosphorous (P) using the Bray 1 extraction method.

Data processing consisted of various statistical methods, and data visualisation using figures and graphs. The research presented in this project will provide evidence that restoration treatments containing brush packing improves the physical and chemical properties (soil quality indicators) of bush encroached arid and semi-arid soils regarding: 1) soil infiltration rate; 2) soil moisture; 3) soil bulk density; 4) pH; 5) electrical conductivity (EC); 6) soil organic matter; and 7) soil nutrient status. Six treatment methods or so-called “restoration treatments” were implemented, which

incorporated a mixture of soil disturbance, clearing of bush, re-seeding and brush packing. The project lastly substantiated which of the restoration treatments applied after bush clearing will best restore soils of bush encroachment savanna areas. The D'Nyala study area, containing medium-grained sandy soils, indicated greater success in improving overall soil quality after the application of the restoration treatments containing brush packing combined with re-seeding. The Shongoane site, consisting of fine-textured, calcareous, shallow soils, indicated little success in the improvement of soil quality, although the treatments containing re-seeding and brush packing did slow the decline in soil quality indicators (soil bulk density, soil moisture, pH, EC and soil organic matter). Evidence from this study concluded that brush packing, and brush packing combined with re-seeding, increases soil quality when applied and managed correctly. The success of these restoration treatments is dependent on the soil type and co-operation of the human population managing the rangeland area. In areas with sub-optimal soil types, poor treatment application or poor rangeland management, brush packing and brush packing combined with re-seeding reduced soil quality decline. This study recommends further research on the topic with a wider variety of soil types and frequent maintenance of the study areas to lessen the effects of brush packing removal by local inhabitants.

Key Words: Bush encroachment, brush packing, rangeland management, restoration, soil bulk density, soil infiltration, soil moisture, soil nutrients, soil organic matter

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LIST OF ABBREVIATIONS

Al	:	Aluminium
BP	:	Brush packing
C	:	Clearing only
Ca	:	Calcium
CBP	:	Clearing and brush packing
CEC	:	Cation exchange capacity
CRS	:	Clearing and re-seeding
CRSBP	:	Clearing, re-seeding and brush packing
CSRSBP	:	Clearing, soil disturbance, re-seeding and brush packing
Cu	:	Copper
DEA	:	Department of Environmental Affairs
DSS	:	Decision Support System
EC	:	Electrical conductivity
Fe	:	Iron
K	:	Potassium
Mg	:	Magnesium
Mn	:	Manganese
Mo	:	Molybdenum
Na	:	Sodium
NWU	:	North-West University
P	:	Phosphorous

SOC	:	Soil organic carbon
SOM	:	Soil organic matter
UC	:	No clearing or Uncontrolled (so called “UC method”)
Zn	:	Zinc

CHAPTER 1: INTRODUCTION

1.1 Background

Land degradation is the decrease or loss of ecosystem function either by natural or human disturbances and poses a threat to arid and semi-arid rangelands of South Africa (Belayneh & Tessema, 2017; Bolo *et al*., 2019; Ward, 2005). Lack of adequate vegetative cover and decreasing or lack of soil quality (due to loss of topsoil, erosion and reduction in soil structure) and soil moisture are indicators of degraded land (Belayneh & Tessema, 2017; Bolo *et al*., 2019; Mangani, 2021; Marquart *et al*., 2019). Karlen *et al*. (1997) defines soil quality as the capacity of soils to maintain biological activity, sustain environmental quality, promote animal and plant productivity, and support human habitation. Soil quality is evaluated based on soil functions (i.e., nutrient cycling, water maintenance, buffering, carbon storage and biotic regulation) within an ecosystem (Karlen *et al*., 1997). The integration of soil physical, chemical, and biological properties are key indicators of soil quality (Barrios *et al*., 2006). Bush encroachment is also a contributing factor to land degradation in arid and semi-arid savannas and grasslands, which poses a threat to sustainable development (Belayneh & Tessema, 2017; Bolo *et al*., 2019).

According to Eldridge *et al*. (2011) and Roques *et al*. (2001), woody encroachment by shrubs and/or trees (so-called “bush encroachment”) has claimed 13 million hectares (ha) of savanna in South Africa. Bush encroachment has also been reported in semi-arid grasslands of Australia and Eurasia (Peng *et al*., 2013). Globally, savannas and grasslands account for 30-35% of net primary production (NPP) and savannas are threatened by bush encroachment and soil degradation (Belayneh & Tessema, 2017; Hutley & Setterfield, 2008; Knap *et al*., 2008). Bush encroachment is the increase (‘densification’) of woody plant abundance, which disrupts the natural equilibrium between the herbaceous layer (plants with a non-woody stem) and the woody plant layer (plants with a woody stem) densities in grasslands of arid and semi-arid areas (Bolo *et al*., 2019; Chen *et al*., 2014; Eldridge *et al*., 2011; Harmse *et al*., 2016; Knap *et al*., 2008; Roques *et al*., 2001). Belayneh and Tessema (2017) contribute to the above definition and explain that bush encroachment entails the rapid growth and/or the undesirable growth of woody species (native or invasive) in grasslands and savannas. Studies determined that grazing potential could experience a 7% decline with an 11% increase in woody species density, which could compromise resources in semi-arid rangelands (Belayneh & Tessema, 2017; Oba *et al*., 2000).

Ecosystems in African savanna biomes are used for raising livestock, industries related to wildlife, fuel wood for people and medicinal plants (Scheiter *et al*., 2018; Ward, 2005). Savannas are highly susceptible to bush encroachment and degradation by overgrazing (Hoffman, 2014; Marquart *et al*., 2019; Marquart *et al*., 2020). Bush encroachment suppresses palatable grasses

by woody species which are usually unpalatable to local livestock, thus decreasing the carrying capacity for livestock and other herbivores, threatening the livelihood of populations and economic profit in South African savannas (Belayneh & Tessema, 2017; Buitenwerf *et al*., 2012; O'Connor *et al*., 2014; Ward, 2005). Climate change, habitat loss, soil moisture, elevated carbon dioxide (CO_2), rangeland fire suppression, availability of soil nutrients, rangeland degradation and intensification of land use (such as over-grazing and the absence of rotational grazing) are accountable for the loss of biodiversity and bush encroachment in South Africa (Beylayneh & Tessema, 2017; Buitenwerf *et al*., 2012; Du Preez *et al*., 2011; Harmse *et al.* 2016; Scheiter *et al*., 2018). Domestic animals nourish and trample the herbaceous layer due to overgrazing and overstocking, causing an imbalance between the grass plant layer and the woody plant layer in rangelands (Bolo *et al*., 2019; Fynn & O'Connor, 2000; Marquart *et al*., 2019; Roques *et al*., 2001). Rangeland degradation, through overstocking and overgrazing, leads to bush encroachment and influences soil physical (compaction and aggregate breakdown), chemical (nutrient leaching, pH, diminishing of organic matter and salinization) and biological properties (Bolo *et al*., 2015; Marquart *et al.,* 2019; Marquart *et al*., 2020). Belayneh and Tessema (2017) explain that woody species could also increase resource stocks such as NPP and below-ground nitrogen and carbon.

A study conducted by O'Connor *et al*. (2014) concluded that increasing atmospheric CO_2 concentrations is the most likely driver of increasing woody densities in their savanna study areas. Scheiter *et al*. (2018) support this claim by further stating that savanna and grassland biomes are susceptible to climate change and land-use change. Inducing CO_2 fertilizing or carbon fertilizing ultimately increases the rate of photosynthesis and induces a spur in plant growth (O'Connor *et al*., 2014; Scheiter *et al*., 2018). The CO_2 fertilization effect increases water use efficiency and growth rates of trees, favouring the increase in woody densities (Buitenwerf *et al*., 2012; O'Connor *et al*., 2014; Scheiter *et al*., 2018).

To restore and mitigate bush encroached rangelands, strategies such as livestock management, bush clearing, re-vegetation (or so-called "re-seeding") and brush packing are implemented (Bolo *et al*., 2015). Bush clearing techniques comprise the removal of shrubs and trees by manually (or mechanically) cutting the stems, chemically treating the cut stems with an arboricide, or biologically by rangeland burning (Bolo *et al*., 2015; Harmse *et al*., 2016; Mangani, 2021; Roques *et al*., 2001). Brush packing is "the packing of brush (woody branches or other plant material and organic matter)" on bare degraded soils for restoration purposes (Mangani, 2021; Roques *et al*., 2001; Ward, 2005). Studies conducted by Kellner *et al*. (2021), Mangani (2021) and Naude (2019) have concluded that brush packing is a cost-effective method, which increases biomass production, enhances biodiversity and vegetation establishment, ultimately restoring degraded rangelands.

Research on the restoration of bush encroached rangelands in arid and semi-arid savannas is being conducted by the North-West University's Terrestrial Land Degradation Team in association with the Natural Resource Management Programs of the Department of Environmental Affairs (DEA). The DEA now forms part of the Department of Forestry, Fisheries and the Environment (DFFE). The goal was to increase species diversity and grass biomass production of semi-arid savanna rangeland by using a combination of bush clearing, re-seeding and brush packing as a restoration method (so-called "restoration treatment") to ultimately improve the grazing capacity. Kellner *et al*. (2021) describe a series of procedures/steps for implementing brush packing as a restoration technique and this is used in studies by Mangani (2021), Mokgosi (2018) and Naude (2019). The study (which formed part of the Bush Expert DSS) conducted by Naude (2019), evaluated brush control and brush packing as a restoration technique to restore grazing capacity of bush encroached savanna and concluded that sample areas containing brush packing indicated an increase in biomass production and ultimately improved grazing capacity. The re-seeding and brush packing combination treatment also increased species diversity. A study conducted by Mangani (2021) assessed the socio-economic benefits and ability of brush packing to improve grass diversity and aboveground biomass in areas after bush clearing was applied. This study supports the findings of Naude (2019) and indicated improvement and increase of aboveground biodiversity and biomass in the D'Nyala Nature Reserve and Shongoane communally-managed area when identical restoration treatments were applied as tested by Naude (2019). The studies conducted by Kellner *et al*. (2021), Mangani (2021) and Naude (2019) form part of the DEA project and are the basis for this study.

1.2 Problem statement

De Klerk (2004) and Ward (2005) argue that all factors involved in driving the co-existence between herbaceous and woody species (trees and shrubs), such as climatic conditions, biodiversity, parent material, soil type, soil quality and nutrient availability, should be considered to fully understand bush encroachment. O'Connor *et al*. (2014) and Scheiter *et al*. (2018) seconded this statement and concluded that elevated CO_2 concentrations and future climate conditions could trigger biome shifts, altering savannas and grasslands into woodlands and forests. The above-mentioned studies encourage management and mitigation efforts of biomes susceptible to biodiversity loss and bush encroachment. The study conducted by Naude (2019) suggested that further studies be conducted regarding the effects of brush packing on soil organic matter, soil moisture, and soil chemical and physical properties. Thus, a research or literature gap exists concerning the effects of brush packing on soil properties after the clearing of bush has commenced on arid and semi-arid areas of South Africa.

1.3 Motivation of the study

The alteration of one ecosystem function can result in ecological consequences, such as changes in soil properties, the regional carbon balance, the alteration of species interaction, and biodiversity loss (Buitenwerf *et al*., 2012; Chen *et al*., 2014; Li *et al.*, 2016). Soil is considered the anchor for all life on Earth and facilitates interactions between the environment, economy, and society (Briassoulis, 2018). Naude (2019) and Roques *et al*. (2001) explain that bush encroachment can alter soil moisture, micro-climate and nutrient conditions due to the high density of woody plant roots. Soil properties indicate a change with bush encroachment, therefore they should also indicate change regarding the application of restoration treatments to combat bush encroachment (bush clearing, re-seeding and brush packing). Sufficient knowledge of restoration methods (i.e., clearing, re-seeding, control and brush packing treatments) on soil properties and soil functions is vital to combat rangeland degradation and increase soil quality, ultimately contributing to the regrowth of herbaceous plants (Du Preez *et al*., 2011). The success of rangeland degradation management using bush clearing, re-seeding and brush packing will greatly increase with research regarding the properties of the soil component of an ecosystem. Increasing soil quality and the regrowth of herbaceous plants are vital to combat rangeland degradation and for agriculture and grazing to continue (Chen *et al*., 2014; Du Preez *et al*., 2011).

1.4 Hypothesis

The research presented in this project will provide evidence that the restoration treatments containing brush packing will improve the physical and chemical properties (so-called “soil quality indicators”) of bush encroached arid and semi-arid soils regarding: 1) soil infiltration rate; 2) soil moisture; 3) soil bulk density; 4) pH; 5) electrical conductivity (EC); 6) soil organic matter, and 7) soil nutrient status, ultimately improving soil quality.

1.5 Project aims

- Identify and compare the influence of the six restoration treatments on the soils of two bush encroached savanna areas (D’Nyala Nature Reserve and Shongoane communally-managed area) regarding the chemical and physical properties (nutrient status, pH, EC, soil bulk density, soil moisture, soil infiltration rate and soil organic matter).

- Determine whether soil type influences the success of the six different treatments in terms of soil quality.

1.6 Project objectives

- Determine the soil types of D'Nyala Nature Reserve and Shongoane communally-managed area.
- Measure the effect of all six restoration treatments on the physical and chemical soil properties of D'Nyala Nature Reserve and Shongoane communally-managed area.
- Compare the two sites with respect to the results of each restoration treatment.

1.7 Chapter overview

CHAPTER 1: INTRODUCTION

Provides an overview, background, objectives and the hypothesis of the study.

CHAPTER 2: LITERATURE REVIEW

Includes a review of published literature and concepts relevant to the study.

CHAPTER 3: STUDY AREA

Describes the locality, geology and climate of the selected study areas.

CHAPTER 4: METHODOLOGY

Discusses the field and laboratory methods implemented in the research areas.

CHAPTER 5: RESULTS AND DISCUSSION

Elaborates on the findings of the research and provides possible causes to the observations.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

Summarises the results and address the objectives of the research and provides recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Savanna Biomes

2.1.1 African savanna biome

The savanna biome forms part of a tropical grassland biome with a ground cover dominated by grass species and sparse to medium shrub and tree densities (Hutley & Setterfield, 2008; Mucina & Rutherford, 2006; Sankaran & Ratnam, 2013). Savannas account for approximately 50% of Africa's land surface and 30% of South Africa's land surface (Hutley & Setterfield, 2008; Shackleton & Scholes, 2011). The African savanna biome is characterised by two seasons: 1) hot humid summers; and 2) dry winters (2 - 8 months) (Huntley, 1982; Hutley & Setterfield, 2008). Southern Africa is characterised by fine-leaved and broad-leaved savannas. Low-laying, semi-arid areas with relatively fertile soils exhibit fine-leaved savannas dominated by Acacia species (Hutley & Setterfield, 2008). Weathered and infertile soils are characterised by bread-leaved savannas such as the *Brachystegia, Burkea africana*, and *Combretum* (Hutley & Setterfield, 2008). Rainfall in the Southern Africa savanna biome usually occurs in the summer months and most plants become dormant in the dry (winter) season and rivers tend to dry up (Hutley & Setterfield, 2008; Sankaran & Ratnam, 2013). Arid and semi-arid savannas in Southern Africa receive an annual precipitation of less than 500 mm according to the Köppen-Geiger classification of climate zones (Engelbrecht & Engelbrecht, 2015; Huntley, 1982; Hutley & Setterfield, 2008).

2.1.2 Savanna soils

Savanna soils are relatively infertile and highly weathered with a low cation exchange capacity, and most nutrients in these soils are found near the thin layer of humus at the soil surface (Hutley & Setterfield, 2008; Lock, 2013). This layer of organic matter is comprised of decomposed animal and plant material, which decays rapidly due to high temperatures (Hutley & Setterfield, 2008). Soil properties such as soil moisture, temperature and plant-available nutrients vary spatially due to discontinuous canopy cover present in savannas (Holdo & Mack, 2014). Large herbivores also impose various impacts on savanna soils through excretion, physical disturbance of soil and consumption of vegetation (Holdo & Mack, 2014).

Soils in African savanna biomes are usually highly weathered, typically porous (sand to sandy loams) and well-drained with low soil moisture-holding capacity (Hutley & Setterfield, 2008). These soils are either red in colour due to high iron content, or brownish and clay-rich (Lock, 2013). In South African savannas (with specific reference to the Limpopo ecosystem), ridge and hill tops exhibit leached gravelly or sandy soils with typically kaolinite clay, while hill slopes consist of finer soils and valleys comprised of dark-coloured swelling clays, usually montmorillonite clay

(Lock, 2013). Typical clay minerals derived from weathered primary minerals include gibbsite and kaolinite, which exhibit low cation exchange capacity (Hutley & Setterfield, 2008). Savanna soils in South Africa usually have a phosphorus deficiency due to aluminium (Al) and iron (Fe) sesquioxides restricting nutrient availability and phosphate sorption, while volatile nutrients such as sulphur and nitrogen are decreased by dry season fires (Hutley & Setterfield, 2008; Lock, 2013).

African savanna grasslands consist of four soil layers: 1) humus at the surface; 2) hardpan of laterite; 3) re-deposited silica and red clays, and 4) bedrock (Hutley & Setterfield, 2008; Lock, 2013). The most typical types of soils found in savannas include the following (Hutley & Setterfield, 2008; Lock, 2013):

- Deep sand – the most unfertile of the possible soil types. This soil type tends to be very sandy and coarse-textured with low water holding capacity, similar to the desert biome (FAO, 2021b)
- Lithosols – shallow soils consisting of mostly gravel and stones, with little fertility
- Red and yellow earths – these soils are deficient in nutrients and red soils owe their colour to the presence of Fe oxide. Red soils are found in low rainfall areas
- Lateritic – reddish soils enriched with iron and aluminium oxides and generally infertile
- Saline and alluvial – soils become saline due to the weathering of primary minerals, or when dissolved salts in the water table rise to the soil surface and accumulates due to evaporation. Alluvial soils are transported and deposited by surface water and thus these soils occur near estuaries and waterways
- Cracking clays – soils difficult to cultivate with low hydraulic conductivity, good water retention capacity and poor internal drainage (FAO, 2021a). These clays are prone to water logging and in the dry season may form deep and wide surface cracks.

2.1.3 Vegetation in African savannas

Depending on dry season length, savannas are divided into wet, dry and thornbush savannas (Mucina & Rutherford, 2006; Sankaran & Ratnam, 2013; Smith, 2016). The savanna vegetation type is characterised by continuous tall grass with an open tree canopy above (Hutley & Setterfield, 2008; Smith, 2016). In South African and Australian savannas, the rainfall gradient is directly proportional to the woody density (amount of trees and shrubs) and height of canopy cover, thus climate is a major determining factor in the dynamics of the woody layer and the herbaceous plant layer (Shackleton & Scholes, 2011).

Savanna vegetation experiences annual periods of water scarcity and thus inadequate soil moisture for continued growth in plants (Hutley & Setterfield, 2008; Smith, 2016). These periods of water scarcity dry out shallow-rooted grasses and make them prone to fire. Savanna grasses

are coarse and grow in patches to heights rarely exceeding 1.5 m (Mucina & Rutherford, 2006; Sankaran & Ratnam, 2013). During rainy periods, sandy soils supply generous amounts of moisture but dry out in warm temperatures and in the absence of continuous rain. The grassy vegetation type favours sandy soils and is dominated by C4 grasses enabling high photosynthetic rates at low water availability and high temperatures (Hutley & Setterfield, 2008). Grass-rich savannas exhibit few trees and favour sandy soils, and grasses common in South Africa include *Chloris gayana* (Rhodes grass), *Cenchrus ciliaris* (Buffalo grass) and *Themeda triandra* (Red Oat grass) (Mucina & Rutherford, 2006; Hutley & Setterfield, 2008). Tree-rich savannas exhibit less grass and favour stony soils with deep soil layers and require water during all seasons (Smith, 2016). The tree or woodland species have thick insulating bark to resist fires, long tap roots to reach the water table and trunks that store water (Hutley & Setterfield, 2008). During the dry season, leafy plants or trees are deciduous, meaning they shed their leaves to conserve water by reducing transpirational losses. Savanna trees adapt to low nutrient availability prior to leaf fall by translocating sequestered nutrients from their leaves to other tissues (Hutley & Setterfield, 2008). Common plant species found in South African savannas include the *Vachellia farnesiana* (Prickly acacia), *Prosopis* (Mesquite), *Adansonia digitata* (Baobab), *Cryptostegia grandiflora* (Rubbervine), *Opuntia* (Prickly Pear), *Burkea africana* (Wild Syringa) and *Lantana* (Mucina & Rutherford, 2006).

The structure and function of savannas are determined by herbivory, fire regime, plant available nutrients and plant available moisture (Hutley & Setterfield, 2008; Smith, 2016). Plant available nutrients and moisture are determined by climate and soil type (Hutley & Setterfield, 2008).

2.2 Rangeland degradation and bush encroachment

Rangelands are ecosystems in arid and semi-arid areas used for grazing (Bolo *et al*., 2019). Mussa *et al*. (2016) state the main drivers for rangeland degradation are natural factors such as drought and climate change while anthropogenic factors include changes in land use systems, overgrazing, overstocking, government policies and population pressure. Bush encroachment is the encroachment of woody species (trees and shrubs) which disrupts the natural equilibrium between the herbaceous plant layer and the woody or shrubby plant layer densities in grassland biomes, creating a biome shift from grasslands to woody (tree and shrub) dominated landscapes (Chen *et al*., 2014; Harmse *et al*., 2016; Mussa *et al*, 2016; Ward, 2005). Bush encroachment is a form of land degradation in South Africa and has claimed between 10 and 20 million hectares of rangeland, which resulted in a decline in biodiversity and grazing capacity (Kellner *et al*., 2021; Ward, 2005). Namibia has experienced an annual loss in agricultural productivity of N$700 million due to bush encroachment (De Klerk, 2004). Bush encroachment alters ecosystem functions such

as carbon storage capacity, fire regimes, biodiversity and herbivore carrying capacity (Buitenwerf *et al*., 2012).

