The combined effect of slash burning and repeated disc harrowing on changes in fuel loading, soil properties, root growth and stand productivity of Eucalypts in Mpumalanga: South Africa

by

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Thesis presented in partial fulfilment of the requirements for the degree of
Master of Science in Forestry

at
Stellenbosch University
Department of Forest and Wood Science, Faculty of AgriSciences

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December 2019

Declaration

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Abstract

In many South African plantation forestry regions, repeated disc harrowing (after clear felling and during stand development) among other objectives is used as a fuel load reduction measure to minimise wildfire damage. This study reports the effects of this treatment on fuel loading, soil properties and stand growth. The implementation of repeated disc harrowing throughout the rotation of *Eucalyptus grandis x nitens* stands significantly reduced fuel loading of the most active (i.e. the finer) fuel classes. In a fence line study of adjacent experimental plots, repeated disking (BD) was contrasted with non-disking (B0) treatments. Repeated disc harrowing reduced the average oven dried fuel loading of the 1 hour fuel class by 29.0 t ha^{-1} and that of the 10 hour fuels by 4.3 t ha^{-1} when compared to the non-disked treatments. Repeated disc harrowing significantly altered the forest floor structure. The non-disking treatment consisted of the litter (L), fermented (F), and humus (H) strata on top of the mineral soil (MS) layer. Following numerous harrowing application in the BD treatment, the forest floor structure was reduced to only a sparse L layer directly on top of the MS layer. This indicated a considerable change in fuel loading and forest floor structure as a result of disc harrowing.

Repeated disc harrowing significantly increased topsoil exchangeable cation quantities, S-value, and reduced bulk density. Topsoil exchangeable K, Ca, Mg, Na, and S-value increased by 0.04, 0.34, 0.12, 0.01 and 0.51 $cmol_c$ kg^{-1} respectively following repeated disking. The topsoil pH_{KCl}, extractable P, total N and C were not significantly different among the two treatments.

The above and below ground tree growth variables examined in this fence line study indicated no significant differences following repeated disc harrowing treatment. The BD treatment exhibited similar stand density of 1168 stems ha^{-1} over 1141 stems ha^{-1} for B0 treatment. Likewise, stand productivity was similar among treatments, with basal area, volume, and plant biomass in the B0 treatment being 24.6 m^2 ha^{-1}, 212.5 m^3 $ha^{-1}$and 134.4 t ha^{-1} *versus* 23.5 m^2 ha^{-1}, 202.6 m^3 ha^{-1} and 127.5 t ha^{-1} for the BD treatment. Using a profile wall root study method, B0 treatment was observed to have a non-significantly higher root count of 30% on the top 10 cm soil depth when contrasted to BD treatment, which was 22% (percentage of the total root count on a 1 x 1 m vertical profile wall). All the differences observed on the tree growth and stand productivity

parameters among the two treatments were not significant at (p<0.05). The negligible growth reduction in repeatedly disked treatment is surpassed by the significant fuel load reduction and reduced wildfire risk.

Opsomming

ʼn Aantal bosboustreke in Suid-Afrika eg stroke grond met ʼn skotteleg na kaalkap (maar daarna ook herhaaldelik gedurende die rotasie), ten einde brandstof lading te verminder en sodoende skade deur veldbrande te beperk. In hierdie studie word die effek van hierdie behandeling op brandstoflading, grondeienskappe en opstandsgroei ondersoek.

Herhaalde eg operasies gedurende die rotasie in *Eucalyptus grandis x nitens* opstande het gelei tot vermindering in brandstof lading van die aktiefste (d.w.s die fynste) brandstofklasse. In 'n studie van aangrensende persele is herhaalde egting (BD) gekontrasteer met onbewerkte (B0) behandelings.

Die oonddroë brandstoflading van die 1 uur brandstofklas is deur herhaalde egting verminder met 29,0 t ha^{-1} en die brandstof van 10 uur klas met 4,3 t ha^{-1} vergeleke met die onbewerkte persele. Herhaalde egting het ook ʼn wesenlike verandering in die struktuur van die bosvloer teweeggebring. Die onbewerkte behandeling het bestaan uit die onlangs gekapte materiaal (L – laag), gefermenteerde (F) en humus (H) laag bo-op die minerale grondlaag (MG). Na 'n gereelde egting in die BD-behandeling, is die bosvloer struktuur verskraal tot slegs 'n ylerige L-laag direk bo-op die MG-laag. Dit dui op 'n aansienlike verandering in brandstoflading en bosvloerstruktuur as gevolg van herhaalde egting.

Herhaalde egting het die hoeveelheid uitruilbare katione, die S-waarde en die bulkdigtheid van die bogrond beduidend verhoog. Die bogrondse uitruilbare K, Ca, Mg, Na en S-waarde het met herhaalde egting onderskeidelik met 0.04, 0.34, 0.12, 0.01 en 0.51 $cmol_c$ kg^{-1} gestyg. Die bogrondse pH_{KCl}, ekstraheerbare P, totale N en organiese koolstof het nie beduidend verskil tussen die twee behandelings nie.

Bogrondse en ondergrondse boomgroeiveranderlikes wat in aangrensende persele ondersoek is, het nie beduidend verskil tussen behandelings nie. Die BD-behandeling se opstandsdigtheid van 1168 stamme ha^{-1} was vergelykbaar met die 1141 stamme ha^{-1} vir die B0-behandeling. Net so was die maatstawwe van opstandsproduktiwiteit nie betekenisvol verskillend (p<0.05) tussen die behandelings nie. Die basale oppervlakte, volume en biomassa in die B0-behandeling was 24.6 m^2 ha^{-1}, 212.5 m^3 ha^{-1}, en 134.4 t

ha^{-1} teenoor waardes van 23.5 m^2 ha^{-1}, 202.6 m^3 ha^{-1}, en 127.5 t ha^{-1} vir die BD-behandeling.

Met behulp van 'n profielgat wortelstudiemetode is daar waargeneem dat die B0-behandeling ʼn effens hoër worteltelling van 30% in die grondlaag van 0-10 cm het, in teenstelling met BD-behandeling, wat 22% was. Hierdie effek was egter nie betekenisvol nie. Die weglaatbaar klein negatiewe effek op opstandsgroei na herhaalde egting word oorskadu deur die aansienlike vermindering van die brandstoflading en die gepaardgaande verlaging in die brandrisiko.

Dedication

I dedicate this thesis to my late mother

Vuyiswa Veronica Goldsmith

1968 - 1999

My mother, role model, and inspiration, passed on before I could experience her love and kindness which many people tell me stories about. Mama, your legacy lives on.

Acknowledgements

I give my gratitude to the following persons and organizations for their invaluable assistance in the success of this project:

- Professor Ben du Toit, my supervisor, for your time, patience & academic advice.
- Johané Nienkemper-Swanepoel for your statistical analysis advice.
- Aladrian Elmore for editing this manuscript.
- Dr. Ronn Elmore for being my mentor, counselor, and spiritual advisor.
- Dean da Costa, Paul Viero, Tim Pretorius, and Rudi du Randt for invaluable on-the-ground assistance whenever I needed it.
- Mondi Group for funding and allowing me to use their property to conduct this research.
- Southern African Institute of Forestry for additional funding.
- Daniele Poiati for your contribution throughout the field sapling phase up until laboratory work and data collection and capturing phase. Muzi Khumalo & Scelo Sangweni for offering an extra hand.
- My family at large, especially brothers Patrick & Christopher Goldsmith, & Ali Gaehler for your unconditional love.
- My dear friends Chulumanco Sigcau, Siyababalwa Athenkosi Bhucwa, & Munyaradzi Makoto for your loyal continued support.
- The Earth & Luxe Scholars for moral support.
- “The Small Things Fund” community, especially Rhoda Malgas for creating & offering me a supportive environment for the duration of my study.
- Above all, I give absolute glory to God our heavenly Father for entrusting me with such a great opportunity.

- Genesis 2:15 (NIV) [15] The Lord God took the man and put him in the Garden of Eden to work it and take care of it.