The most common drivers of bush encroachment include: 1) elevated atmospheric CO_2 concentrations; 2) soil moisture and nutrient availability; 3) overgrazing; 4) overstocking; 5) fire intensity and frequency; 6) climate change; and 7) land-use (Beylayneh & Tessema, 2017; Buitenwerf *et al*., 2012; Du Preez *et al*., 2011; Scheiter *et al*., 2018). Atmospheric CO_2 concentrations increase the growth rate of trees compared to grasses, thus contributing to bush encroachment (Buitenwerf *et al*., 2012; Scheiter *et al*., 2018). Rising CO_2 and additional summer rain will also encourage bush encroachment and alien woody plant invasion (Department of Environmental Affairs, 2015; Scheiter *et al*., 2018). Animals and humans can alter the woody vegetation/grass ratio either by decreasing trees and shrubs or grass species using cultivation, grazing, feeding habits and the use of plants for fuel (Smith, 2016; Ward 2005). Browsers may push grass species to extinction by overgrazing, resulting in a vegetation profile shift from savanna to forest.

Similarly, herbivory (selective grazing) or trampling by other mammals in large populations may push tree and shrub species to extinction (Eldridge *et al*., 2016). Smith (2016) provides an example where a rise in elephant population destroyed woody plant species in the Virunga National Park, Congo, which transformed the wooded savanna into a grass savanna. An increase in grass species while woody species decrease would promote more severe fires (O'Connor *et al*., 2014). Studies on the impact of grazing on soil properties has indicated an increase in soil compaction, a reduction in biocrust cover and soil porosity, ultimately increasing soil runoff and erosion (Aubault *et al*., 2015; Byrnes *et al*., 2018; Daryanto *et al*., 2013a; Eldridge *et al*., 2014; Eldridge *et al*., 2016; Pulido *et al*., 2018). Alien plant invasions and bush encroachment also result in loss of ecosystem services and land degradation by altering the species balance (Stafford *et al*., 2017). Semi-arid savannas usually have limited water resources and climate change will increase the growth of woody biomass as a result of the carbon fertilisation effect, which will further limit water resources (Stafford *et al*., 2017). Changes in climate (rainfall and temperature) can influence evaporation and soil moisture, resulting in a decline in vegetation quantity and quality (Bolo *et al*., 2015; Mussa *et al*., 2016). Climate change thus contributes to rangeland degradation and bush encroachment.

2.3 Restoration treatments

Different types of restoration methods or so-called "treatments" exist to reduce woody (tree and shrub) species density and improve grass establishment. These include tree and shrub/bush clearing (chemical or mechanical), cultivation (re-seeding), fertilization and brush packing (Barac,

2003; Mussa *et al*., 2016; Naude, 2019). Clearing includes manual or mechanical cutting of tree and shrub species with a stem of more than 10 cm to knee height and chemically treating the cut stump with an arboricide using one of the following active ingredients: ethiozin ($C_9H_{16}N_4OS$), picloram ($C_6H_3Cl_3N_2O_2$) or triclopyr ($C_7H_4Cl_3NO_3$) (Naude, 2019). Biological means of bush clearing include the burning of rangelands (Bolo *et al*., 2015). Grass densities can be re-established after restoration treatments such as bush clearing by either natural regeneration of seed in the soil or re-seeding (Mussa *et al*., 2016). Re-seeding is used to re-vegetate the soil-seed bank using perennial grass species. Brush packing is the "packing of brush (trees, shrubs, or twigs)" on the bare soil surface for restoration purposes (Naude, 2019). The goal of bush control is to create a suitable habitat for increasing grass production to restore the grass/woody balance and ultimately satisfy grazers (Mussa *et al*., 2016). Studies conducted by Naude (2019) and Mangani (2021) suggest that brush packing is used to increase water infiltration, add soil organic matter (SOM) to the soil and allow the seed bank to build up again by providing a barrier to restrict grazers. Brush packing provides surface soil and vegetation with a protective cover against rain splash, erosion, surface runoff, grazers and severe sunburn, thus assisting in surface temperature regulation and the restriction of soil and organic litter movement by wind and water, ultimately combatting erosion (Naude, 2019). Mussa *et al*. (2016) argue that bush removal generates changes in microbial communities and soil chemistry, thus promoting either grass species establishment or encroachment (bush re-growth).

2.4 Soil properties

Soil properties such as texture, nutrient status, salinity and pH all differ regarding different types of savanna soils (Hutley & Setterfield, 2008; Lock, 2013; Tinley, 1982). Sandy soils restrict root growth at higher densities and are less likely to encourage surface crusting, while clayey soils restrict roots at lower densities and are more likely to encourage surface crusting and decrease infiltration rates (Soil Quality Institute *et al*., 2003). Soil texture is thus considered an important factor when analysing soil variables. Soil classification is needed to determine soil properties such as texture, structure, and type. Various soil properties are indicative of density, moisture retention and infiltration rate.

2.4.1 Soil moisture

Soil moisture is the most influential factor affecting the land productivity and spatial distribution of grasslands and savannas (Marquart *et al*., 2019; Tinley, 1982). Volumetric water content (v/v) is used to measure soil moisture and is the proportion of water volume to soil volume, calculated using Equation 2.1.

$$\theta_w = \frac{\theta_m}{D_s} \cdot 100$$

Equation 2.1

where θ_w is the percentage of volumetric water, θ_m is the soil moisture volume and D_s is the total soil volume (Reddy, 2002). Gao *et al*. (2017) explain that ecological, hydrological, and agricultural systems are influenced by soil moisture in the root-zone profile (upper 200 cm of soil). Surface soil moisture is the soil moisture contained in soil aggregates or pores of the upper 10 cm of the ground surface. Root-zone moisture partially determines infiltration, runoff and water availability to vegetation (Gao *et al*., 2017). Reddy (2007) expresses the importance of water content as an index used for establishing the correlation between soil properties and the interaction between those properties and soil production. The ratio of the mass of "free" or pore water to the mass of dry soil solids in the soil is defined as the water content and is expressed as a percentage (Reddy, 2002). Water content determines fine-grain soil consistency and is also used to express the phase relationship of solids, water and air in a given volume of soil (Reddy, 2002).

The variability in climate, land-surface conditions and soil moisture control nutrient availability in the soil (De Klerk, 2004; Lawrence & Hornberger, 2007). In rain-fed semi-arid regions, soil moisture is the source of water for plants and crops and serves as a reagent in hydrolytic and photosynthetic processes for plants, as well as a solvent for solutes such as salts (Mweso, 2003). Soil moisture availability is essential to plant growth and is affected by pore spaces in the soil. Processes such as nitrification and evaporation, as well as vegetation type, are dependent on soil moisture, highlighting the importance thereof (Lawrence & Hornberger, 2007). Plant available moisture is the most significant ecological determinant in the competition between grassy and woody species in savannas (Hutley & Setterfield, 2008).

2.4.2 Surface crusting, penetration resistance and infiltration

Infiltration rate can be defined as the speed or velocity at which water enters and moves through the soil and is usually measured in millimetres per hour (Soil Quality Institute *et al*., 2003). For example, an infiltration rate of 10 mm/h indicates that a 10 mm water layer will take one hour to infiltrate into the soil.

The response of soil under precipitation is dependent on the infiltration rate, thus determining the quantity of water entering the unsaturated soil zone (Mweso, 2003). Infiltration rate increases with larger soil pore sizes and a low infiltration rate can result in excess surface water, an increase in water runoff and ultimately erosion (Mweso, 2003). A soil's properties determine how the soil will respond to a lack of cover (Gregory *et al*., 2015). Crusting, penetration resistance and soil texture

determine the infiltration rate of soils. Surface crusting (a form of compaction) restricts water infiltration, plant root penetration and seedling emergence, which ultimately results in soil erosion and poor soil quality (Soil Quality Institute *et al*., 2003). High bulk densities exist in compacted soils with little pore space (Soil Quality Institute *et al*., 2003). Sandy soils are more susceptible to structure loss, while clayey soils are susceptible to compaction caused by cohesion. Surface runoff and soil erosion are increased due to an increase in raindrop impact and a reduction in soil infiltration rate, caused by a decrease in grass species density (Soil Quality Institute *et al*., 2003).

Soils in Africa are nutrient-poor and prone to waterlogging in rainy seasons, due to ground flatness or the presence of a hardpan near the soil surface (Mweso, 2003; Soil Quality Institute *et al*., 2003). These soils are often associated with decreased penetrability to tree and grass roots, ultimately curbing vegetation growth (Mweso, 2003).

2.4.3 Soil chemical properties

2.4.3.1 Soil organic matter and soil organic carbon

The carbon pool in soil consists of soil organic matter (SOM) and fresh organic matter (FOM). FOM includes root exudates and plant litter, where SOM is considered organic compounds containing carbon and consists of material no longer recognisable as plant litter (Thiessen *et al*., 2013; Zhang, S. *et al*., 2019). Sources of SOM include applied organic fertilizer, microbial, plant and animal residues at various stages of decomposition (Zhang, S. *et al*., 2019). Soil organic carbon (SOC) is a more recalcitrant carbon pool and is a measure of the carbon contained in SOM. The main products from conversion and composition of SOM are methane (CH_4) and carbon dioxide (CO_2) (Zhang, S. *et al*., 2019).

The studies conducted by Li *et al*. (2016) provided evidence that bush encroachment in grasslands indicated an increase in SOC, while studies conducted by Lett *et al*. (2004) indicated a decrease or minor changes. Soil properties were indicated as the most important factor influencing SOC regarding bush encroachment (Li *et al*., 2016). Abiotic factors such as soil moisture and temperature also influence SOM decomposition and soil respiration (Li *et al*., 2016). Different particle-size structures and pH levels influence the changes in SOC, while soil texture combined with other chemical and physical properties of soil affects SOC accumulation (Li *et al*., 2016). SOC increases in sandy soil and decreases in clay or silty soils, due to coarse-textured soil exhibiting a significant capacity to increase SOC compared to finer textured soils such as silt or clay regarding bush encroachment. (Li *et al*., 2016). Thus, changes in SOC content regarding bush encroachment varied with biotic (plant) and abiotic (soil and climate) factors. Carbon stocks in soil decrease with a decrease in soil organic matter (SOM) or with decreasing SOM degradation (Thiessen *et al*., 2013). SOM influences water retention and drainage, which reduces the risk of

nutrient leaching and soil erosion (Li *et al*., 2016). Thus, SOM improves soil quality and is an important soil quality indicator.

Natural vegetation types determine carbon stocks. Savannas usually have low soil fertility, cation exchange capacity and SOM, but variations do exist (Hutley & Setterfield, 2008; Thiessen, 2013). According to Thiessen (2013), soil fertility is greatest near trees where tree litter and dead leaves drop and decompose to release nutrients. An increase in trees and shrubs increases terrestrial carbon stocks, thus combating bush encroachment might result in a loss of carbon stocks (Stafford *et al*., 2017).

2.4.3.2 Soil pH and salinity

Soil pH is a measure of soil acidity or alkalinity, while electrical conductivity (EC) is a measure of soil salinity (Brady & Weil, 2014). Natural processes such as the leaching of cations and decomposition of organic matter can cause a change in soil pH. Arid and semi-arid areas can exhibit soils that contain excessive salt (Ca, Mg and Na), which affects the water and soil balance by hindering plant growth (Artiola *et al*., 2019; USDA, 2014). EC correlates with ammonia, chloride, sodium, sulphate, nitrates and potassium, and soil EC is usually inherited form from parent materials. Land management, irrigation and cropping can influence salt levels in soils (USDA, 2014). Clayey soils conduct more electrical current compared to sand and silt particles. A low EC level indicates low nutrient availability (which could lead to nutrient deficiency, and a very high EC indicates an excess of nutrients (which could give rise to toxicity), both of which inhibit plant growth (Ding *et al*., 2018). The optimal EC varies according to the plant's needs and the environment (Ding *et al*., 2018).

Cation exchange capacity (CEC) (expressed in $cmol_c/kg$) is an indication of soil fertility and the soil's capacity to hold exchangeable cations (Hazelton & Murphy, 2007; Zhang, S. *et al*., 2019). This inherent soil characteristic provides a buffer against soil acidification and determines the ability of soils to hold onto nutrients (Zhang, S. *et al*., 2019). A higher CEC is usually present in SOM and soils with high clay fractions. Nutrient retention in the topsoil of sandy soils is reliant on SOM (Hazelton & Murphy, 2007). Near-neutral pH provides greater CEC development in SOM compared to acidic conditions (Zhang, S. *et al*., 2019). Acidification through SOM decomposition in soil and/or the addition of fertilizer can decrease CEC (Hazelton & Murphy, 2007). Cation deficiencies such as magnesium and potassium develop in low CEC soils.

2.4.4 Bulk density and compaction

The most important variable identified in calculating SOM and soil quality is the measurement of soil bulk density (the dry soil mass per unit volume) (Gebre, 2018; Nawaz *et al*., 2013). It

influences plant nutrient availability, rooting depth, soil micro-organism activity and infiltration (Reddy, 2016). Table 2.1 below illustrates the general relationship between plant growth or root restriction and bulk density for different soil textures, using USA examples. Soil bulk density can also be used to measure soil compaction and different methods of measuring soil bulk density yield different results (Soil Quality Institute *et al*., 2003), thus selecting an adequate method is important when measuring soil density (Gebre, 2018). Soil compaction is defined as the decrease in void spaces between soil grains resulting in an increase in bulk density (Nawaz *et al*., 2013). Compaction can negatively affect soil biodiversity, soil chemistry and plant growth, depending on soil texture and soil water content (Nawaz *et al*., 2013). Soil compaction and an increase soil bulk density restricts root growth and reduces soil total porosity, reducing soil infiltration rate and decreasing oxygen diffusion (Nawaz *et al*., 2013). A decrease in soil infiltration can contribute to surface water logging and an increase in runoff. According to Silveira *et al*. (2010), a significant decrease in bulk density could lower CO_2 efflux (carbon mineralization) and ultimately contribute to a decrease in soil quality.

Table 2.1: The effect of soil bulk density on root/plant growth based on soil texture (Minnesota Pollution Control Agency, 2021; USDA, 1987).

Soil texture	Ideal bulk densities (g/cm^3)	Bulk densities that may affect plant growth (g/cm^3)	Bulk densities that restrict root growth (g/cm^3)
sands, loamy sands	<1.60	1.69	>1.80
sandy loams, loams	<1.40	1.63	>1.80
sandy clay loams, loams, clay loams	<1.40	1.6	>1.75
silts, silt loams	<1.30	1.6	>1.75
silt loams, silty clay loams	<1.40	1.55	>1.65
sandy clays, silty clays, clay loams (35-45% clay)	<1.10	1.49	>1.58
clays (>45% clay)	<1.10	1.39	>1.47

CHAPTER 3: STUDY AREA

3.1 Location and climate

Both study areas are situated in the Limpopo province and Waterberg District Municipality (Lephalale Local Municipality, 2017; Lephalale Local Municipality, 2018). The D'Nyala Nature reserve is a site located 15 km south-east of Lephalale and 60 km south-west from Shongoane, at approximately S 23° 44' and E 27° 48' (Figure 3.1). Both study areas are located in the Central Bushveld Bioregion, which boasts the highest number of vegetation types, with an average altitude of 1000 m above sea level (Mucina & Rutherford, 2006). The study areas are located in the Ellisras-Limpopo Basin and the topography is relatively flat - 0.5-to-1-degree slopes or concave midslopes (Bohlweki Environmental (Pty) Ltd., 2006; GCS Water & Environmental Consultants, 2022; Kongiwe Environmental (Pty) Ltd., 2017; Lephalale Local Municipality, 2017). The nature reserve covers an area of 8 281 ha and is a conversion land-use type (Lephalale Local Municipality, 2017; Lephalale Local Municipality, 2018).

Shongoane communally-managed area, also known as Ga-Shongoane, is a rural site located approximately 40 km north-east of Lephalale at approximately S 23° 30' and E 28° 7' and exhibits a communal land-use type of 1 823 ha. The Waterberg District consists mainly of game farms, commercial farms, small farmers, small towns, and rural settlements, while a smaller area comprises conservation, mining, and urban settlements (Lephalale Local Municipality, 2017; Lephalale Local Municipality, 2018; Scheiter *et al*., 2018). The municipal area also consists of degraded woodlands, thickets, bush clumps and forests (Lephalale Local Municipality, 2017).

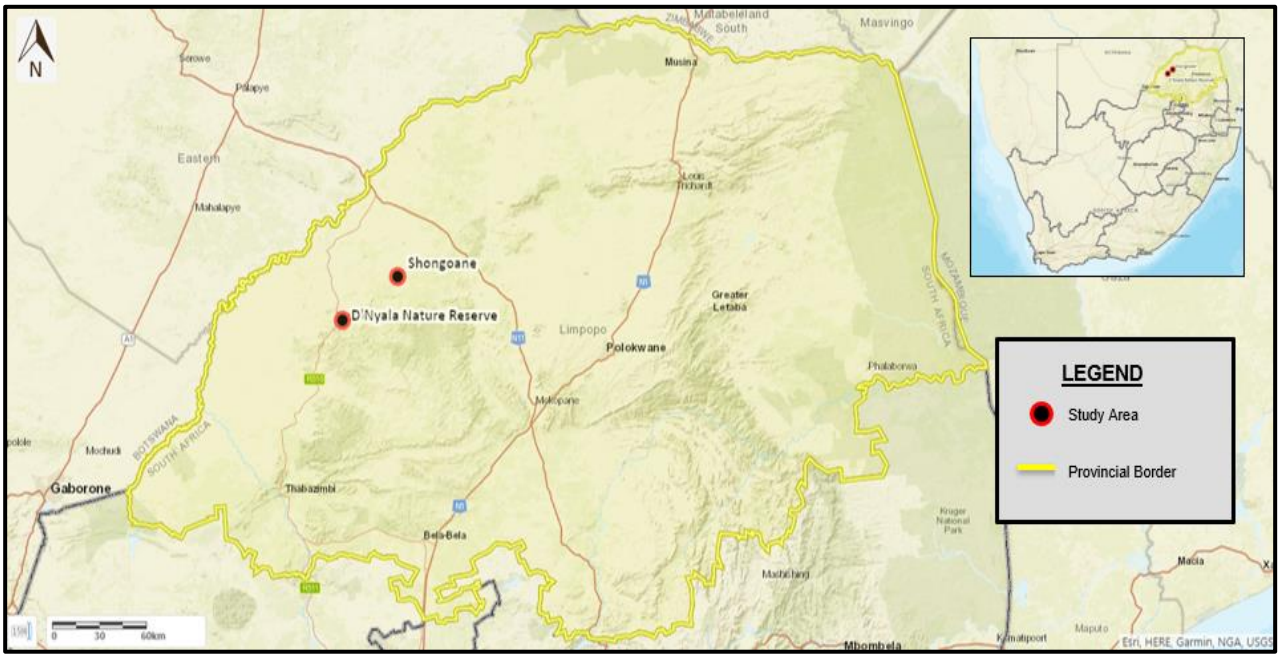

Figure 3.1: Location of Shongoane communally-managed area and the D'Nyala Nature Reserve in the Limpopo province of South Africa (created using ArcGIS 10.3; Esri, 2014).

The study areas form part of a semi-arid region with climate typically associated with the savanna biome and share similar climate conditions to Lephalale in the Limpopo province and the average climate for Lephalale for the past 10 years is summarised in Table 3.1 (Scheiter *et al*, 2018; World Weather Online, 2022). The Central Bushveld Region has a 79% of mean annual soil moisture stress, thus 79% of days the evaporation demand is double the supply of soil moisture (Mucina & Rutherford, 2006). The long-term annual rainfall of Lephalale is estimated between 400-450 mm and the rainy season for Lephalale starts in October and lasts up until March, providing the area with rain in the summer and temperatures varying between 25 °C – 39.2 °C, but daily maximums of >40 °C have been recorded (Bohlweki Environmental (Pty) Ltd., 2006; Engelbrecht & Engelbrecht, 2015; Hutley & Setterfield, 2008; Lephalale Local Municipality, 2018; Mangani, 2021; Mucina & Rutherford, 2006; Roffe, 2019). In the winter season temperatures range between 4 °C – 20 °C. Lephalale receives its lowest average monthly rainfall in July and August (<0.2 mm per month), while the highest average monthly rainfall occurs in December and January (100-300 mm per month) as seen in Figure 3.3. Temperatures vary between 4 and 20 °C in the winter months and between 17 and 32 °C in the summer months (Engelbrecht & Engelbrecht, 2015; Mangani, 2021; Mucina & Rutherford, 2006; (Lephalale Local Municipality, 2018). The highest rainfall was recorded in December, January and February for the 2019 and 2020 year. The maximum, minimum and average temperatures of Lephalale for 2010 to 2022 are illustrated in Figure 3.2 and the average rainfall (mm) and rainy days of Lephalale for 2010 to 2022 are illustrated in Figure 3.3

Table 3.1: Lephalale climate for the years field work commenced (World Weather Online, 2022)

		Max (°C)		Min (°C)		Rainfall (mm)		Rain days	
	Year	2019	2020	2019	2020	2019	2020	2019	2020
Month	January	28	27	17	17	298.8	156.4	8	6
	February	29	27	17	17	89.6	152	6	5
	March	30	27	15	16	15.4	16	2	2
	April	26	25	14	14	37.6	41.9	3	3
	May	25	22	10	11	0.1	0	0	0
	June	21	19	7	7	0.1	1.9	0	1
	July	21	19	6	6	0	0	0	0
	August	25	23	9	8	0	0.2	0	0
	September	27	27	10	13	1.4	5.3	1	1
	October	30	28	14	17	22.3	110.2	1	4
	November	29	28	16	17	209	146.3	5	6
	December	27	27	16	17	102.8	166.7	7	8

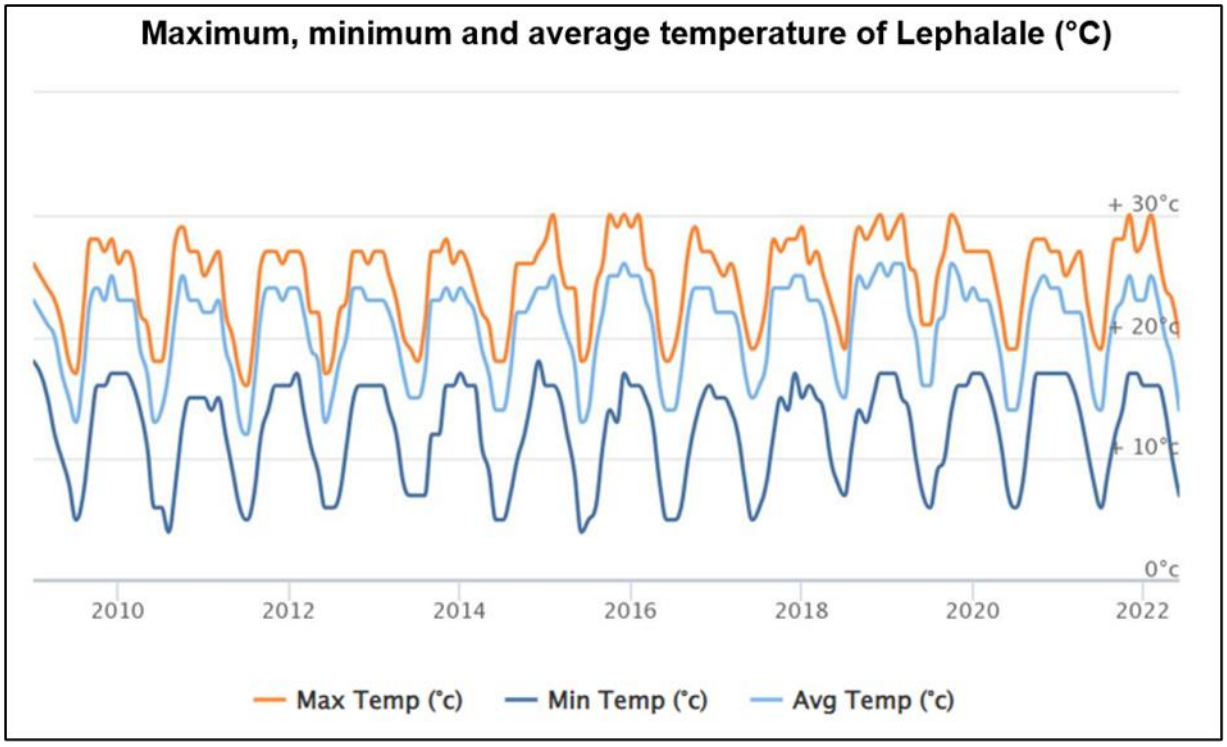

Figure 3.2: The maximum, minimum and average temperatures of Lephalale for 2010 to 2022 (World Weather Online, 2022)

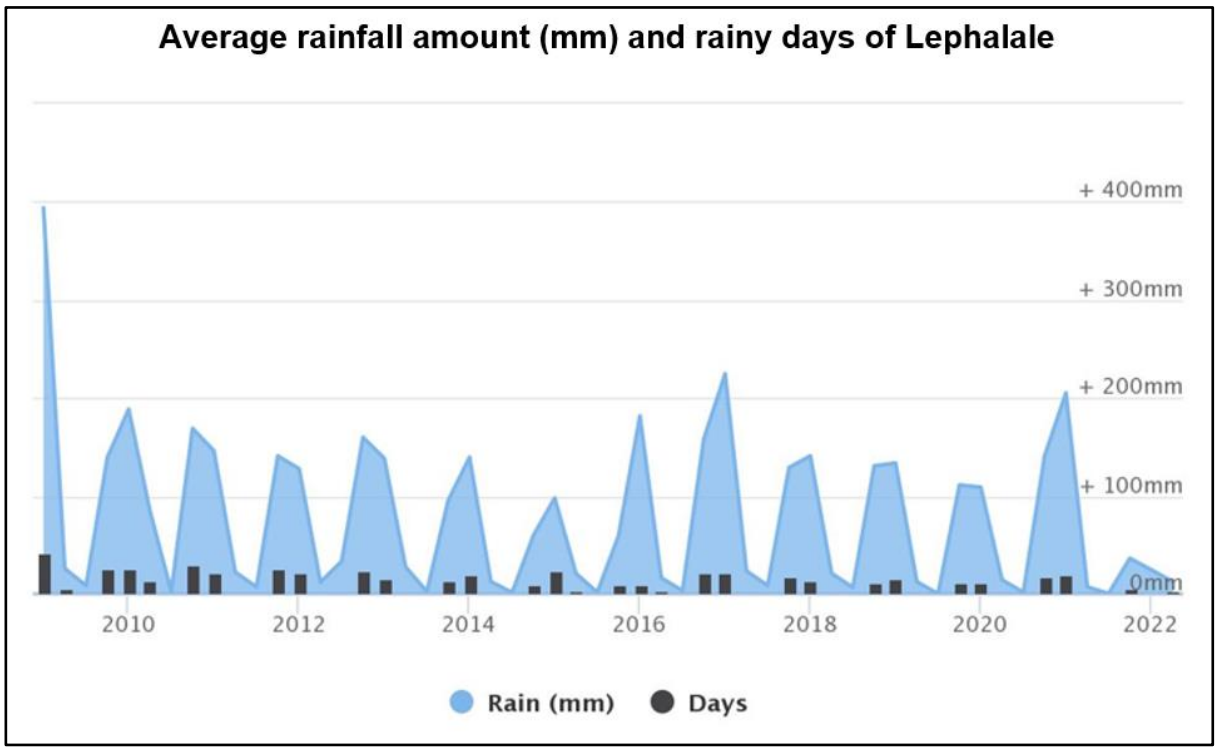

Figure 3.3: The average rainfall (mm) and rainy days of Lephalale for 2010 to 2022 (World Weather Online, 2022)

3.2 Geology and soil

The geology of the study areas was obtained by using the 1:250 000 scale Geological Map of Ellisras 2326 (Brandl, 1993). Although both study areas are geographically close in proximity, the difference in geology is evident (Brandl, 1993; Corcoran *et al*., 2013). D'Nyala Nature Reserve exhibits the uppermost Mogalakwena Formation of the Precambrian Waterberg Group, consisting of coarse-grained purplish/beige brown granular sandstone, quartz-conglomerate and interbedded siltstone (Bamford, 2014; Brandl, 1993; Corcoran *et al*., 2013). Chert and ferricrete might also be present. According to Corcoran *et al*. (2013), the Mogalakwena formation was formed in fluvial environments and can contain muscovite and chlorite as accessory minerals. Mucina *et al*. (2014) reported Waterberg light brown sandy soil or Kalahari sand overlying lime in the area. These soils were identified as yellow, red, or greyish in colour with a high base status (Bohlweki Environmental (Pty) Ltd., 2006; Kongiwe Environmental (Pty) Ltd., 2017; Mucina *et al*., 2014).

Geology of the Shongoane study area is predominantly the northern limb/lobe of the Bushveld Igneous Complex, the Villa Nora Sub-limb (Brandl, 1993). The existing lithology comprises one or more of the following rocks: anorthosite, gabbro, norite and/or gabbro-norite (Bamford, 2014; Brandl, 1993; Hattingh & Pauls, 1994; Van der Merwe, 2007). Breccia, calcrete and/or magnetite

might also be present in the landscape. Due to the composition of the above-mentioned rocks, the soil composition found in the area will likely be more clayey than sandy. Mucina *et al*. (2014) determined that the majority of soils at the Shongoane study are saline with high concentrations of calcium. Clay minerals such as ilmenite, kaolinite and halloysite are probable. Soils found in the Shongoane study area will most likely be Kalahari sand overlying lime or semi-arid brown soils overlying calcareous crusts (Bohlweki Environmental (Pty) Ltd., 2006; Kongiwe Environmental (Pty) Ltd., 2017; Mucina *et al*., 2014; Van der Merwe, 2007).

3.3 Vegetation and landscape

The Limpopo province comprises diverse vegetation types due to environmental gradients (Mucina & Rutherford, 2006; Scheiter *et al*., 2018). Mucina and Rutherford (2006) classify the Limpopo province as savanna, except for small grassland patches.

According to Mucina *et al*. (2014), the Limpopo Sweet Bushveld vegetation type is found in the D'Nyala Nature Reserve study area (Figure 3.4). This flat savanna plain includes various trees, shrubs, herbs, grasses and graminoids. The Roodeberg Bushveld vegetation type is found in the Shongoane study area (Figure 3.4) with a poorly developed grass layer and various woodlands (Geocortex Viewer, 2018; Mucina *et al.*, 2014). Shongoane features a combination of relatively flat plains and slightly undulating plains. In a study conducted by Mangani (2021) the following woody- and grass species were found at the D'Nyala and Shongoane areas (Table 3.2):

Table 3.2: Summary of woody and grass species at the study areas (Mangani, 2021)

Woody species	Grass species
Asparagus laricinus (Bushveld Asparagus)	*Andropogon chinensis* (Hairy Blue grass)
Combretum imberbe (Leadwood)	*Aristida adscensionis* (Annual Three-awn, Annual bristle grass)
Combretum zeyheri (Bushwillow)	*Aristida bipartita* (Rolling Three-awn grass)
Dichrostachys cinerea (Sickle bush)	*Aristida canescens* (Pale Three-awn grass)
Dombeya rotundifolia (Wild pear)	*Aristida congesta* (Spreding Three-awn, Tassel Three-awn grass)
Grewia bicolor (White raisin)	*Aristida diffusa* (Iron grass)
Grewia flava (Velvet raisin or Wild currant)	*Aristida rhinochloa* (Large-seeded Three-awn grass)
Grewia flavescens (Sandpaper raisin or Rough-leaved raisinbush)	*Aristida stipitata* (Long-awned Three-awn grass)
Lantana camara (Cherry pie)	*Bothriochloa radicans* (Stinking grass)
Sclerocarya birrea (Marula)	*Bracharia deflexa* (False Signal grass)
Senegalia mellifera (Black thorn)	*Bracharia distachya* (Armgrass millet, Green summer grass)
Tarchonanthus camphoratus (Camphor bush)	*Cenchrus ciliaris* (Blue Buffalo grass)
Vachellia tortilis (Umbrella thorn)	*Centropodia glauca* (Gha grass)
Ziziphus mucronata (Buffalo thorn)	*Chloris gayana* (Rhodes grass)
	Chloris virgata (Feathered Chloris grass),
	Cynodon dactylon (Bermuda grass, Buffalo grass, Couch grass)
	Cynodon nlemfuensis (Star grass)
	Digitaria eriantha (Finger grass)
	Digitaria longiflora (False Couch Finger Grass)
	Digitaria ternata (Black-seed Finger grass)
	Enneapogon cenchroides (Nine-awn grass)
	Enneapogon desvauxii (Nine-awn Pappus grass)
	Eragrostis curvula (Weeping Love grass)
	Eragrostis lehmaniana (Lehmann's Love grass)
	Eragrostis pallens (Broom Love grass)
	Eragrostis rigidior (Broad-leaved Curly Leaf grass)
	Eragrostis tef (Teff grass)
	Eragrostis trichophora (Hairy Love grass),
	Melinis repens (Natal Red Top grass)
	Panicum deustum (Broad-leaved Panicum)
	Panicum maximum (Guinea grass)
	Perotis patens (Cat's Tail grass)
	Pognarthria squarrosa (Herringbone grass)
	Schmidtia pappophoroides (sand Quick grass)
	Tragus berteronianus (Common Carrot-seed grass)
	Urochloa mosambicensis (Bushveld Signal grass)
	Urochloa panicoides (Graden Signal grass)

Figure 3.4 was created using Geocortex Viewer from the South African Institute of Biodiversity (SANBI) website and illustrates both study areas and their corresponding vegetation type).

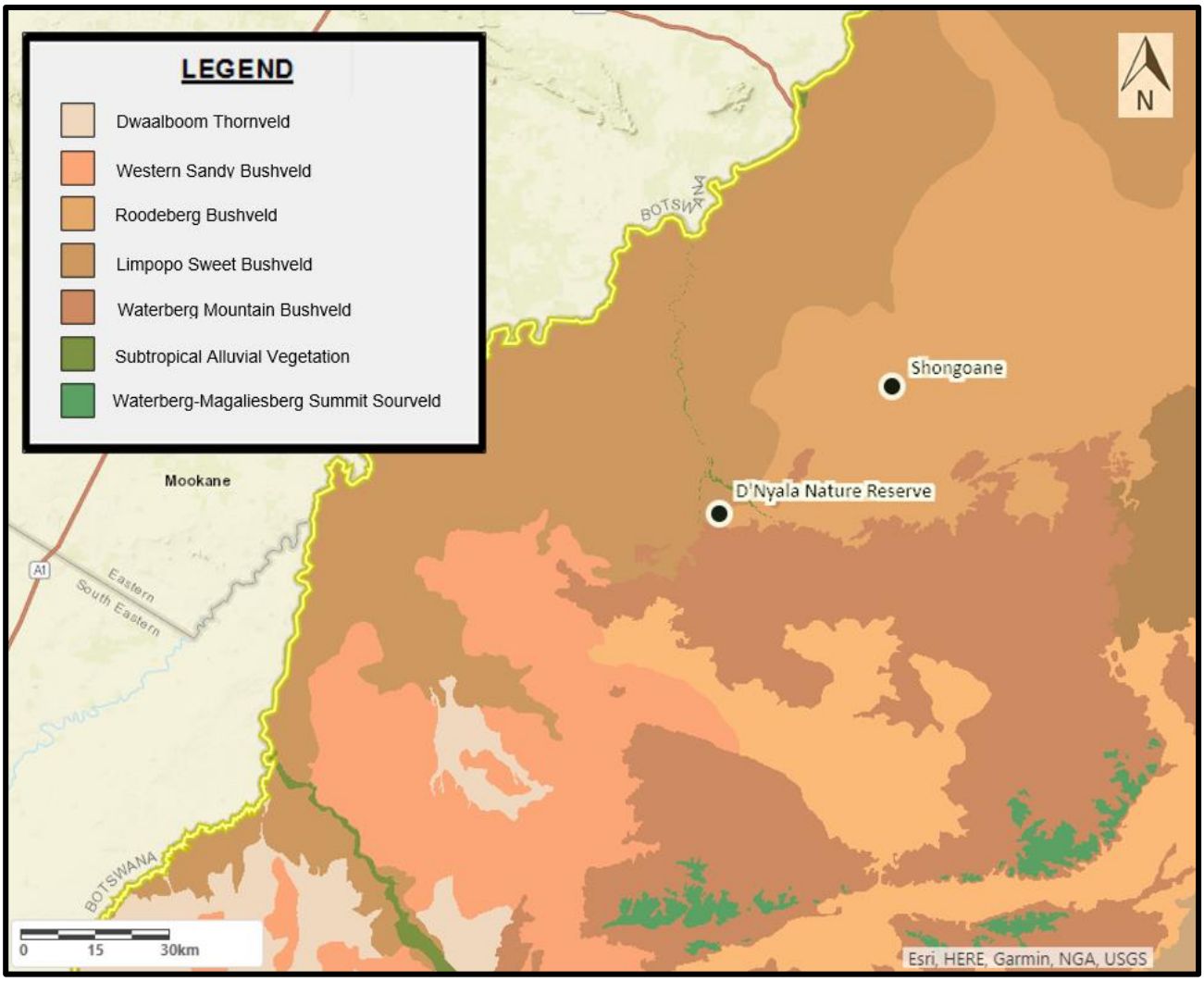

Figure 3.4: Vegetation types of study areas (created using ArcGIS 10.3; Esri, 2014)

CHAPTER 4: METHODOLOGY

This chapter describes the site layout, different restoration treatments, analytical and data processing methods conducted in this research. Fieldwork or field surveys took place February 2019 and February 2020 (towards the end of the growing season) at each study site followed by soil analysis at two laboratories: Eco-Analytica® (an independent laboratory) and the NWU Potchefstroom soil science laboratory.

4.1 Field survey

4.1.1 Site layout and methods

Soil sampling and field analysis were conducted using the grid sampling procedure. The study areas were identified in February 2017 by Mangani (2021) and severely degraded areas (areas with little or no grass cover) were selected. Each study area was divided into three blocks and each with six plots. Managani (2021) chose sampling blocks based on vegetation species homogeneity and distributional patterns. Each of the six plots represents a different restoration treatment. The three blocks represent each treatment replicated three times at each site in no particular order. Thus, a study area consisted of 18 restoration plots of each 20 x 20 metres (400 m^2), with a 2.5 m spacing between each plot and a 7 m spacing between each block. The six restoration treatments are (Figure 4.2 and Figure 4.3):

CSRSBP : Clearing, soil disturbance, re-seeding and brush packing

C : Clearing only

CBP : Clearing and brush packing

CRS : Clearing and re-seeding

CRSBP : Clearing, re-seeding and brush packing

UC : No clearing or uncontrolled (also referred to as “UC method”)

Bush clearing was done by manually and mechanically cutting the woody vegetation using handsaws and chainsaws according to DEA bush clearing standards, which include: 1) woody plants with a stem diameter of 15 cm or smaller; 2) woody plants at knee height or shorter than 2.5 m; and 3) to cut/clear 75% of the trees and shrubs. The cut stems/stumps were treated chemically using the hand-spray technique with an arboricide (chemical herbicide), in this study specifically Kaput gel (with picloram and triclopyr as active ingredients) (Naude, 2019; Mangani,

2021). The following coated grass seeds were sown on the plots containing re-seeding as a restoration treatment for both areas using the hand-broadcast method: *Cenchrus ciliaris, Chloris gayana, Cynodon dactylon, Digitaria eriantha* and *Eragrostis curvula*. No irrigation or fertilizer was added, and one restoration treatment (CSRSBP) included soil disturbance (<5 cm) using shovels, rakes and pitchforks before re-seeding/sowing (Naude, 2019). The plots containing brush packing (CSRSBP, CBP and CRSBP) were evenly and loosely covered with the cleared/cut brush (branches, leaves and woody twigs) to a height of 1.5 m. An example of a typical site layout is illustrated in Figure 4.1, where a block with all six treatments is shown in arial view. The treatments in Figure 4.1 are as follows: 1) CBP, 2) CRS, 3) CRSBP, 4) CSRSBP, 5) UC and 6) C. Figure 4.2 and Figure 4.3 represents the site layout and treatment order for the Shongoane communally-managed area and D'Nyala Nature Reserve sites, respectively.

Figure 4.1: Arial view of one block at the D'Nyala study area indicating the six restoration treatments (Mangani, 2021)

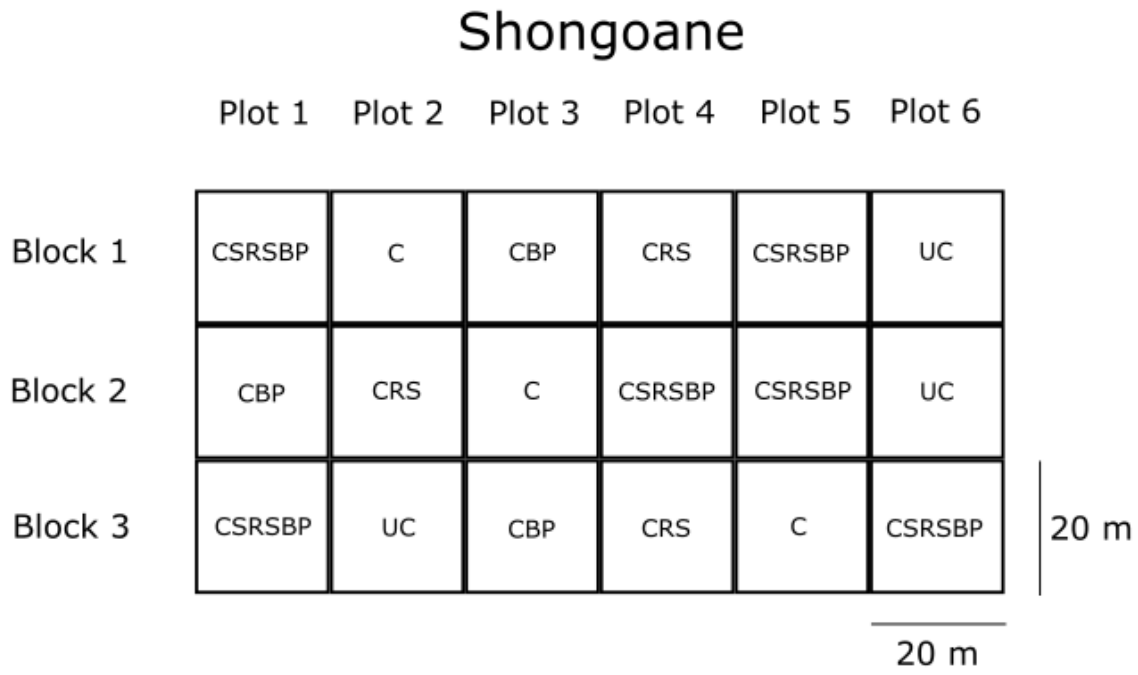

Figure 4.2: Site layout and restoration treatment order of the Shongoane communally-managed area

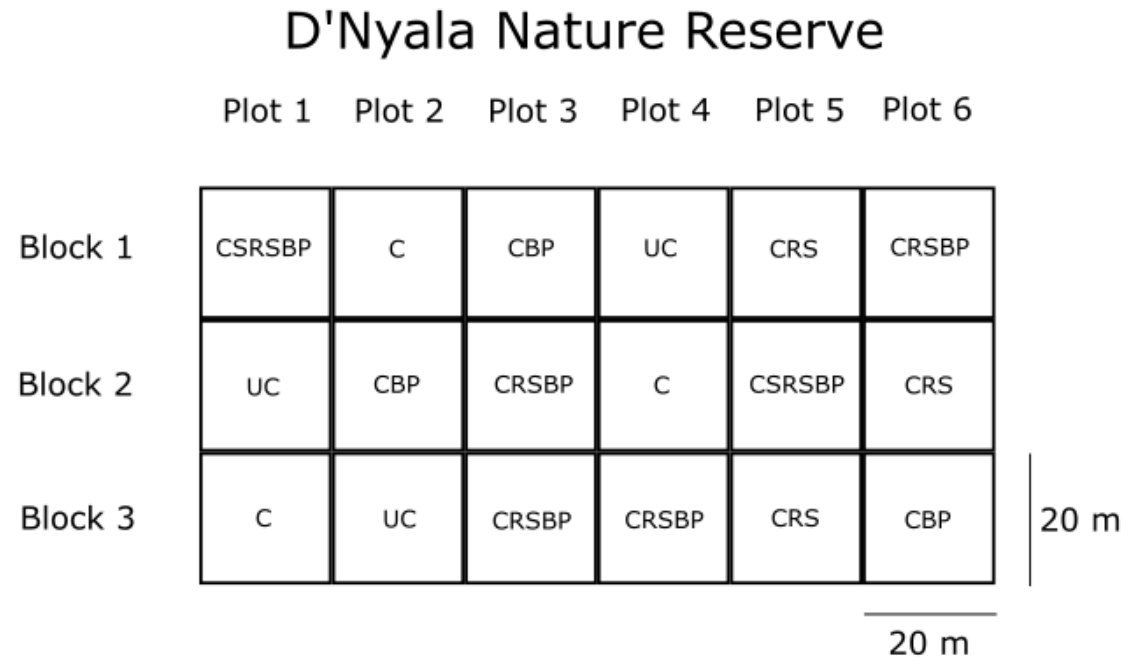

Figure 4.3: Site layout and restoration treatment order of the D'Nyala Nature Reserve site

4.1.2 Soil sampling

A hand auger was used to drill holes at the centre of each plot. The extracted soil was visually observed to determine soil properties and analysed to determine the soil form (Section 4.1.4 below). Each soil horizon was sampled, bagged and tagged for further laboratory analysis. Five replicate samples were taken at each plot (18 samples in total for each study area) using Kopecky rings. The five samples were taken as follows: one in the centre, two in the top corners and two at the bottom corners of the plot (Figure 4.4). The average of the replicate samples was used to perform loss-on-ignition analysis and soil bulk density. Soil samples were collected and sampled according to laboratory standards prescribed by the literature (Hossain *et al*., 2021; Jones, 2001). Figure 4.4 illustrates grid sampling and the method in which soil sampling and *in-situ* testing were conducted.