Thank you very much.

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1. INTRODUCTION

Potential benefits around the application of prescribed burning, as well as the negative effects of uncontrolled wildfires are well documented on the available literature with regard to plantation forests (Norris, 1993). These include reduction of surplus woody fuels and elimination of unwanted vegetation for improved site access, the negative effects being excessive soil erosion, nutrients depletion and increased soil water repellence.

De Ronde et al. (2004) suggested numerous strategies and techniques to reduce forest fuel loading that would minimize the chances of uncontrolled wildfire damage. Placement of firebreaks on plantation boundaries had become a standard practice. This is done to counteract wildfires from adjacent properties spreading into the plantation or to contain fire within the plantation not to spread onto adjacent property. However, operations like thinning, pruning, and coppice reduction tend to increase the amount of available fuel within compartments. De Ronde (1982) proposed the practice of under canopy prescribed burning to be conducted in *Pinus patula* stands. The practice was reported to be effective in reducing fuel loading during the rotation. This was especially true with 1 hour and 10 hour fuel classes with minimal impact on soil, and with tree growth when a low to moderate burn is conducted (Gresse, 2016).

Similarly under canopy prescribed burning practice is also implemented in Eucalyptus stands. According to Potgieter (2016), this operation requires thorough planning, must be conducted under ideal weather conditions, and only in stands above six years old. However, many *Eucalyptus* species are fire sensitive due to thin bark; under canopy burning in these stands may result in high tree motility. The applicability of under canopy burning in *Eucalyptus* stands is further limited by special fire ignition techniques and is a time consuming operation. There is limited research publication on the available literature regarding under canopy burning in *Eucalyptus* stands in South Africa. Hence the majority of literature presented in this paper is cited from under canopy prescribed burning practice conducted in *Pinus patula* stands.

The implementation of repeated disc harrowing in *Eucalyptus* plantations of South Africa is practiced as an alternative to reduce stand fuel loading. The idea with this practice is to create a break in fuel horizontal continuity in order to reduce rate of spread of surface fires as well as to reduce fuel loading on the disc swathes, thus reducing fire intensity.

Fine and medium sized fuel classes are the main target fuels since these classes are more active in influencing fire behaviour. Altering the latter mentioned fuel characteristic presents an ideal situation to prevent wildfire occurrence as well as a great opportunity to safely control and suppress fire with much more ease if it does occur. Disc harrowing is done using an agricultural tractor pulling a disc harrow to break up and incorporate slash and forest floor material into the soil. This is commonly done in swathes between tree rows, after every seven rows of trees (Figures 3.6 - 3.8). This tillage operation is commonly done repeatedly throughout the stand rotation. It should be noted that the strategic placement of disked swathes may vary from site to site, depending on the degree of fire risk and vulnerability of the compartment. Nevertheless, the efficiency and effectiveness of this operation on fuel reduction as well as its impact on tree growth have not been examined and documented in the available literature; henceforth this study was conducted.

Eucalyptus forest plantations in South Africa are commercially planted primarily for pulp and paper production, and various other products (Godsmark and Oberholzer, 2019). These stands are intensively managed; in addition, numerous research studies have been conducted to ensure holistic sustainable forest management practices, to improve wood quality, and to strengthen forest protection against external biotic and abiotic risk factors (du Toit et al., 2014). Over the past four decades uncontrolled wildfires have been reported to account for majority of damage to forest plantations of about 669 439 hectares, (Godsmark and Oberholzer, 2019). Wildfires remain a major threat to the forestry industry, particularly with the increased rate of climate change and common episodic drought occurrence in South Africa (Strydom and Savage, 2016).

Tillage at site preparation, middle rotation or throughout the rotation in Eucalyptus forest plantations is done to achieve various other objectives: to enhance soil properties such as soil structure and incorporation of organic material for improved fertility (Dedecek et al., 2007); to improve tree survival and growth (Mhando et al., 1993; Jones et al., 1999; Smith et al., 2001); and, to manage under canopy vegetation and fuel loading (Carneiro et al., 2007; Madera et al., 2012; Carneiro et al., 2009).