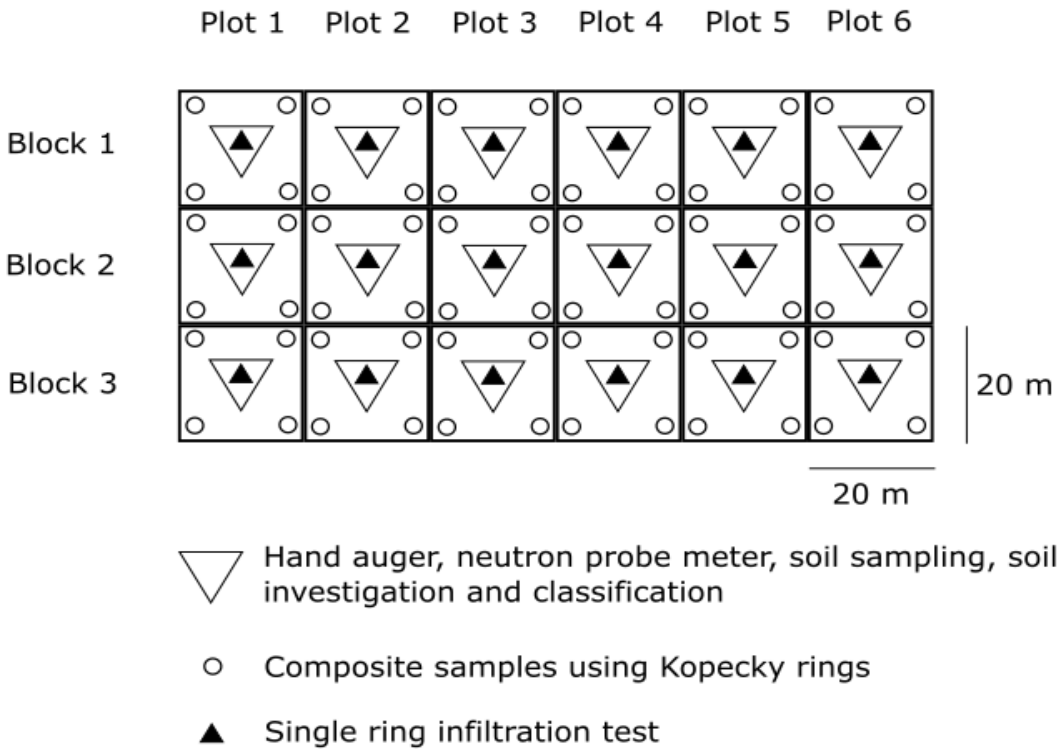

Figure 4.4: Sampling layout and method representation

4.1.3 Soil infiltration rate

A Single ring infiltration test was conducted to estimate the soil infiltration rate, using an infiltration ring as stipulated by ASTM D 5126 standards (Riverside County Flood Control and Water Conservation District, 2011). An infiltration ring is a cylindrical ring consisting of an 11 cm diameter

and 50 cm length that is driven approximately 5 cm into the soil. One litre of water was poured into the ring. Care was taken to release all the water at the same time and not to disturb the soil surface with the water impact by using plastic wrap to cover the ring before pouring water onto it. The plastic wrap was gently pulled off releasing all the water at once. The timer was started immediately once the water has been released by the plastic wrap. Once all water was drained into the soil and only a small layer was glistening on the soil surface, the timer was stopped, and the time was noted. The test was conducted multiple times on one plot for data accuracy. The infiltration rate was estimated by determining the amount of time it takes for water to drain into the soil (Riverside County Flood Control and Water Conservation District, 2011). Figure 4.5 illustrates a single ring infiltration test done at one of the plots.

Figure 4.5: Demonstration of a single ring infiltration test

4.1.4 Visual classification of soil

The book 'Soil classification: A Natural and Anthropogenic System for South Africa' (Soil Classification Working Group, 2018) and a 'Munsell Colour Chart' (Munsell Color, 1994) were used in the field to determine the soil forms of the four study areas according to adapted ASTM

D2488 standards (ASTM International, 2017). The ‘hand texturing’ method or texture-by-feel analysis modified from Thien (1979) was used to estimate soil clay content and texture in the field. Approximately 25 g of moist soil is manipulated into different shapes and the soil texture is determined by the coherence or ability of the soil to remain in either a spherical, cylindrical, or bent cylindrical shape.

4.2 Analytical methods

The preparation of soil samples at the NWU Potchefstroom soil science laboratory entails samples to be air-dried at temperatures not exceeding 38 °C (ideally 20 °C to 27 °C). The samples should be crushed using a mortar and pestle (Reddy, 2002).

4.2.1 Bulk (dry) density

The soil bulk density of soil samples was conducted using the core method according to ASTM standards D7263-21 (ASTM International, 2003). Five replicate soil samples (cylindrical cores of soil) were collected on each of the plots by inserting metal rings (Kopecky rings) into the soil to a desired depth (mark inside the metal ring) using a hammer. The metal rings are carefully removed and trimmed using a knife. The soil sample length and diameter of the Kopecky ring is calculated, which is the volume of the soil sample (v). After oven drying at 102 °C for 48 hours the samples are sieved through a 2 mm sieve and the weight of the soil samples (w) is determined. Bulk (dry) density is then calculated using Equation 4.1:

$$BD = \frac{w}{v}$$

Equation 4.1

Where BD is the bulk density of the soil in g/cm^3, w is the weight of the dried soil sample in gram (g) and v is the total volume of the soil sample in cm^3.

4.2.2 Particle size analysis

The particle size analysis is conducted to estimate the percentage of each grain size contained within the soil sample, ultimately to better classify the soil (Hossain *et al*., 2021). Particle size analyses were conducted in the laboratory using sieve and hydrometer analyses. A grain size distribution curve was constructed using the results from both methods.

4.2.2.1 Hydrometer analysis

The sedimentation method is used to determine particle size distribution (gradation) of soils with particle sizes smaller than 0.075 mm in diameter, using a hydrometer. The analysis was conducted using ASTM D7928 standards (ASTM International, 2021). The following materials a-re needed to conduct the sedimentation method (Reddy, 2002):

1) an ASTM hydrometer;

2) one-litre sedimentation cylinders;

3) a 2 mm sieve;

4) a thermometer;

5) sodium hexametaphosphate or Calgon (40 g/L ratios);

6) a pan;

7) glass bottles (250 ml); and

8) a mass balance.

Method:

- Record the mass of the 2 mm sieve and weigh 100 g of soil.
- Sieve the 100 g soil (2 mm sieve) and record the mass of soil remaining on the 2 mm sieve. Subtract the weight of the 2 mm sieve to estimate the percentage of sand larger than 2 mm.
- Weigh 50 g of the soil remaining in the pan (<2 mm) into a 250 ml glass bottle and saturate with deionized water, followed by adding 125 ml of Calgon and stirring the suspension. Leave the suspension to soak while preparing a one-litre control cylinder using 125 ml Calgon and 875 ml deionized water.
- Place a funnel into a one-litre cylinder and place a 53 µm sieve into the funnel. Wash the soil suspension over the 53 µm sieve into the sedimentation cylinder using deionized water and a brush. When the water passing through the sieve is clear, the soil slurry is completely washed through.
- Transfer the remaining soil fraction from the 53 µm sieve into a glass beaker and oven-dry the sample at 105°C for 12 hours (this sample will be used in the sieve analysis section).
- Fill the one-litre cylinder containing the soil slurry up to the 1 L mark with deionized water. Stir or shake the cylinder to ensure all particles are in suspension. Carefully place the hydrometer

into the suspension and record the first reading at 40 seconds. Record the temperature after removing the hydrometer by placing the thermometer into the suspension.

- After two hours record the final set of hydrometer and temperature readings by inserting the hydrometer and there after the thermometer.
- Note that the thermometer (cleaned) and hydrometer (cleaned) should be placed in the control cylinder after each reading. Thus, a separate set of readings should be recorded using the control cylinder at 40 seconds and 2 hours.
- Use the recorded temperatures to correct the hydrometer readings (as the hydrometer is calibrated at 20 °C) with Equation 4.2 for temperatures below 20 °C or Equation 4.3 for temperatures above 20 °C.

$$CHR = MHR - 0.36(20 - ST)$$

Equation 4.2

$$CHR = MHR + 0.36(ST - 20)$$

Equation 4.3

where CHR is the corrected hydrometer reading in g/L, MHR is the measured hydrometer reading in g/L and ST is the suspension temperature in °C.

- Calculate the corrected Calgon factor once the hydrometer readings have been corrected with Equation 4.4 temperatures below 20 °C or Equation 4.5 temperatures above 20 °C

$$CCF = CHR - 0.36(20 - CT)$$

Equation 4.4

$$CCF = CHR + 0.36(CT - 20)$$

Equation 4.5

where CCF is the corrected Calgon factor, CHR is the Calgon hydrometer reading in g/L and CT is the Calgon temperature in °C.

- Calculate the final corrected 40 seconds and 2-hour hydrometer readings by subtracting the Calgon correction factor (Equation 4.4 or Equation 4.5) from the corrected hydrometer reading (Equation 4.4 or Equation 4.5), as per Equation 4.6 or Equation 4.7

$$FC40SHR = CHR - CCF$$

Equation 4.6

$$FC2HHR = CHR - CCF$$

Equation 4.7

where FC40SHR is the final corrected 40-second hydrometer reading and FC2HHR is the final corrected 2-hour hydrometer reading, both in g/L.

- Calculate the percentage of sand, clay and silt using Equation 4.8, Equation 4.9 and Equation 4.10

$$\%SC = \frac{FC40SHR}{W} \cdot 100$$

Equation 4.8

$$\%C = \frac{FC2HHR}{W} \cdot 100$$

Equation 4.9

$$\%S = 100 - \%SC$$

Equation 4.10

where W is the mass of the sample in g %SC is the weight percentage silt and clay, %C is the weight percentage clay and %S is the weight percentage sand in the sample.

Figure 4.6 illustrates the workspace set out for the hydrometer analysis in the NWU Potchefstroom soil science laboratory.

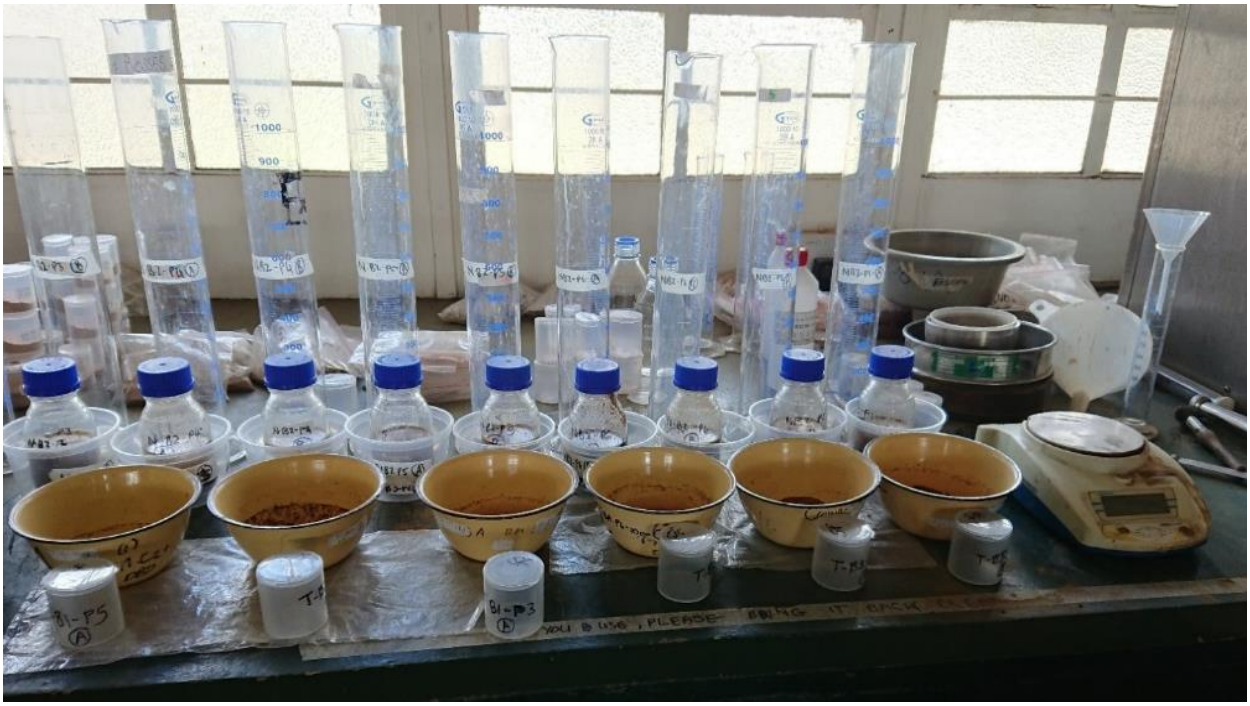

Figure 4.6: Visual representation of conducting a hydrometer analysis

4.2.2.2 Sieve analysis

The sieve analysis method is used to determine the particle size distribution (gradation) of soils with particle sizes larger than 0.075 mm in diameter (Hossain *et al*., 2021). This method was adapted from ASTM D6913 (ASTM International, 2019b; Hossain *et al*., 2021). Sieve analysis is used mostly for gravel and sand. Particles are separated into size ranges and the mass of particles in each range is measured. The following sieve analysis method was used (Reddy, 2002; ASTM international, 2019b; Hossain *et al*., 2021):

Method:

- Determine the mass of the oven-dried soil sample in grams from the previous section.
- Use the following sieve sizes for the analysis: 53 μm, 0.1 mm, 0.25 mm, 0.5 mm, 1 mm and 2 mm.
- Weigh all and record the mass of all the sieves including the pan separately before filling them with soil.
- Stack the sieves on top of one another. The sieves with larger openings should be placed on top of those with smaller openings, thus the 2 mm sieve will be on top with the 53 μm sieve at the bottom, followed by the pan.

- Pour the prepared soil in the topmost sieve and place a cover over the sieve stack. Place the stack on a sieve shaker and fasten the clamps. Set the timer for 3 minutes, put on protective earmuffs and start the shaker.
- When the sieve shaker stops, weigh and record the mass of each sieve with its retained soil.
- Use the table and sample equations provided by Hossain *et al*. (2021) and plot the values on a semi-log graph.

Figure 4.7: A stack of sieves on a sieve shaker, with a lid and clamps fastened in place

4.2.3 pH and electrical conductivity

The pH (in water) and EC readings of soil samples were determined using an XS PC 5 Tester and the 1:2.5 ratio method following the Soil Science Society of South Africa (1990). A mass balance, deionized water, 50 ml glass beakers, glass rods, pill containers, a 2 mm sieve and various buffer solutions were used in this method.

The XS PC 5 Tester was calibrated for EC using a 12.88 mS and 1413 µS buffer solution, while a 4.1 and 7.0 pH buffer solution were used to calibrate the tester for pH. Soil samples were prepared before testing by oven drying 50 g of each sample for 2 days at 70°C. The dried soil

was then sieved using a 2 mm sieve after which 20 g of the sieved soil (soil contained in the pan) was weighed down and placed in a clean pill container for testing with 50 ml of deionized water. The contents of the container were stirred for approximately 5 seconds using a glass rod and left to stand for 50 minutes. The soil solution was stirred again for 5 seconds and left for 10 minutes. The EC and pH of each solution were estimated after placing the XS PC 5 Tester in the soil solution (without the electrodes having contact with the soil at the bottom of the pill container). EC readings should be corrected using Equation 4.11.

$$ECC = EC \times 2.3$$

Equation 4.11

where ECC is the EC corrected reading and EC is the electrical conductivity in µs.

4.2.4 Nutrient element status

The samples were oven-dried and sieved (2 mm) before being sent to Eco-Analytica®. The following analyses were conducted by Eco-Analytica® using standard methods (Soil Science Society of South Africa, 1990):

- The ammonium acetate method was used to determine CEC and exchangeable cations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{2+}) by displacing exchangeable cations in soils. This method entails using an excess of ammonium acetate solution (1 mol/dm^3) buffered at pH 7.0, resulting in exchangeable cations in the soil to exchange with the ammonium cations of the solution (McKeague, 1981; Soil Science Society of South Africa, 1990). The excess ammonium is removed from the solution and exchangeable ammonium is determined.
- Extractable or plant-available P was analysed using the P-Bray 1 extraction method. The extracted P forms a reaction with ammonium molybdate resulting in a 'Molybdenum Blue' colour which is recorded colourimetrically using a UV-Vis spectrometer.
- The soil pH and EC were determined using a calibrated pH/EC multi-meter with the 1:2.5 ratio method (see section 4.2.2 above).

4.2.5 Soil moisture

Soil moisture was estimated using two methods: the gravimetric method and the neutron probe method.

4.2.5.1 Gravimetric method

The gravimetric method is used to determine soil moisture content in the NWU Potchefstroom soil science laboratory and was executed according to ASTM 2216 standards (ASTM International, 2019a):

- Record the mass of a clean, empty moisture tin.
- Place moist soil in the tin and record the mass.
- Place the moisture can in a drying oven overnight at 105°C.
- Remove the moisture can (containing a now dry soil sample) and record the mass.
- Use Equation 4.12, Equation 4.13 and Equation 4.14 to determine water content in the soil sample (Reddy, 2002).

$$m_d = m_b - m_c$$

Equation 4.12

$$m_e = m_b - m_d$$

Equation 4.13

$$w = \frac{m_d}{m_e} \times 100$$

Equation 4.14

where m_a is the mass of the moisture tin in g, m_b is the mass of the moisture tin and moist soil in g, m_c is the mass of the moisture tin and the dry soil in g, m_d is the mass of pore water in the sample in g, m_e is the mass of soil solids in the sample in g and w is the water content in the sample as a mass percentage.

4.2.5.2 Neutron probe method

A neutron probe measures soil water content by detecting and measuring thermal neutrons. The two main components of a neutron probe are a gauge and a probe (Chanasyk & Naeth, 1996). A probe is a metallic cylinder that emits fast neutrons in all directions which interact with atoms in the soil and become scattered (Chanasyk & Naeth, 1996; Reichardt *et al.*, 2007). These scattered neutrons lose energy and have thus become thermalised or slow neutrons, forming a neutron cloud around the probe. The detector measures the neutron cloud density, and the results are

displayed on the gauge. Thus, the flux of these scattered slow neutrons is then monitored by the gauge.

Most neutron probe readings were recorded in 2019 at the end of the rainy season and follow up readings were recorded at the end of the rainy season in 2020. At the centre of each plot, a hole was drilled into the soil using an auger followed by the installation of polyvinyl chloride (PVC) tube. The neutron probe is lowered into the soil through the PVC pipe at depths of 10 cm intervals and readings are recorded (Chanasyk & Naeth, 1996; Reichardt *et al*., 2007). The PVC tubes were covered with a plastic cap and reopened only on the second round of neutron probe readings in 2020. In this study, the thermal neutron count was converted to soil moisture using Equation 4.15.

$$y_2 = 0.3002x_1 - 0.2158$$

Equation 4.15

where x_1 is the thermal neutron count ratio (or MD reading on the neutron probe) and y_2 is the volumetric moisture content (*v/v*) (Reichardt *et al*., 2007). Figure 4.8 depicts the neutron probe meter used in this study.

Figure 4.8: Illustration of a neutron probe meter

4.2.6 Soil organic matter

The quality and quantity of SOM or soil organic carbon (SOC) in soils are indications of soil quality and therefore this component was selected for analysis using the loss-on-ignition (LOI) method. Loss-on-ignition is a simple protocol that uses weight losses associated with carbon dioxide evolutions (mostly the oxidation of organic carbon to CO_2) before and after heating at high temperatures (Abella & Zimmer, 2007). The soil samples were analysed using the method provided by Van Reeuwijk (2002) and according to ASTM D2974 standards (ASTM International, 2020), soil samples are firstly oven-dried at 105°C to determine soil moisture content and thereafter burnt at 450°C to estimate loss-on-ignition (loss of sample mass). The organic matter is estimated from the loss of sample mass by using the following method (Reddy, 2002; Van Reeuwijk, 2002):

- Place a clean porcelain crucible in a muffle furnace at 450 °C. Remove the crucible after 8 hours and place it in a glass desiccator for cooling.
- Use the mass balance and weigh the empty crucible (W).
- Transfer 5 to 10 g of fine soil (< 2 mm) into the crucible. Reweigh the crucible with the fresh sample (X).
- Place the crucible with the fresh sample in the oven overnight at 105 °C.
- Allow cooling in a glass desiccator after removing the crucible from the oven. Weigh the crucible with the dry sample when cool (Y).
- Preheat a muffle furnace at 450 °C and place the crucible with the dry sample in the furnace for 4 hours.
- Allow the crucible to cool in a glass desiccator after being removed from the furnace. Weigh the crucible with the burnt sample (*Z*).
- Use Equation 4.16, Equation 4.17 and Equation 4.18 to determine the moisture content, moisture correction factor loss-on-ignition and ash content.

$$MC = \frac{X - Y}{Y - W} \cdot 100$$

Equation 4.16

$$LOI = \frac{Y - Z}{Y - W} \cdot 100$$

Equation 4.17

$$AC = 100 - LOI$$

Equation 4.18

where W is the mass of the crucible in g, X is the mass of the fresh soil sample and the crucible in g, Y is the mass of the sample and crucible after drying in g, Z is the mass of the sample and crucible after burning in g, MC is the moisture content of the sample as a mass percentage, LOI is the loss-on-ignition as a mass percentage and AC is the ash content as a mass percentage of the dry sample weight.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Soil classification

D'Nyala Nature Reserve (hereafter referred to as "D'Nyala") consists of topsoil with low average clay content (<15%) and a well-graded sand exhibiting soil particles from fine to coarse in size (0.02 mm – 2 mm) (Figure 5.2, Figure 5.3 and ANNEXURE A – Soil Classification of field data). Figure 5.1 depicts the D'Nyala site landscape. The topsoil investigated at D'Nyala comprised approximately 5% clay, 20% silt and 75% sand, and classified as a loamy sand according to the texture triangle and particle size distribution graph of the D'Nyala site soils depicted in Figure 5.2 and Figure 5.3, respectively. The average soil depth at D'Nyala for the A-horizon is 20 cm and 45 cm for the B-horizon, with most particles (approximately 88%) ranging between 0.01 mm and 2 mm according to sieve analysis (Figure 3.1). Medium to coarse (0.25 mm – 2 mm) size quartz grains were also found along with coarse-sized (1 mm to 2 mm) ferricrete gravels. The A-horizon and B-horizons for the D'Nyala site were classified as an Orthic A on a Yellow Brown Apedal B on a Soft Plinthic B (ANNEXURE A – Soil Classification of field data). The dominant soil form observed at D'Nyala was the Avalon soil form (ANNEXURE A – Soil Classification of field data).

Figure 5.1: Illustrations of D'Nyala Nature Reserve site soils (Photos by N. du Toit)

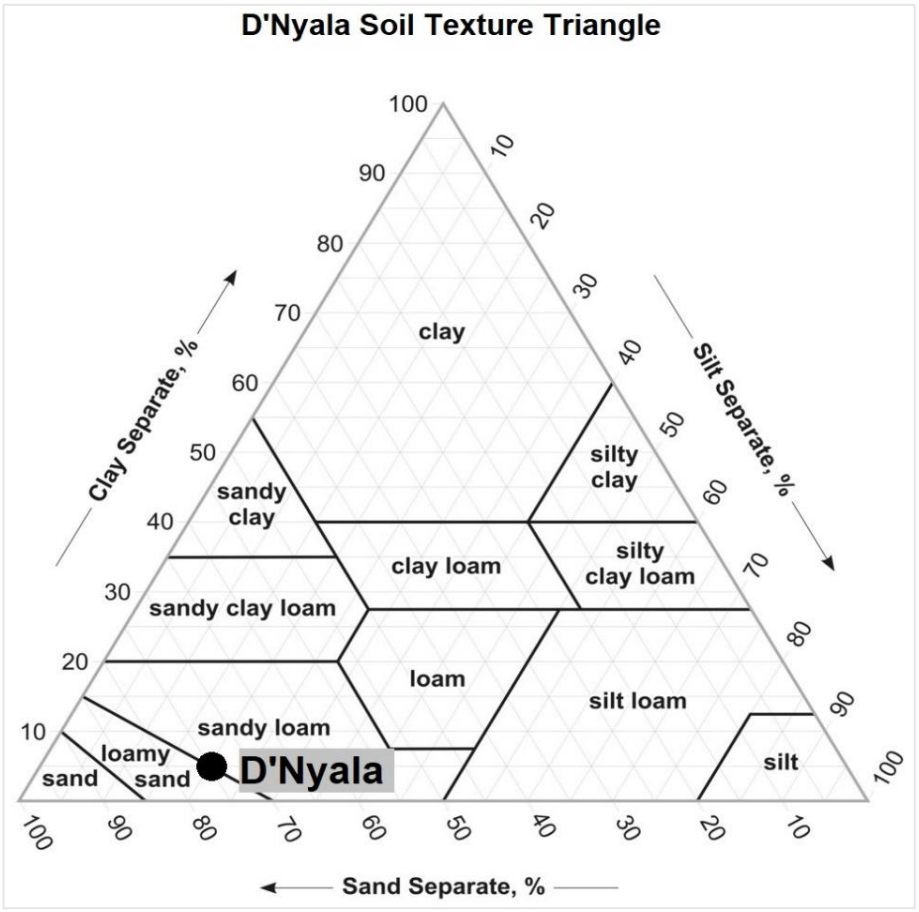

Figure 5.2: D'Nyala Nature Reserve soil texture triangle

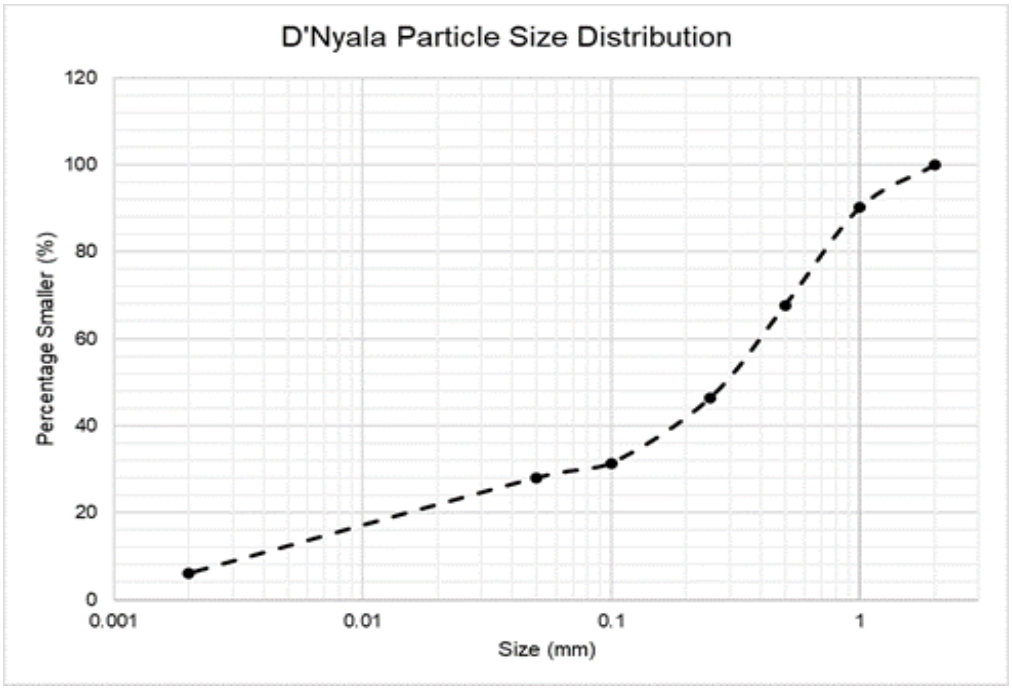

Figure 5.3: D'Nyala Nature Reserve grain size distribution curve

The Shongoane communally-managed area consists of shallow soils, with an A-horizon (topsoil) approximately 15 cm deep (classifying as an Orthic A) and the average B-horizon (classifying as a Soft Carbonate B) which is 10 cm deep (ANNEXURE A – Soil Classification of field data). Outcrops of anorthosite were found (Figure 5.5) and soils were calcareous (tested positive for lime using a 10% hydrochloric acid solution). Various sizes of calcium carbonate ($CaCO_3$) rocks and nodules were present (see Figure 5.4) which is common for soils found in sub-humid to arid regions (Pankaj *et al*., 2002). The soil type identified at Shongoane was estimated to contain a higher clay percentage according to the 'hand texturing' method or texture-by-feel analysis (Thien, 1979) and site observation indicated deep cracks characteristic of swelling clays, as per Figure 5.4. Upon closer inspection using the hydrometer and sieve analysis, Shongoane soils comprised approximately 15% clay, 5% silt and 80% sand, and was classified as a sandy loam (see Figure 5.6 and Figure 5.7). Shongoane soils also exhibited fine-grained sand (0.063 mm – 0.25 mm), with 40% of particles smaller than 0.25 mm and more than 20% of particles 0.01 mm or smaller (Figure 5.7). Figure 5.7 depicts the particle size distribution of the Shongoane site soils. The study area was identified as consisting of mainly the Brandvlei soil form. Appendix A contains the comprehensive field soil classification sheet for both study areas.

Figure 5.4: Illustration of Shongoane site soils (Photos by N. du Toit)

Figure 5.5: Anorthosite outcrop at the Shongoane study area with a ball-point pen for scale (Photo by N du Toit)

Figure 5.6: Shongoane soil texture triangle

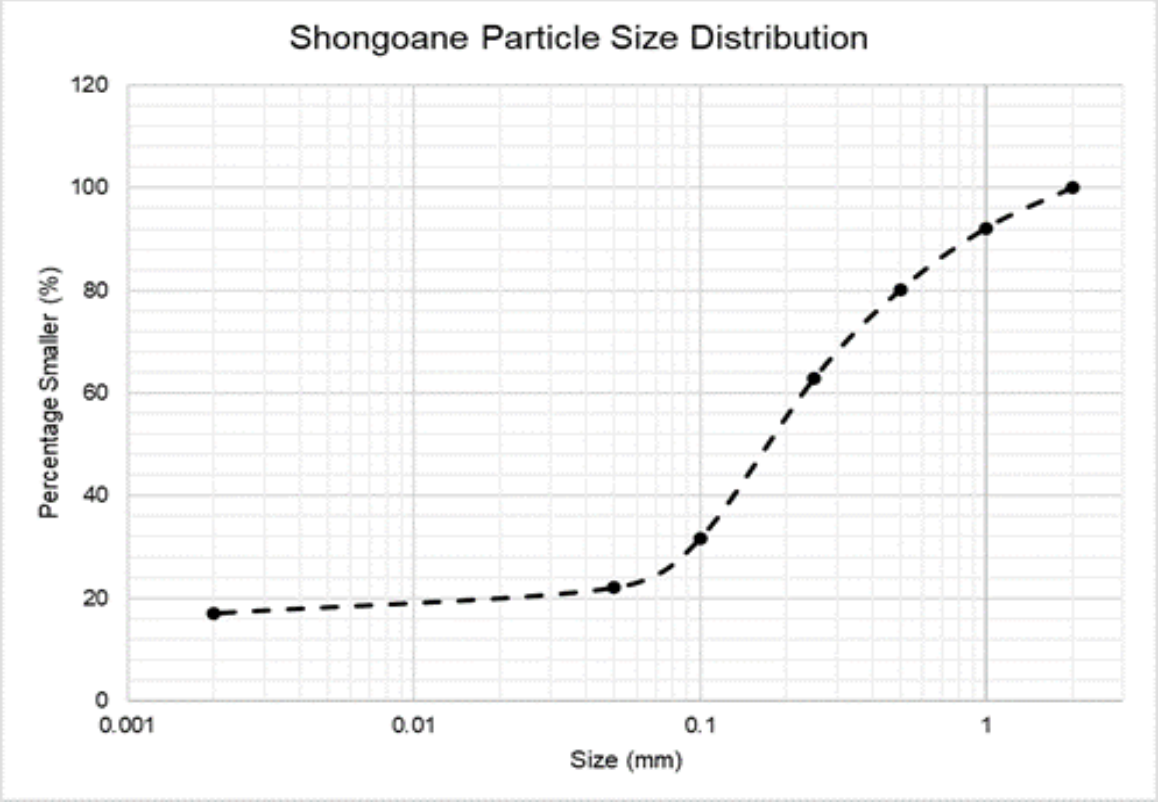

Figure 5.7: Shongoane grain size distribution curve

5.2 Soil analysis

5.2.1 Soil physical properties

5.2.1.1 Bulk (dry) density

D'Nyala indicated a slight drop in soil bulk density from 2019 to 2020 regarding all restoration treatments, especially treatments containing re-seeding (Figure 5.8 and Table 5.3). The total pore space in sandy soils (D'Nyala) is greater compared to silt and clay soils. According to Nawaz *et al*. (2013) and Zhang, S. *et al*. (2019) sandy soils are less susceptible to compaction compared to fine or medium-textured loam and clay soils. The CRS treatment indicated a 0.29 g/cm^3 decrease in bulk density, while the CRSBP and CSRSBP treatment indicated a 0.12 g/cm^3 and 0.14 g/cm^3 decrease, respectively (Figure 5.8). The growth of plant roots where re-seeding was applied as restoration technology decreased bulk density and increased porosity (Zhang, S. *et al*., 2019). In 2020, the C and UC cover methods indicated a slightly higher bulk density (1.65 g/cm^3 and 1.66 g/cm^3, respectively) compared to CRS (1.44 g/cm^3), CBP (1.62 g/cm^3), CRSBP (1.50 g/cm^3) and CSRSBP (1.51 g/cm^3) for D'Nyala soils. According to Figure 5.8 and Table 5.3, soils covered with the UC and CBP treatments indicated the smallest decrease in bulk density (<1 g/cm^3 decrease). Nawaz *et al*., (2013) explain that rainfall also contributes to compaction

alongside animal trampling and a decrease in SOM. The treatments containing 'clearing' (the removal of woody vegetation) without re-seeding (thus, C and CBP) resulted in a loss of soil cover (a protective layer against rain drop impact) and no addition of vegetation to contribute to SOM or the amount of plant roots present in the soil. Accumulating SOM in soils and vegetation decreases compaction and thus soil bulk density (Murphy, 2015; Zhang, D. *et al*., 2019). Brush packing also limits grazers by providing a protective barrier, thus the application of BP and re-seeding decreased compaction and bulk density of D'Nyala from 2019 to 2020 (Figure 5.8). D'Nyala soils indicated the largest decrease in bulk density and a decrease in compaction for treatments containing re-seeding (CRS), re-seeding combined with BP (CRSBP) and re-seeding combined with BP and soil disturbance (CSRSBP) (Figure 5.8). The soil bulk density of D'Nyala soils (loamy sands), at the end of this study (2020), for treatments containing re-seeding is in the ideal bulk density range for plant growth (<1.60 g/cm^3), while the soil bulk densities of the UC, C and CBP cover methods are in the range where plant roots will be affected (1.60 - 1.69 g/cm^3), but below the soil bulk density value that restricts root growth (1.80 g/cm^3) (see Table 2.1).

The bulk density of all Shongoane soils increased slightly, indicating an increase in compaction except for soils covered with the CRS treatment (Table 5.3), which indicated a 0.1 g/cm^3 decrease in soil bulk density from 2019 to 2020 (Figure 5.8). According to Nawaz *et al*., (2013), increases in SOM (provided by re-seeding/increase in vegetative cover) can increase soil's resistance to deformation and can even reduce soil compactibility even at high moisture levels in silt and clay soils. Thus, treatments containing re-seeding indicated a smaller increase in soil bulk density (<0.06 g/cm^3 for soils covered with the CRSBP and CSRSBP treatments) and a decrease in soil bulk density (0.04 g/cm^3 for CRS covered soils) for the Shongoane area, while treatments not containing re-seeding (C, UC and CBP) indicated a larger increase in soil bulk density (0.04 – 0.1 g/cm^3). Shongoane soils where no restoration treatment (UC) was applied or where the CBP treatment was applied indicated the highest increase in bulk density compared to the other four treatments (Figure 5.8). The C, CRSBP and CSRSBP methods indicated a less than 0.1 g/cm^3 increase in bulk density for Shongoane soils from 2019 to 2020 (Figure 5.8). Compaction decreases soil infiltration, increases runoff and weakens shallow plant root systems (Daryanto *et al*., 2013a; Zhang, D. *et al*., 2019). Shallow rooted plants can easily be trampled by grazers or washed away by water runoff (Zhang, S. *et al*., 2019). Finer-grade soils have smaller pore spaces (narrower 'pipes' for water to travel through) and thus a lower infiltration rate compared to sandy soils (Soil Quality Institute *et al*., 2004; Nawaz *et al*., 2013). The increase in soil bulk density is likely due to the combination of soil texture, lack of SOM and grazing or animal trampling (Daryanto *et al*., 2013b). Overgrazing decreases plant root density (which decreases bulk density) and suppresses soil infiltration (Cai *et al*., 2021). Trampling by animals can result in soil structure degradation, resulting in an increase in bulk density (Nawaz *et al*., 2013). The soils covered with

CRSBP and C treatments indicated the smallest change in soil bulk density for both study areas (Figure 5.8 and Table 5.3). Regarding all treatments not containing re-seeding, Shongoane soil illustrated a higher increase in soil bulk density and D'Nyala soils indicated a smaller decrease in bulk density (Figure 5.8), which can be ascribed to plant roots and SOM (Figure 5.11) decreasing compaction (Zhang, S. *et al*., 2019). The soil bulk density of Shongoane soils (sandy loams), at the end of this study (2020), for all treatments are still in the ideal bulk density range (< 1.40 g/cm^3). While still in the optimal range, the soil bulk densities of the C, UC and CBP cover methods are rapidly increasing towards the range where plant growth may be affected (1.40 - 1.63 g/cm^3) (Table 2.1). As seen with D'Nyala soils (loamy sands), all treatments containing re-seeding (regardless of containing BP) for Shongoane soils (sandy loams) indicated a more positive effect on soil bulk density compared to treatments not containing re-seeding. The variations in soil bulk density concerning the different restoration treatments are depicted in Figure 5.8.

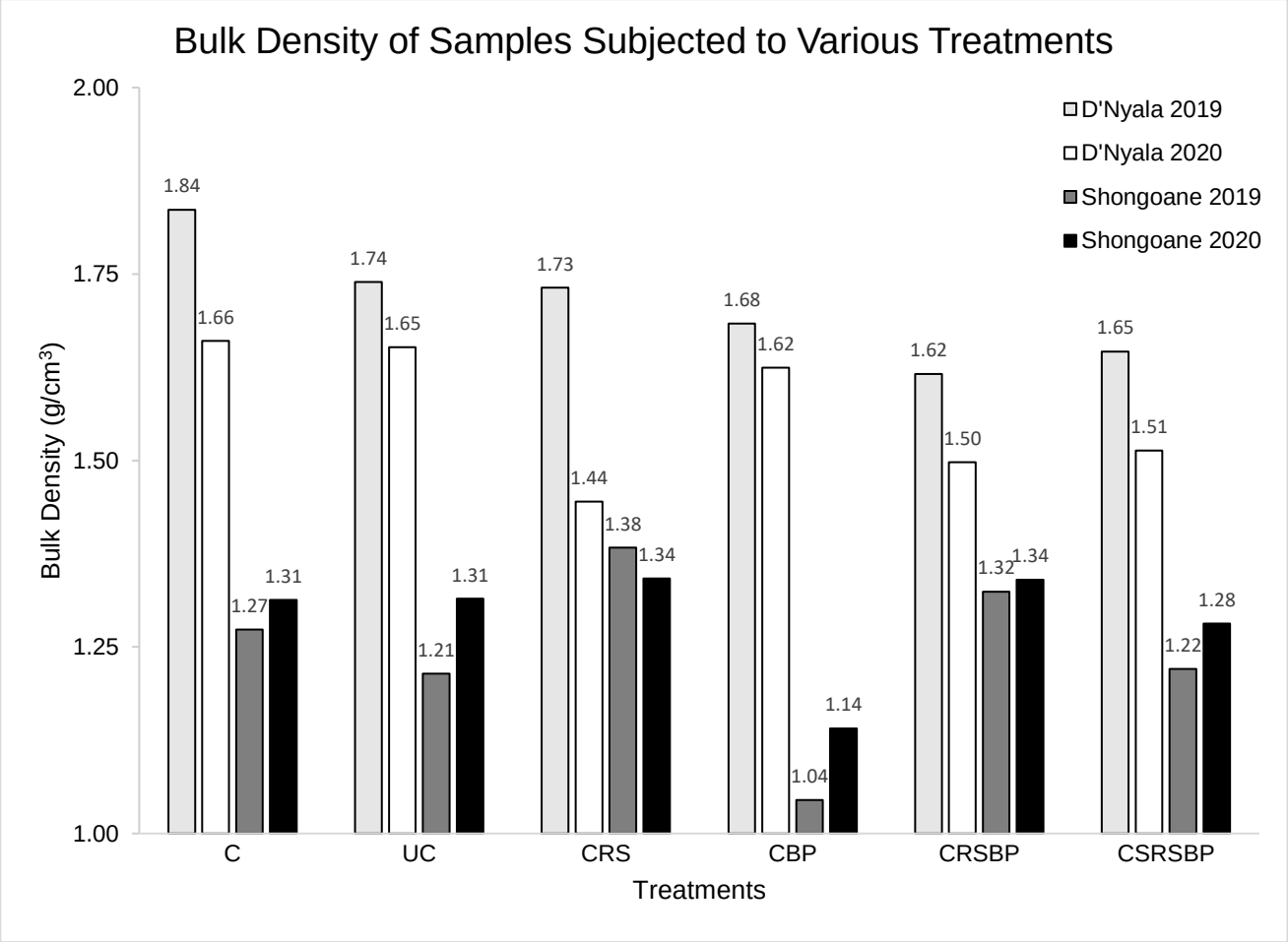

Figure 5.8: Variations in bulk density for different restoration treatments at the D'Nyala and Shongoane study sites for 2019 and 2020

5.2.1.2 Soil Infiltration

The overall infiltration rate of D'Nyala soils increased slightly from 2019 to 2020 except for the UC and C cover methods which decreased with 0.1 mm/h, and the CBP treatment which decreased with 0.2 mm/h (Figure 5.9). The most notable difference was the increased infiltration rate of D'Nyala soils for treatments containing re-seeding. Soil infiltration rate of the CRS, CRSBP and CSRSBP covered soils increased with 0.4 mm/h, 0.3 mm/h and 0.4 mm/h, respectively (Figure 5.9). The soil infiltration rate under vegetation (e.g., grasses) is higher due to a larger number of macropores (Eldridge & Freudenberger, 2005). Macropores counteract runoff by providing sub-surface soil layers with preferential water flow. Sandy soils, as found at the D'Nyala study area (Figure 5.2 and Figure 5.3), have larger pores which promote water percolation and infiltration, thus an increase in plant roots promotes further porosity and aggregate formation, increasing infiltration and recharging ground water and increasing soil moisture (Zhang, D. *et al*., 2019; Zhang, S. *et al*., 2019). All cover treatments containing re-seeding or re-seeding combined with BP indicated the most success in increasing the infiltration rate of D'Nyala soils (Figure 5.9 and Table 5.3).