Plant roots are responsible for colonising the site to absorb water and essential plant nutrients, enabling the plant to grow optimally and compete with its neighbouring vegetation. They penetrate the soil depth to anchor trees to the ground, preventing wind throws at a later stage, thus improving tree growth and survival (Grant et al., 2012). This makes it particularly important to understand the implication of repeated disc harrowing on root growth in this study.

Several studies reported in the literature may shed light on the effects of slash burning followed by repeated disc harrowing practices as it is currently practiced in Mpumalanga. These are slash burning studies, effects of bio charcoal application on soil, and soil tillage research trials; however, most of these treatments were implemented in isolation (du Toit, 2003; Gonçalves et al., 2004; Smith and Little, 2001). The proposed study is to evaluate the combined effects of the above-mentioned practices in *Eucalyptus* plantations in South Africa. The following effects will be investigated: the changes in forest fuel loading and forest floor structure, above ground tree growth, below ground growth (which is the root distribution patterns in soils), and soil nutrient status.

1.1. Study Objectives and Key Questions

The main goals the study aims to achieve are listed as points 1 - 4. The key questions that need to be answered to accomplish the main goals are listed under alphabetical letters:

1. To examine the effectiveness of repeated disc harrowing throughout the stand rotation on forest fuel load reduction for wildfire management purposes.
    a. Is there a difference in fuel load following treatment?
    b. Which fuel classes underwent change following treatment?
    c. Are there any differences on the forest floor structure?
2. To investigate the effect of harvest slash residue burning incorporated with disc harrowing on total nitrogen, available phosphorus, soil organic carbon, base cation content and ECEC.
    a. Are there any changes to the forest floor and soil profile structure due to treatment?

   b. Did any of the forest floor, topsoil or subsoil horizons show evidence of change in total N, extractable P, total organic C, exchangeable base cation quantity and ECEC?

3. To determine the potential impact of slash burning during site preparation incorporated with repeated disc harrowing throughout the rotation on *Eucalyptus grandis x nitens* stand growth.

   a. Did treatment implementation affect stand density?

   b. Could differences in mean tree or stand level variables be detected among treatments?

4. To investigate whether prescribed slash burning incorporated with repeated disc harrowing has any effect on root distribution patterns of *Eucalyptus grandis x nitens*.

   a. Did any of the soil horizons show evidence of change in the abundance of coarse, medium and fine root size class distribution patterns?

1.2. Relevance of Study

The results from this study will aid forest managers as a decision supporting tool to select the most appropriate harvest slash residue management practice, and evaluate the effectiveness of using repeated disc harrowing to manage forest fuel loading during the rotation of *Eucalyptus grandis x nitens* stand. It will also give a viable indication of long term soil nutrient sustainability, soil fertility as well as tree growth, and stand productivity when these management practices are implemented.

2. LITERATURE REVIEW

2.1. Introduction

Plantation forestry in South Africa is the business of growing trees by making use of various production factors, which include land as the actual planting site. Given the fact that plantation forestry is practiced using natural resources, the South African forestry industry adopted the 'triple bottom line' sustainable forest management practices, which require growers to belong to a certification body and conform to specified standards of practices that promote social, economic and environmental sustainability (Brink, 2012).

Plantation forestry is practiced in an open environment which increases risks and vulnerability to external factors. Amongst the vast variety, impact of uncontrolled wildfires has been reported as the major threat (Forsyth, Kruger, & Le Maitre, 2010). Godsmark and Oberholzer (2019), reported that in South Africa from 1980 - 2017, an area of 1 143 116 hectares suffered some damage from biotic and abiotic external factors; wildfires alone accounted for the highest proportion of about 669 439 hectares (59%), and the remaining 473 677 hectares (41%) shared amongst other abiotic and biotic factors (Figure 2.1).