The infiltration rate of Shongoane soils decreased with values ranging between 0.5 to 1 mm/h from the year 2019 to 2020 (Figure 5.10). Shongoane soils covered with the C and UC cover methods indicated the most obvious differences, where soil infiltration rate decreased by approximately 1 mm/h from 2019 to 2020, while soils covered with treatments containing BP indicated smaller value in soil infiltration rate differences (<1 mm/h) (Figure 5.10). According to surveys conducted by Mangani (2021), the Shongoane site experiences more grazing (unrestricted open grazing) compared to the D'Nyala site (restricted closed grazing) and as mentioned above, grazers trample and consume vegetation, increasing compaction and bulk density, and thus decreasing infiltration rate of soils (Cai *et al*., 2021). Medium to fine-grained soil, as found at the Shongoane site (Figure 5.6 and Figure 5.7), has small pore spaces, indicating a slower infiltration rate compared to coarse-grained soil (Zhang, S. *et al*., 2019). Both study areas indicated a decrease in the infiltration rate of soils covered with the UC and the C cover methods (Figure 5.10 and Table 5.3). The UC method was the least successful in improving soil infiltration for both study areas, but the soil infiltration rate for the UC method remained higher than the rest of the treatments for both study areas apart from the CSRSBP treatment of the Shongoane study area (Figure 5.10). Marquart *et al*. (2020) explains that shrubs (especially larger shrubs) provide a physical barrier that can prevent the movement of livestock and thus preventing livestock trampling, promoting a higher soil infiltration rate and lower soil bulk density. The infiltration rate of soils covered with the CRS treatment indicated the lowest infiltration rate for both study areas (Figure 5.9 and Figure 5.10). The removal or control of shrubs provides easier access to grasses established from re-seeding, promoting trampling by livestock. The soil infiltration rates

concerning different treatments for both the D'Nyala site and the Shongoane site for 2019 and 2020 are depicted in Figure 5.9 and Figure 5.10, respectively.

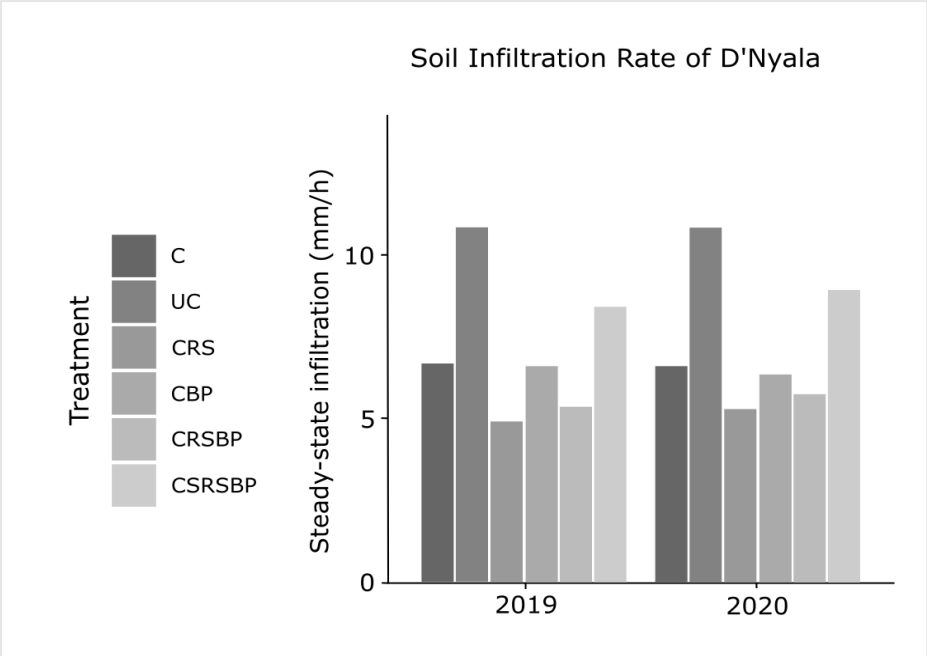

Figure 5.9: Soil infiltration rate of D'Nyala Nature Reserve for different restoration treatments of 2019 and 2020

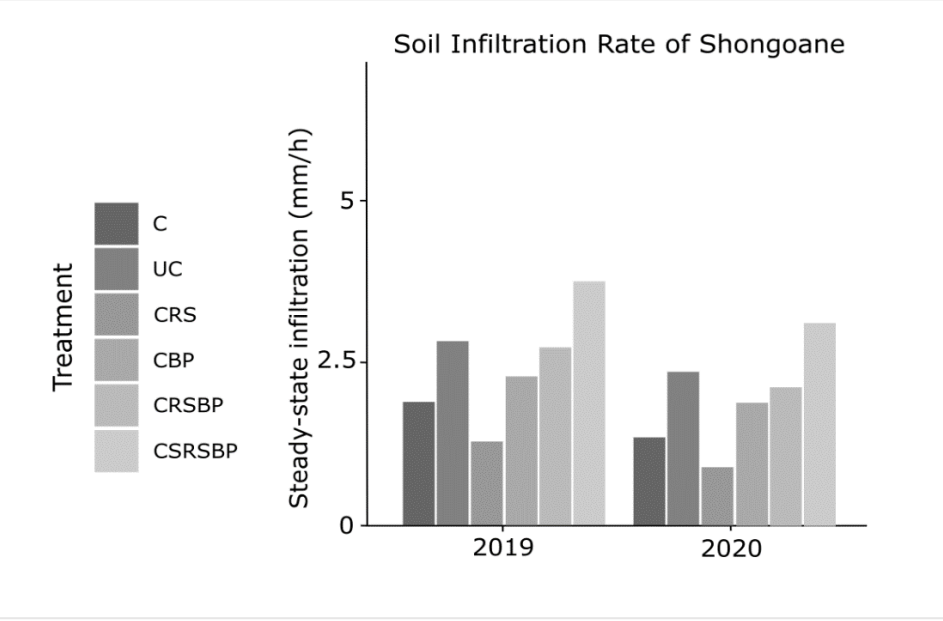

Figure 5.10: Soil infiltration rate of Shongoane for different restoration treatments of 2019 and 2020

5.2.2 Soil chemical properties

5.2.2.1 Soil organic matter (SOM)

Shongoane soils indicated the highest SOM (loss on ignition percentage) content for all six restoration treatments at the start of the soil analysis in 2019 (Figure 5.11). Soils covered with the C (clearing only) treatment exhibited the highest SOM content (2019) and the second-lowest SOM at the end of 2020 for Shongoane soils (Figure 5.11 and Table 5.3). The UC cover method indicated the lowest SOM at the end of 2020 (dropping by 50%). The C treatment indicated the most prominent decrease in SOM with 2020 being one-third of 2019 (decreasing by 68%). Overall, the SOM for Shongoane decreased from 2019 to 2020. Houghton (2003) explains that by removing trees and shrubs (a carbon sink), carbon is likely to decrease in the ecosystem. Shallow and compact soils provide less nutrients, water and mechanical support to plants (Rajakaruna & Boyd, 2008). Shongoane soil is shallow, more compact (presence of lime) and the soil moisture content increases with depth (Figure 5.16 and Figure 5.17), which could prove problematic to re-seeding and grass establishment, thus decreasing SOM sources (Zhang, D. *et al*., 2019). The CBP treatment indicated the lowest decrease (10% decrease) in SOM for Shongoane soils. BP provides plant litter which contributes to SOM (Hutley and Setterfield, 2008). The SOM content of soils covered with the CRS, CRSBP and CSRSBP treatment decreased with 40%, 46% and 44%, respectively (Figure 5.11 and Table 5.3).

D'Nyala soils also indicated a decrease in SOM but only in soils covered with treatments where no re-seeding was applied (Figure 5.11 and Table 5.3). Cover treatments containing re-seeding is more successful with regard to increasing SOM of the D'Nyala study area compared to treatments not containing re-seeding (Figure 5.11). Grasses and trees increase biomass content and SOM in soils (Gray & Bond, 2015; Zhang, D. *et al*., 2019). An increase in grassy vegetation increases root exudates and plant litter which will decompose to produce SOM (Zhang, S. *et al*., 2019). In sandy soils an increase in soil carbon will promote a decrease in bulk density (Nawaz *et al*., 2013; Yost & Hartemink, 2019) and the D'Nyala soils indicated increased SOM (see Figure 5.11 and Table 5.3) and decreased soil bulk density (see Figure 5.8) with treatments containing re-seeding. Soil texture and permeability contributes to the increase in SOM. According to Table 5.3 the CSRSBP treatment was most successful in increasing SOM by almost four times the original percentage followed by the CRS treatment (more than two times), the CRSBP treatment (45% increase), and lastly the UC cover method (less than 10%). The SOM results, provided by the UC cover method (continuation of bush encroachment), supports the study conducted by Li *et al*. (2016) where SOC decreased in clay and silt soils (Shongoane) and increased in sandy soils (D'Nyala) regarding bush encroachment. Thus, SOM indicated a greater increase in sandy soils compared to clay and silt soils regarding bush encroachment. Treatments with re-seeding

could also be more attractive to grazers due to newly established grass species. Grazers also contributes to the carbon sink through excretion (Daryanto *et al*., 2013a). SOM decreased in D'Nyala soils covered by the control only (C) and CBP treatments with 55% and 34%, respectively (Figure 5.11 and Table 5.3). The variations in LOI (mass loss of SOM %) concerning different restoration treatments are displayed in Figure 5.11.

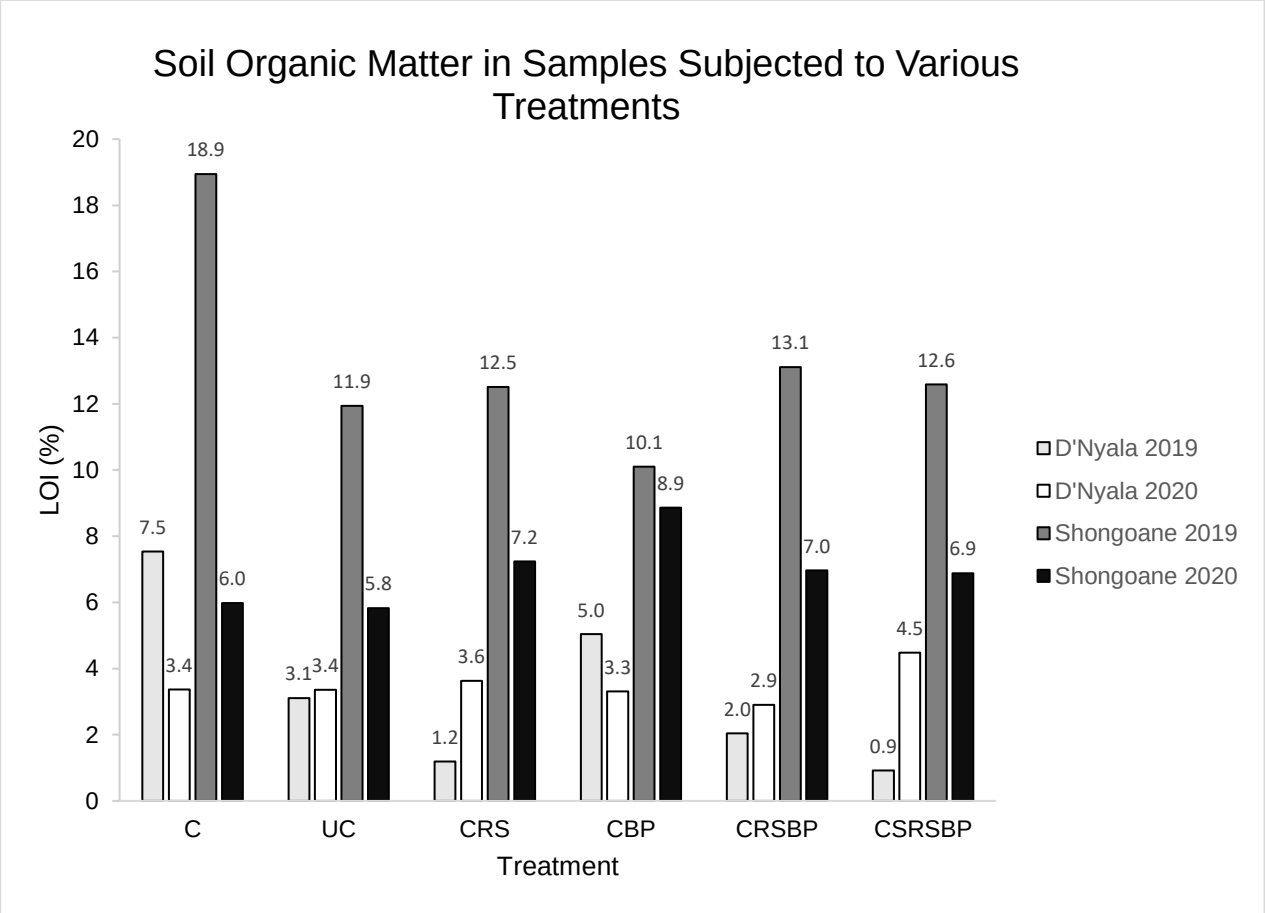

Figure 5.11: Variations in LOI (mass loss of soil organic matter percentage) for different restoration treatments

5.2.2.2 Nutrient status

The nutrient status, CEC and cation ratio results are indicated in Table 5.1 and Table 5.2 for D'Nyala and Shongoane soils, respectively. The analysis was conducted only on the surface soils of the two study areas, where the nutrients are accessible to vegetation.

Shongoane soils indicated a higher nutrient status compared to D'Nyala soils regarding Ca, Mg, K, Na and P, due to differences in parent material (see Table 5.1 and Table 5.2). The acidic pH of Shongoane soils (Figure 5.12) will decrease the availability of these nutrients and influence agricultural production capabilities, indicating less success in treatments containing re-seeding

(Rengasamy & Churchman, 1999). Rengasamy & Churchman (1999) explains that CEC is an indicator of a soil's ability to supply and retain nutrients (cations). SOM and clay are negatively charged soil particles and indicators of the CEC present in the soil thus, the higher the CEC of soil the more cations or nutrients can be held (Rengasamy & Churchman, 1999). D'Nyala soils exhibited an increase in SOM (Figure 5.11 and Table 5.3) corresponding with an increase in soil moisture (Figure 5.16) for treatments containing re-seeding. This was expected when compared to research conducted by Yost and Hartemik (2019), stating that in sandy soils SOM increases soil moisture if soil pH remains stable or increases. Shongoane soils can retain more nutrients compared to D'Nyala soils, but due to an acidic pH, less of these are available to plants. The D'Nyala study area indicated greater soil moisture levels compared to Shongoane soils in 2020 (Figure 5.16 and Table 5.3) which, as mentioned in Section 5.2.3 below, positively influences nutrient availability (Hutley and Setterfield, 2008). Murphy (2015) explains that SOM is mineralised during nutrient cycling and consequently phosphorus (P), nitrogen (N) and sulphur (S) become more readily available to plants. The Ca:Mg ratio affects plant nutrient solubility at different pH levels and a K:Mg ratio of more than 0.5 could lead to Mg deficiency in soil (Sanik *et al*., 1952). Shongoane soils contain medium levels of P (Table 5.2), which is deficient in D'Nyala soils (less than 3 mg/kg) (Table 5.1). P is used by plants for photosynthesis, where energy (sunlight) is used by plants to synthesize organic sugar molecules from an inorganic carbon source (Hutley & Setterfield, 2008). P availability corresponds with a pH below 5 and reduces crop yields (Haynes & Mokolobate, 2001). Shongoane soils (Table 5.2) indicated more Ca and Mg compared to D'Nyala soils (Table 5.1) due to the presence of lime nodules ($CaCO_3$) in the soil (Figure 3.1). Pankaj *et al*. (2002) explains that $CaCO_3$ formation decreases the Ca/Mg ratio of the exchange site. Potassium (K) is abundant in plants and K deficiency in soils can inhibit plant growth by decreasing photosynthesis rates and promoting tissue dehydration in plants (Chen *et al*., 2016; Huber, 1985).

Table 5.1: Nutrient status, CEC and cation ratios of D'Nyala soils

D'Nyala													
	Nutrient Status (mg/kg)					Exchangeable cations (cmol(+)/kg)					Cation Ratio		
Treatment	Ca	Mg	K	Na	P	CEC (S-value)	Ca	Mg	K	Na	Ca:Mg	Mg:K	Ca+Mg:K
C	214.11	21.14	43.13	1.79	1.97	1.36	1.07	0.17	0.11	0.01	127.59	1.21	13.02
UC	339.26	36.73	54.92	0.50	1.16	2.14	1.69	0.30	0.14	0.00	6.53	2.06	14.12
CRS	406.09	68.72	57.69	1.13	2.29	2.74	2.03	0.57	0.15	0.00	3.75	3.71	17.15
CBP	412.82	48.45	69.98	0.94	0.57	2.64	2.06	0.40	0.18	0.00	9.89	1.66	13.59
CRSBP	347.18	347.18	64.22	1.63	0.66	2.33	1.73	0.42	0.16	0.01	5.45	2.38	12.59
CSRSBP	214.12	351.67	85.21	3.90	0.82	1.59	1.07	0.29	0.22	0.02	5.32	1.28	7.37

Table 5.2: Nutrient status, CEC and cation ratios of Shongoane soils

Shongoane													
	Nutrient Status (mg/kg)					Exchangeable cations (cmol(+)/kg)					Cation Ratio		
Treatment	Ca	Mg	K	Na	P	CEC (S-value)	Ca	Mg	K	Na	Ca:Mg	Mg:K	Ca+Mg:K
C	4021.66	563.46	197.83	15.23	15.25	25.28	20.07	4.64	0.51	0.07	4.48	9.40	49.32
UC	4014.67	674.93	200.13	17.97	15.75	26.18	20.03	5.55	0.51	0.08	4.84	10.14	50.79
CRS	4337.71	889.81	270.43	19.48	16.25	29.75	21.65	7.32	0.69	0.08	3.65	10.14	41.99
CBP	3093.44	449.43	157.66	15.87	11.25	26.14	20.58	4.93	0.54	0.09	4.35	9.25	47.50
CRSBP	4089.68	465.70	196.99	12.48	14.00	24.80	20.41	3.83	0.51	0.05	5.77	7.58	49.84
CSRSBP	4039.97	553.69	225.09	20.77	17.28	19.04	15.12	3.42	0.43	0.07	5.02	8.09	43.13

5.2.2.3 Soil pH

The pH samples of the A-horizon (Figure 5.12) of all the study areas in 2019 fall in the slightly acidic and slightly alkaline range (6.0 – 7+) as classified by Brady and Weil (2014). D'Nyala Nature Reserve soils indicated an overall increase/elevation in pH levels (shift from slightly acidic to neutral and/or slightly alkaline) for years 2019 to 2020 (see Figure 5.12), especially soils covered with treatments containing re-seeding (>0.7 increase). D'Nyala soils where the UC method was applied indicated a 0.1 increase in pH and soils treated with the CBP treatment indicated a 0.2 increase in pH. The two treatments (CRSBP and CSRSBP) containing brush packing and re-seeding indicated the most success in achieving soil neutrality (pH increased with 0.9), followed by the CRS treatment (0.7 increase), regarding the D'Nyala site. D'Nyala soils covered with the treatments (i.e., C, CRS, CRSBP, and CSRSBP) indicated a larger (>0.5) increase in pH from 2019 to 2020, now classified as neutral and no longer ranging between slightly acidic and slightly alkaline. The pH for D'Nyala soils is classified as being in the optimum pH range (5.5 to 7.5) for vegetation growth.

The pH of Shongoane topsoils (Figure 5.12) decreased/lowered drastically (became more acidic) with all treatments. Shongoane soils covered by the UC method indicated the largest decrease in pH (2.1 decrease), followed by the CRS treatment (1.9 decrease), the CSRSBP treatment (1.8 decrease), the CBP treatment (1.7 decrease), the CRSBP treatment (1.6 decrease), and the C cover method (1.5 decrease), for the years 2019 to 2020. Soil acidification occurs naturally as soil weathers, but at a very slow pace and this process is accelerated by variety of factors such as added sources of ammonium, nitrates, or leaching (Meng *et al*., 2013). A possible explanation for soil acidification observed from the UC covered soil and the CRS covered soil is grazing and SOM decomposition. Animal excretion contains ammonium and organic nitrogen which contributes to soil acidification, while ammonium nitrogen from SOM is converted into hydrogen and nitrate ions by bacteria present in the soil, resulting in soil acidification (Department of Primary Industries and Regional Development, 2018). The treatments containing either clearing, re-seeding, soil

disturbance and/or brush packing, lessened the amount with which soil pH lowered. The soil treated with the C treatment indicated a more neutral pH compared to the soil treated with the other treatments. Shongoane topsoil pH shifted from slightly acidic to acidic (pH below 5.5) which will decrease the availability of calcium (Ca), magnesium (Mg), phosphorus (P) and molybdenum (Mo), and increase the availability (and possibly toxicity) of boron (B), iron (Fe), copper (Cu), manganese (Mn) and zinc (Zn) in soil (Fageria & Nascente, 2014; Haynes & Mokolobate, 2001). The soil pH for Shongoane soils is below the optimum (5.5 to 7.5) range.

Decomposition of residue (SOM) assists soil in recovering its natural buffering capacity which corresponds with SOM (Figure 5.11) and pH levels (Figure 5.12) observed of D'Nyala and Shongoane soils (Haynes & Mokolobate, 2001). The oxidation of organic acid anions has a liming effect on soil, which is beneficial for nutrient adsorption (Haynes & Mokolobate, 2001). D'Nyala soil indicated less nutrients, but due to a more neutral pH, increased soil moisture and SOM, these nutrients are more available to plants. Shongoane consists of soils richer in nutrients and a higher CEC compared to D'Nyala, but due to an acidic pH less nutrients are available to plants. Murphy (2015) explains that a pH below 5.5 decreases the effectiveness of SOM to contribute to the liming effect of soil. Figure 5.12 displays the variations in pH for different restoration treatments in the A-horizon.

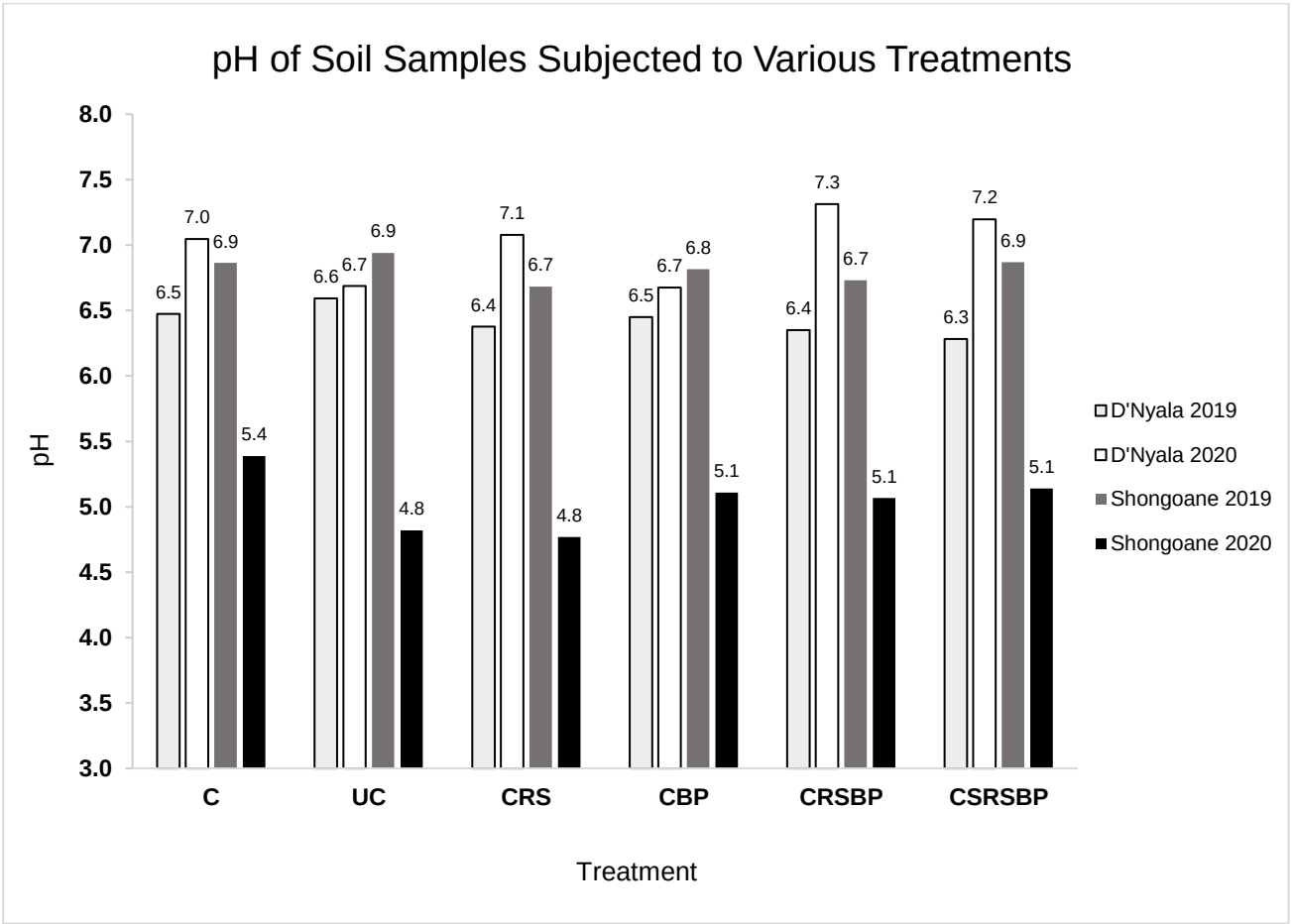

Figure 5.12: Variations in pH in the A-horizon for different restoration treatments for 2019 and 2020 at the D'Nyala and Shongoane study areas

The pH values of the B-horizon for D'Nyala are more acidic compared to the A-horizon, and the B-horizon (soft carbonate) for Shongoane was more neutral or alkaline compared to the A-horizon (Figure 5.13). All values still fall in the slightly acidic to slightly alkaline range (6.0 – 7+). Shongoane exhibits the highest pH, which is probably due to soil composition (lime was found in the B-horizon) and leaching from the A-horizon. The lower pH values of D'Nyala Nature Reserve in the B-horizon compared to the A-horizon could indicate leaching and higher permeability due to percolation of water and the formation of acids (Shukla *et al*., 2013). Figure 5.13 depicts the variations in pH in the B-horizon at the D'Nyala Nature Reserve and the Soft Carbonate B horizon at the Shongoane study area for different restoration treatments for 2019.

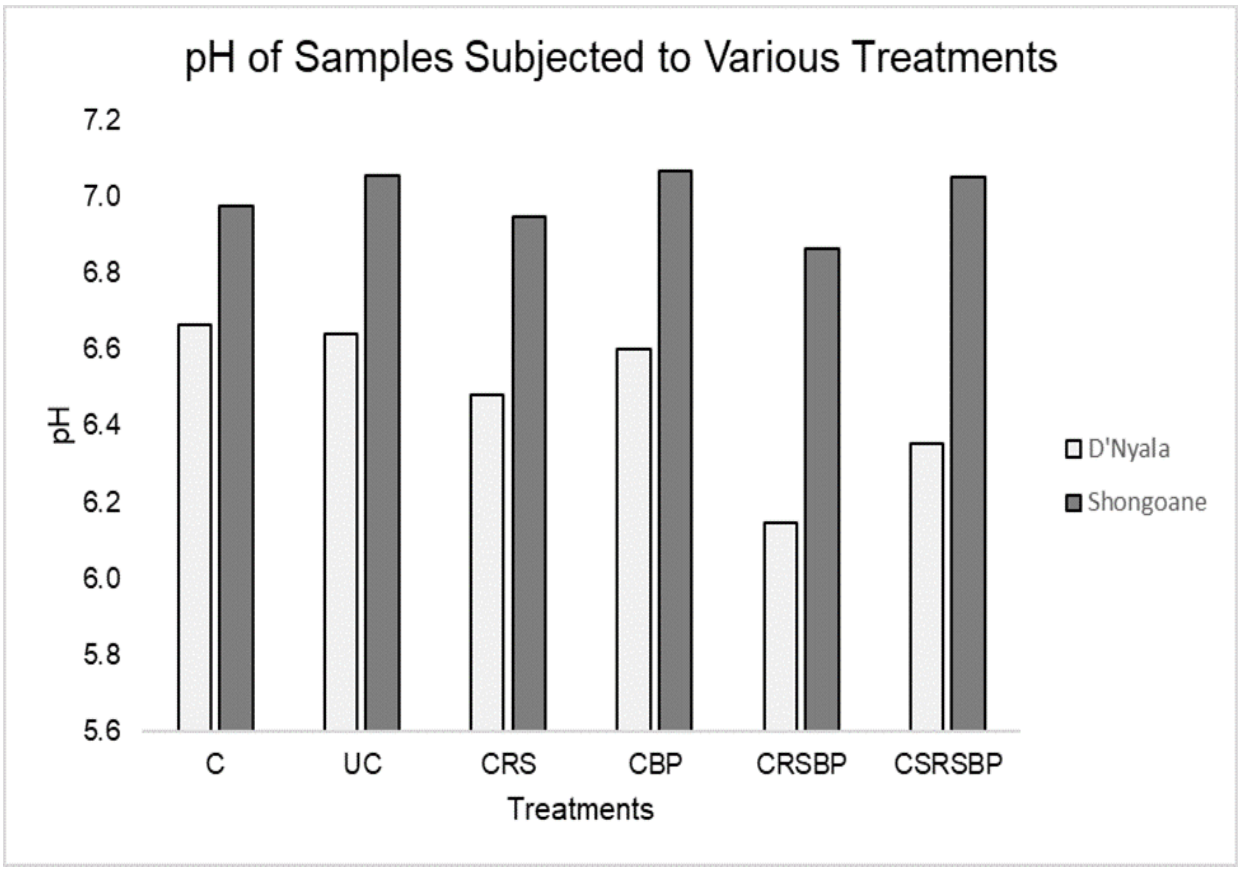

Figure 5.13: Variations in pH in the B-horizon at the D'Nyala Nature Reserve and the Soft Carbonate B horizon at the Shongoane study area for different restoration treatments for 2019

5.2.2.4 Electrical conductivity

The EC of D'Nyala increased significantly in the topsoil from 2019 to 2020 (>68%), especially for the treatments containing re-seeding (>120%) (Figure 5.14 and Table 5.3). An increase in EC is correlated with an increase in SOM for all treatments containing re-seeding of the D'Nyala study area. The CRSBP treatment indicated the largest increase in EC (147%). The UC method indicated the smallest increase in EC (68%).

Soil in Shongoane indicated large decreases (>72%) in the EC of all treatments, with the UC cover method being the only restoration treatment indicating an EC below 100 µs in the topsoil. The CBP treatment indicated the smallest decrease (72%) in EC compared to the other treatments. The SOM and EC of Shongoane are also correlated, especially regarding the UC cover method. Figure 5.14 and Table 5.3 displays the variations in EC in the A-horizon for different restoration treatments.

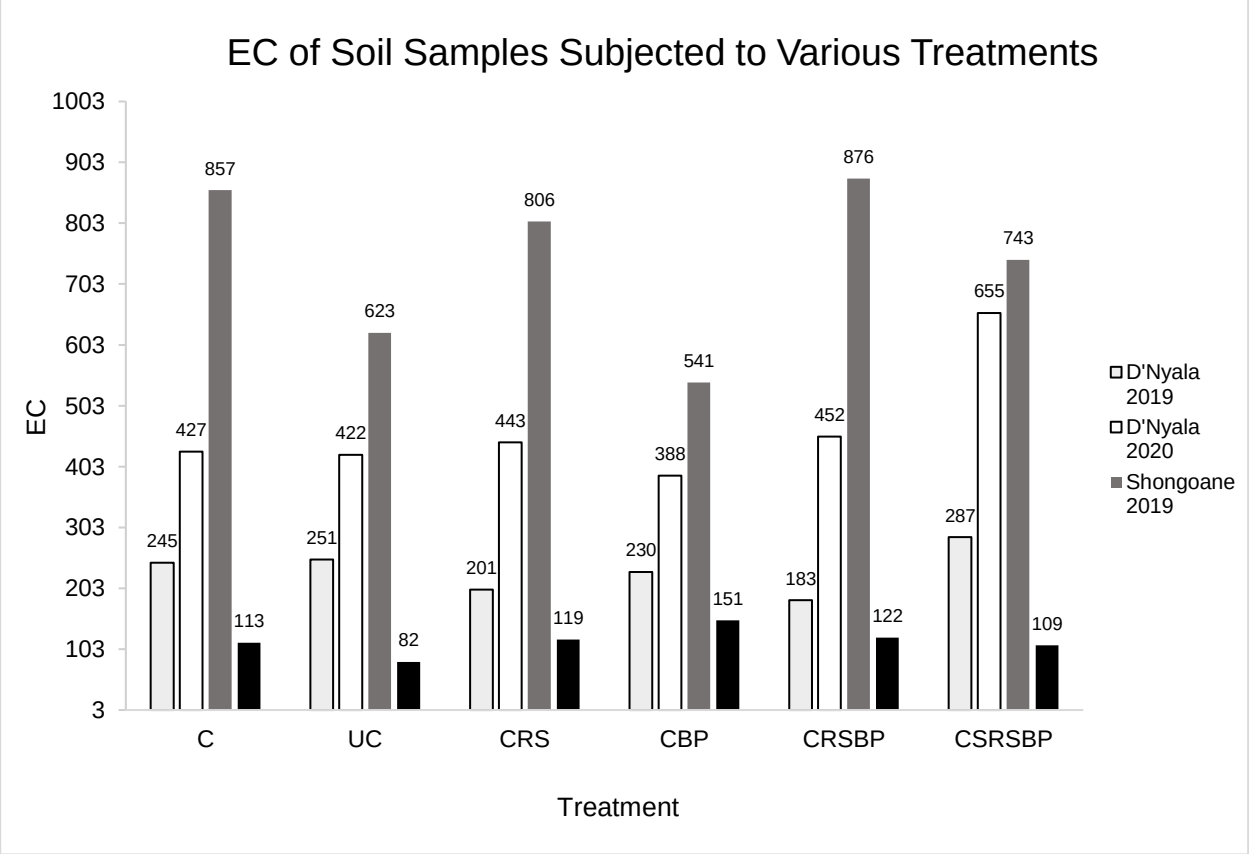

Figure 5.14: Variations in EC in the A-horizon for different restoration treatments at the D'Nyala and Shongoane study areas for 2019 and 2020

According to Figure 5.15 below, the EC values of the B-horizon for Shongoane soils and D'Nyala soils were below 145 µS, which indicates low salinity and the presence of more calcium,

magnesium, and bicarbonate ions (Ahmad and Nazia, 2013). These EC results of Shongoane also support the higher pH observed in the soil B-horizon. EC values decreased with depth for all the study areas. Figure 5.15 depicts the EC in the B-horizon of both study areas for different restoration treatments.

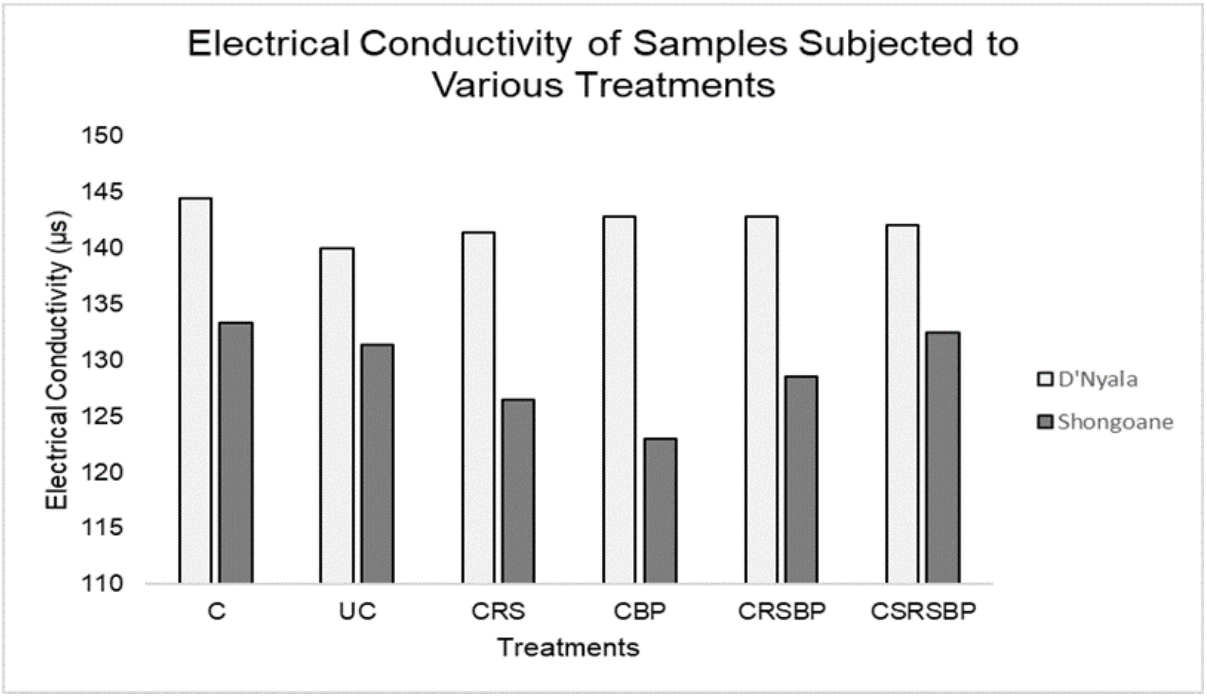

Figure 5.15: Variations in EC in the B-horizon at the D'Nyala Nature Reserve and the soft carbonate horizon at the Shongoane study area for different restoration treatments for 2019

5.2.3 Soil moisture

Volumetric soil moisture values increased with depth at the D'Nyala study site for 2019 and 2020 (Figure 5.16, Figure 5.17 and Table 5.3). The soils treated with BP treatments for D'Nyala exhibited higher volumetric soil moisture values (37-55 v/v increase) in the upper 10 cm (topsoil) of the soil profile compared to soils treated with non-brush packing treatments, except for the UC cover method (54 v/v increase). An increase in vegetation (trees and shrubs not removed in the area) protects against soil moisture loss through evaporation by providing shade and decreasing the soil surface temperature. Based on the previous concept, the C cover method indicated the smallest increase in volumetric soil moisture (29 v/v) due to the removal of trees and shrubs, followed by the CSRSBBP method (37 v/v increase). The overall volumetric soil moisture content for D'Nyala increased from 2019 to 2020 regardless of the restoration treatment used. Soil covered with treatments containing re-seeding indicated a smaller volumetric moisture increase (45 v/v) in 2020 compared to the soils treated with the CBP treatment (55 v/v increase). Increasing

vegetation (re-seeding) will decrease available water in the soil since bush encroachment and the removal of grasses improves soil water status and these newly established grasses use water for growth and transpiration (Huntley, 1982). Murphy (2015) reported similar results indicating an increase in plant available water with an increase in SOM, especially in sandy soils. The spike in moisture for D'Nyala could be due to a heavy increase in SOM, decreased compaction, less evaporation from the soil surface due to vegetation cover, and an increase in rainfall (Table 3.1) (Daryanto *et al*., 2013b). February 2020 (152 mm) received more rainfall compared to February 2019 (89.6 mm) and since the first and second round of soil sampling took place during these two months, respectively, the overall volumetric moisture values for 2020 will be higher.

Volumetric soil moisture of Shongoane increased from 2019 to 2020 (3-9 v/v) except for the clearing only treatment (14 v/v decrease) and the CSRSBP treatment (4 v/v decrease) (Figure 5.16). The clearing only treatment indicated the greatest decrease in soil moisture due to 'removed' tree and shrub species no longer providing cover and litter to the soil surface, thus increasing soil temperature, and no longer moderating soil evaporation (Daryanto *et al*., 2013b). Shongoane soil covered with the CRSBP treatment and CRS treatments increased in soil moisture content with 36% (49.5 v/v) and 30.6% (45 v/v), respectively (Figure 5.16 and Table 5.3). Treatments containing BP seem to increase moisture content overtime (with 26-36%) except when combined with soil disturbance, which result in a decrease in volumetric soil moisture (12.1%). Grazing and overstocking changes bulk density, root biomass and hydraulic conductivity (ease with which soil pores transmit water), thus decreasing soil moisture (Cai *et al*., 2021). Rainfall increased from February 2019 to February 2020 by 62.4 mm; however, the volumetric soil moisture of the subsoil (20-30 cm) decreased which could be due to a combination of compaction (from grazing and overstocking as mentioned above) and evapotranspiration. Soil moisture influences nutrient availability to plants which releases available nutrients through mineralization (Hutley & Setterfield, 2008), which explains the correlation between soil moisture, nutrient status and the decreased density of grasses (after re-seeding) for Shongoane compared to D'Nyala (D'Nyala indicated increased richness in species and increased grass density (Mangani, 2021)). The volumetric moisture content of the D'Nyala and Shongoane site for depths of 0 – 10 cm and 20 – 30 cm are depicted in Figure 5.16 and Figure 5.17, respectively.

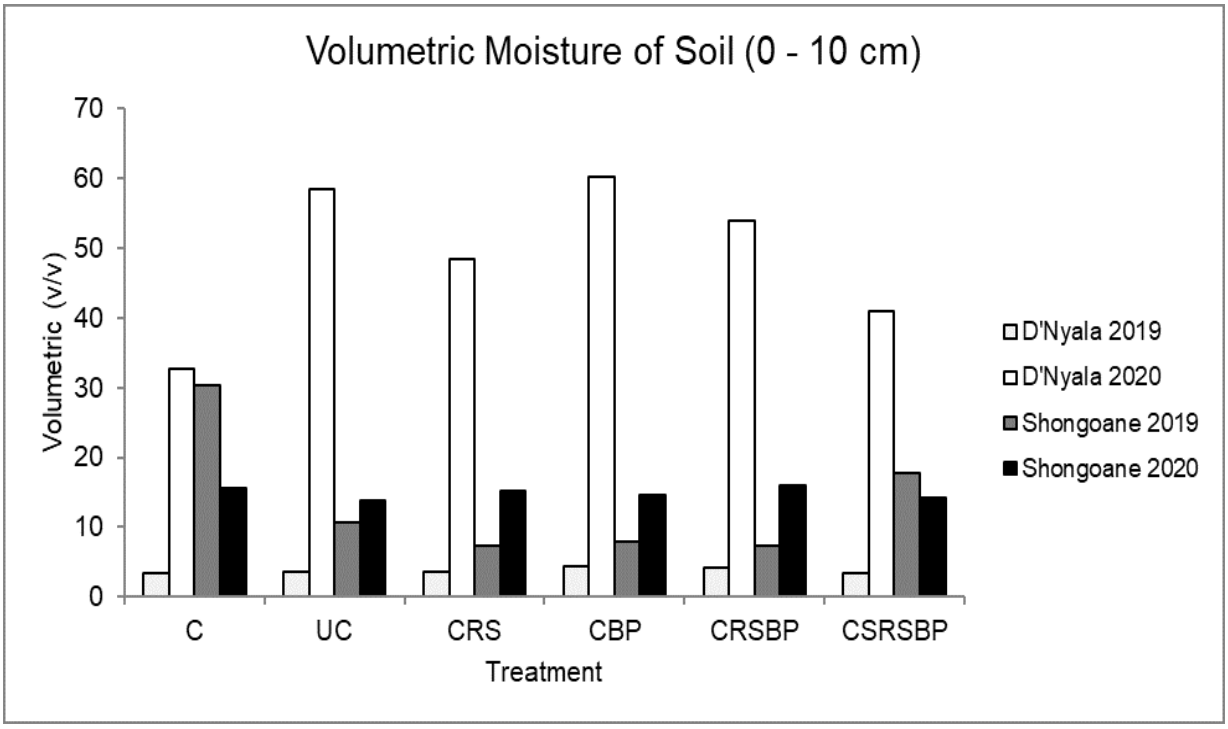

Figure 5.16: Volumetric moisture content at 0 – 10 cm soil depth for different restoration treatments

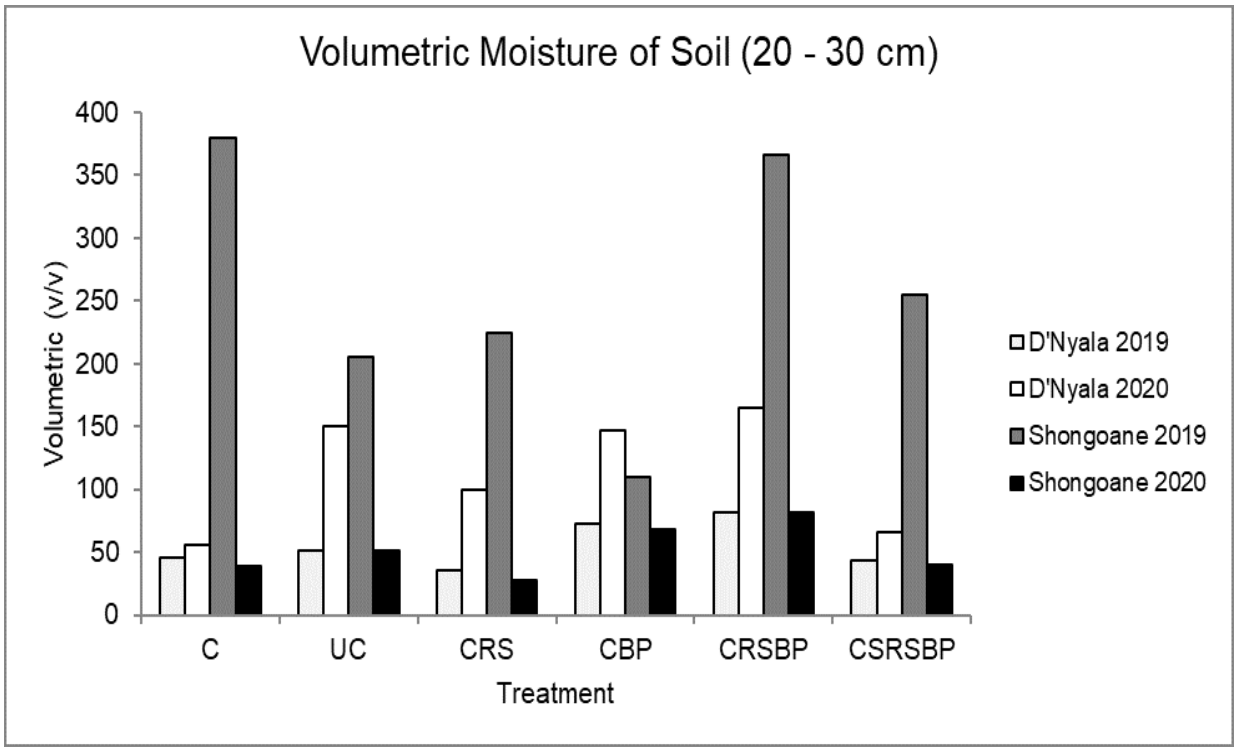

Figure 5.17: Volumetric moisture content at 20 – 30 cm soil depth for different restoration treatments at the D'Nyala and Shongoane study areas for 2019 and 2020

Table 5.3 summarises the percentage increase from 2019 to 2020 for the soil properties of the D'Nyala and Shongoane study areas regarding the various treatments. A Positive percentage indicates an increase from 2019 to 2020 for the soil property, while a negative value indicates a decrease. For example, -10% for the bulk density of the C treatment indicated that the soil bulk density decreased with 10% in 2020 (from its original value in 2019).

Table 5.3: Percentage (%) increase in soil properties from 2019 to 2020 regarding various treatments for D'Nyala (D'N) and Shongoane (S)

		Treatment/Cover method					
		C	**UC**	**CRS**	**CBP**	**CRSBP**	**CSRSBP**
Soil property	**Bulk density (D'N)**	-10	-5	-17	-4	-7	-8
	Bulk density (S)	3	8	-3	10	2	5
	Infiltration (D'N)	-2	1	8	-3	6	9
	Infiltration (S)	-17	-11	-31	-17	-19	-14
	SOM (D'N)	-55	10	200	-34	45	400
	SOM (S)	-68	-51	-40	-12	-47	-45
	pH (D'N)	8	2	11	3	14	14
	pH (S)	-22	-30	-28	-25	-24	-26
	EC (D'N)	74	68	120	69	147	128
	EC (S)	-87	-87	-85	-72	-86	-85
	Moisture (D'N)	725	1350	1125	1100	1100	925
	Moisture (S)	-30	12	30	26	36	-12

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The hypothesis of the project was proven true and according to data produced by this study, restoration treatments containing BP improves (combats decline in) the physical and chemical properties (so-called “soil quality indicators”) of bush encroached arid and semi-arid areas regarding 1) soil infiltration rate; 2) volumetric soil moisture; 3) soil bulk density; 4) pH (soil neutrality); 5) electrical conductivity (EC); 6) soil organic matter (SOM), and 7) soil nutrient status. Additionally, re-seeding contributes (increases) to the success of BP as a restoration treatment. All the project aims, and objectives were achieved using field and laboratory analysis methods as described in Chapter 4 and the following conclusions were made:

- The study areas of D’Nyala (conservation land-use type site) and Shongoane (communally-managed area) consisted mainly of the Avalon and Brandvlei soil form, respectively.

- The UC cover methods (continuation of bush encroachment) applied to D’Nyala soils indicated the lowest impact on soil properties (i.e., soil bulk density, infiltration rate, SOM, pH, EC and volumetric soil moisture), while the UC covered soils of Shongoane had a negative impact regarding the same soil properties (except for bulk density and soil moisture, which remained relatively constant). Thus, the continuation of bush encroachment (UC) has a very low impact on sandy soils and a low to negative impact on finer-grained soils. The C (clearing only) treatment indicated a decrease in bulk density, infiltration and SOM for both D’Nyala and Shongoane soils, except for pH, EC and volumetric soil moisture, which indicated an increase for D’Nyala soils (Table 5.3).

- The D’Nyala Nature Reserve soils covered with treatments containing re-seeding or brush packing combined with re-seeding (CRS, CRSBP and CSRSBP) indicated an increase in SOM (45-400% increase), soil moisture (45-90% increase), soil infiltration (<10% increase), and a decrease in bulk density (7-16% decrease) (Table 5.3). The CBP (clearing and BP only) treatment without re-seeding proved less effective in improving soil quality indicators and experienced a decrease in soil infiltration (3% decrease) and SOM (34% decrease) except for soil moisture content (increasing 11-times its original value), bulk density (4% increase) and pH (3% increase). Soil organic matter and plant roots (re-seeding) promote porosity and aggregation of soil particles and reduces bulk density (Nawaz *et al*., 2013). The CRS, CRSBP and CSRSBP treatments proved to be the most successful in improving soil bulk density, SOM, soil infiltration rate, pH (achieving soil

neutrality), volumetric soil moisture, CEC and EC from 2019 to 2020 for D'Nyala soils. The CRS and CSRSBP treatment were identified as the optimal treatment for increasing all soil quality indicators, the CBP treatment was identified as least optimal of all the treatments containing BP.

- Shongoane soils indicated a steady decline in soil properties (bulk density, soil infiltration rate, pH, EC and soil moisture content), except for soil moisture content for soils covered with treatments containing BP and/or re-seeding (Table 5.3). Rainfall increased in February 2020 (compared to February 2019) and the various treatments or cover methods had a clear effect on volumetric soil moisture (Figure 3.1), which contributed to the success of treatments containing re-seeding and/or brush packing for the D'Nyala study area but worsened the state of Shongoane soils regarding runoff and decreased infiltration (Figure 5.10) due to the compaction of soils (all treatments). EC and pH values dropped drastically (72-87% and 22-24% of the 2019 values, respectively) for soils covered with all treatments, resulting in Shongoane soils now classifying as acidic. The UC cover method indicated the greatest decrease in pH (2.1 decrease) and treatments containing BP indicated a smaller decrease (<1.8). Bulk density correlated directly with soil infiltration (soil infiltration rate decreased as soil bulk density increased), while SOM decreased by approximately half (45-51%) regarding all treatments except the C treatment (68% decrease in SOM) and the CBP treatment (10% decrease in SOM). Volumetric soil moisture decreased deeper in the soil for the clearing treatment only for Shongoane, due to a lack of woody vegetation (trees and shrubs) cover to reduce soil temperature and reduce evaporation on the soil surface (Daryanto *et al*., 2013b). The lowered (acidic) pH and SOM of Shongoane soils will result in Ca, Mg, P and K deficiencies. Shongoane has shallow, more compact soils and an acidic pH which could prove challenging for root establishment of grass species and the success of re-seeding efforts (Rajakaruna & Boyd, 2008).

In summary, the worst treatment/cover method (indicating little or no success) applied to D'Nyala soils and Shongoane soils is the C treatment (clearing of bush) followed by the UC cover method (allowing bush encroachment to continue and applying no restoration treatments to the soil). The treatment indicating the most success to improve soil properties for D'Nyala soils (sandy or coarse-grained soil) is the CRS (clearing and re-seeding) treatment followed by the CSRSBP (clearing, soil disturbance, re-seeding and brush packing) treatment and lastly the CRSBP (clearing, re-seeding and brush packing). Shongoane communally-managed area (fine- to medium-grained soil – sandy loam) did not indicate improvement of soil quality indicators or soil properties regarding all treatments, although treatments containing re-seeding and brush packing did slow the decline of soil quality indicators (bulk density, moisture, and SOM). The treatments

indicating the most success in slowing the decline of soil quality indicators for Shongoane soils are the CRSBP (clearing, re-seeding and brush packing) treatment, followed by the CBP (clearing and brush packing), the CRS (clearing and re-seeding), and lastly the CSRSBP (clearing, soil disturbance, re-seeding and brush packing) treatment.

6.2 Concluding remarks

In conclusion, soil type (i.e., sandy) influences the success of the six different restoration treatments. Compared to Shongoane (fine- to medium-grained or sandy loam), the D'Nyala study area (sandy or coarse-grained soil – loamy sand) indicated greater success of improvement in overall soil quality or soil quality indicators (i.e., soil bulk density, soil infiltration rate, soil moisture, SOM, pH and EC) of bush encroached savanna soils through the application of restoration treatments containing BP and re-seeding, especially regarding BP combined with re-seeding (Table 5.3). As a conservation site, the vegetation of D'Nyala was less disturbed by local farmers, residents and grazing livestock while Shongoane experienced the opposite (unrestricted, open grazing) as determined by Mangani (2021). Soil degradation, by means of trampling by animals or the removal of sources of SOM and biomass can alter soil properties and ultimately, soil productivity (Nawaz *et al*., 2013). Thus, the success of clearing, soil disturbance, re-seeding and BP is also influenced by external factors. The treatments containing 'clearing' (the removal of woody vegetation) without re-seeding (thus, C and CBP) results in a loss of soil cover (a protective layer against rain drop impact) and no addition of vegetation to contribute to SOM or the number of plant roots present in the soil. Thus, clearing only (C) and clearing combined with BP is less effective without re-seeding. Evidence from this study concluded that brush packing, and brush packing combined with re-seeding decelerate the decline of soil quality indicators (soil chemical and physical properties) in areas with sub-optimal soil types, poor treatment application or poor rangeland management, but increases soil quality when managed and applied correctly to suitable soil types.

6.3 Study limitations

The study sites were identified in February 2017 and the plots were laid out in November 2017 according to vegetation species homogeneity and distributional patterns and the treatments were applied in November 2017 (Mangani, 2021). Soil surveys were not conducted to assist in the identification and selection of the study sites. This study also commenced more than a year after the application of all six treatments and thus the original state of the surface soil was never recorded.

6.4 Recommendations

6.4.1 Identification of experimental plots

The experimental plots of a study area should be investigated before the selection and application of different restoration treatments in terms of soil properties in addition to vegetation patterns. Plots should be chosen with the same average soil depth and particle size distribution. Areas should be chosen which are more protected, where disturbance will be minimized. For example, Shongoane had some of its brush packing randomly removed by residents (throughout the study area and not concentrated in one or two areas only), for the use of firewood, the building of fences and to allow grazers access to the newly grown grasses between 2019 and 2020 (Mangani, 2021).

6.4.2 Recommendation for further studies

The effects of various restoration treatments (clearing, re-seeding and brush packing) should be analysed regarding soil microbes since bush removal disrupts the soil ecosystem, soil moisture and SOM (Buyer *et al*., 2016). Treated sites should be investigated for a longer period to determine the long-term outcome of the brush packing, re-seeding, clearing and soil disturbance treatments as restoration methods in arid and semi-arid savanna biomes.

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ANNEXURE A – SOIL CLASSIFICATION OF FIELD DATA

D'NYALA									
Method	**Block**	**Soil Horizon**	**Depth (cm)**	**Texture**	**Clay%**	**Dry Colour**	**Wet Colour**	**Horizon**	**Soil Form**
CRS	1	A	20	Medium/Coarse	10	10YR 5/3	10YR 4/2	Orthic A	Avalon
	2	A	20	Medium	20	10YR 5/3	10YR 5/2	Orthic A	Avalon
		B1	20	Medium	30	10YR 5/4	10YR 5/2	Yellow Brown Apedal B	Avalon
	3	A	15	Medium	10	10YR 5/3	10YR 4/5	Orthic A	Avalon
		B1	30	Medium	10	10YR 5/4	10YR 5/2	Yellow Brown Apedal B	Avalon
		B2	25	Medium	10	10YR 5/4	10YR 5/2	Yellow Brown Apedal B	Avalon
CSRSBP	1	A	20	Medium/Coarse	<5	10YR 5/2	10YR 4/2	Orthic A	Avalon
		B	40	Medium/Coarse	<5	10YR 5/3	10YR 5/3	Yellow Brown Apedal B	Avalon
	2	A	15	Fine/Medium	10	10YR 5/3	10YR 5/2	Orthic A	Avalon
		B	30	Fine/Medium	10	10YR 5/3	10 YR 5/2	Yellow Brown Apedal B	Avalon
	3	A	15	Medium	5	2.5Y 5/3	10YR 5/3	Orthic A	Avalon
		B1	25	Medium	10	2.5Y 5/6	10YR 5/3	Yellow Brown Apedal B	Avalon
		B2	20	Medium/Coarse	10	2.5Y 5/6	10YR 5/3	Yellow Brown Apedal B	Avalon
CRSBP	1	A	20	Medium/Coarse	10	10YR 5/3	10YR 4/2	Orthic A	Avalon
		B	110	Medium/Coarse	20	10YR 5/4	10YR 5/2	Yellow Brown Apedal B	Avalon
	2	A	10	Fine	22	2.5Y 5/3	2.5Y 5/3	Orthic A	Avalon
		B	50	Fine	35	2.5Y 5/4	2.5Y 4/4	Yellow Brown Apedal B	Avalon
	3	A	10	Coarse	10	10YR 5/3	10YR 4/2	Orthic A	Avalon
		B	40	Coarse	25	10YR 5/4	10YR 5/3	Yellow Brown Apedal B	Avalon
CBP	1	A	30	Fine/ Medium	25	10YR 5/3	10YR 4/2	Orthic A	Avalon
		B1	70	Fine/ Medium	30	10YR 5/3	10YR 5/4	Yellow Brown Apedal B	Avalon
	2	A	20	Medium/Coarse	<5	10YR 5/3	10YR 4/2	Orthic A	Avalon

	3	A	20	Medium	15	10YR 5/2	10YR 4/2	Orthic A	Avalon
		B1	50	Fine	35	10YR 5/3	10YR 5/3	Yellow Brown Apedal B	Avalon
UC	1	A	30	Me-dium/Coarse	5	10YR 5/3	10YR 4/3	Orthic A	Avalon
		B	60	Me-dium/Coarse	10	10YR 5/4	10YR 5/4	Yellow Brown Apedal B	Avalon
	2	A	15	Me-dium/Coarse	5	10YR 6/3	10YR 4/2	Orthic A	Avalon
		B	30	Coarse	10	10YR 5/4	10YR 5/2	Yellow Brown Apedal B	Avalon
	3	A	25	Fine	45	10YR 5/2	5Y 4/3	Orthic A	Avalon
		B1	40	Fine	45	2.5Y 4/3	5Y 4/4	Yellow Brown Apedal B	Avalon
		B2	50	Fine	40	2.5Y 5/33	2.5Y 4/3	Yellow Brown Apedal B	Avalon
C	1	A	30	Me-dium/Coarse	<5	10YR 5/3	10YR 4/2	Orthic A	Avalon
		B1	70	Me-dium/Coarse	<5	10YR 5/3	10YR 4/2	Yellow Brown Apedal B	Avalon
	2	A	20	Me-dium/Coarse	10	2.5Y 5/6	2.5Y 4/3	Orthic A	Avalon
		B1	40	Me-dium/Coarse	10	2.5Y 5/4	2.5Y 4/3	Yellow Brown Apedal B	Avalon
		B2	20	Me-dium/Coarse	10	2.5Y 5/4	2.5Y 4/3	Yellow Brown Apedal B	Avalon
	3	A	15	Me-dium/Coarse	25	10YR 5/3	10YR 5/2	Orthic A	Avalon
		B1	20	Me-dium/Coarse	10	10YR 5/4	10YR 5/2	Yellow Brown Apedal B	Avalon
		B2	10	Me-dium/Coarse	10	10YR 5/4	10YR 5/2	Yellow Brown Apedal B	Avalon

SHONGOANE									
Method	**Block**	**Soil Horizon**	**Depth (cm)**	**Texture**	**Clay%**	**Dry Colour**	**Wet Colour**	**Horizon**	**Soil Form**
CRS	1	A	10	Fine	35	10YR 4/2	2.5Y 4/3	Orthic A	Mispah
	2	A	10	Fine	35	2.5Y 4/2	7.5YR 3/2	Orthic A	Brandvlei
		B	5	Fine	45	7.5YR 3/1	10YR 4/2	Soft Carbonate	Brandvlei
	3	A	10	Fine	45	10YR 5/2	2.5Y 4/3	Orthic A	Brandvlei
		B	25	Fine	40	2.5Y 5/3	10YR 4/2	Soft Carbonate	Brandvlei
CSRSBP	1	A	20	Fine	45	10YR 4/2	10YR 4/3	Orthic A	Brandvlei
		B	15	Fine/ Medium	40	10YR 6/2	2.5Y 4/3	Soft Carbonate	Brandvlei
	2	A	15	Fine	50	2.5Y 4/3	2.5Y 4/4	Orthic A	Brandvlei
		B	20	Fine	45	2.5YR 4/3	2.5YR 4/4	Soft Carbonate	Brandvlei
	3	A	15	Fine	50	10YR 4/2	7.5YR 3/1	Orthic A	Brandvlei
		B	30	Fine	45	2.5Y 4/3	7.5YR 3/1	Soft Carbonate	Brandvlei
CRSBP	1	A	10	Fine	30	2.5Y 4/3	10YR 4/2	Orthic A	Mispah
	2	A	20	Fine	25	10YR 4/2	10YR 4/2	Orthic A	Mispah
	3	A	10	Fine	50	2.5Y 4/3	10YR 4/2	Orthic A	Brandvlei
		B	20	Fine	25	2.5Y 4/3	10YR 4/2	Soft Carbonate	Brandvlei
CBP	1	A	10	Fine	40	10YR 4/3	2.5Y 4/4	Orthic A	Brandvlei
		B	30	Fine	50	2.5YR 4/4	2.5Y 4/3	Soft Carbonate	Brandvlei
	2	A	25	Fine	50	2.5Y 4/3	10YR 4/2	Orthic A	Mispahi
	3	A	10	Fine	45	2.5Y 4/4	2.5Y 4/3	Orthic A	Brandvlei
		B	20	Fine	40	2.5Y 4/3	2.5Y 4/3	Soft Carbonate	Brandvlei
UC	1	A	10	Fine	50	2.5Y 4/2	2.5Y 4/2	Orthic A	Mispah
	2	A	15	Fine	45	2.5Y 4/2	10YR 4/2	Orthic A	Brandvlei
		B	25	Fine	45	10YR 5/2	10YR 4/2	Soft Carbonate	Brandvlei
	3	A	10	Fine	30	2.5Y 4/3	10YR 4/2	Orthic A	Brandvlei
		B	20	Fine	30	2.5Y 4/3	10YR 4/2	Soft Carbonate	Brandvlei
C	1	A	20	Fine	35	10YR 4/3	10YR 4/1	Orthic A	Brandvlei
		B	10	Fine	45	10YR 4/2	7.5YR 5/1	Soft Carbonate	Brandvlei
	2	A	15	Fine	50	2.5Y 4/3	2.5Y 4/4	Orthic A	Brandvlei
		B	30	Fine	50	2.5Y 4/3	2.5Y 4/3	Soft Carbonate	Brandvlei
	3	A	8	Fine	40	2.5Y 4/3	10YR 4/2	Orthic A	Brandvlei
		B	8	Fine	45	10YR 4/2	7.5YR 3/1	Soft Carbonate	Brandvlei