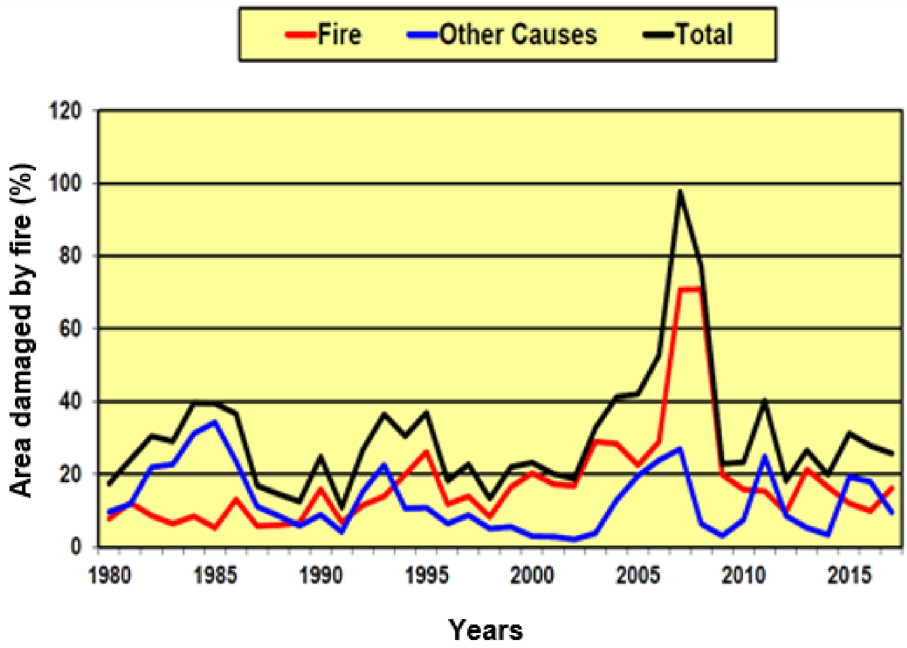


Figure 2.1: Damage to plantation by fire from 1980 - 2017 (Godsmark and Oberholzer, 2019)

Unmanaged forest fuel loading has been identified as one of the chief contributing factors to the occurrence, spread and intense damage caused by wildfires. In an attempt to reduce the incidence of uncontrolled fire, Gorte (2010) mentioned numerous alternative strategies that may be implemented as a means for effectively reducing forest fuel loading to minimal levels. This includes changing characteristics of existing fuel, partial removal of fuel, and partial combustion.

It is critical for fire managers to identify all operations that contribute to an increase in forest fuel loading, such as harvesting, pruning, thinning, coppice reduction and weed control (slashing understory vegetation such as *Solanum mauritianum*), as well as herbicide application operations (de Ronde et al., 2004). Such operations tend to influence the fuel characteristics, resulting in an increase in fuel availability and fuel loading. This necessitates holistic planning of all of operations and the implementation of an integrated management plan to counteract the levels of fuel loading; this will consistently keep risk of uncontrolled fires at minimum levels.

This chapter presents various findings from the available published literature regarding the implementation of numerous fuel loading management methods and their impact on site long-term productivity. This chapter specifically focuses on fire and fuel management practices, application of soil tillage, bio charcoal application and slash management in commercial forestry plantation in relation to fuel loading, impact on soil fertility and tree growth in Eucalypt stands. Research publications regarding under canopy burning in *Eucalyptus* stands is limited in the literature. Thus, the majority of literature presented in this chapter is cited from under canopy prescribed burning practice conducted in *Pinus patula* stands.

The South African forest industry is faced with a huge challenge of an increased demand for timber while land suitable for planting is continuously decreasing. The decrease is due to land claims amounting to about 40% of privately owned plantations, 70% of the state-owned plantation land, and strict environmental policies on water licensing and wetland restrictions (Chirwa, 2015). In order to keep up with the ever increasing timber demand, growers plant fast growing species that will grow to maturity and be ready for market within a short rotation; this has resulted in an increased interest in farming with *Eucalyptus* species. Godsmark and Oberholzer (2019) noticed a trend from 1980 to 2017 of an increasing plantation productivity while plantation area continued to decrease (Figure 2.2).

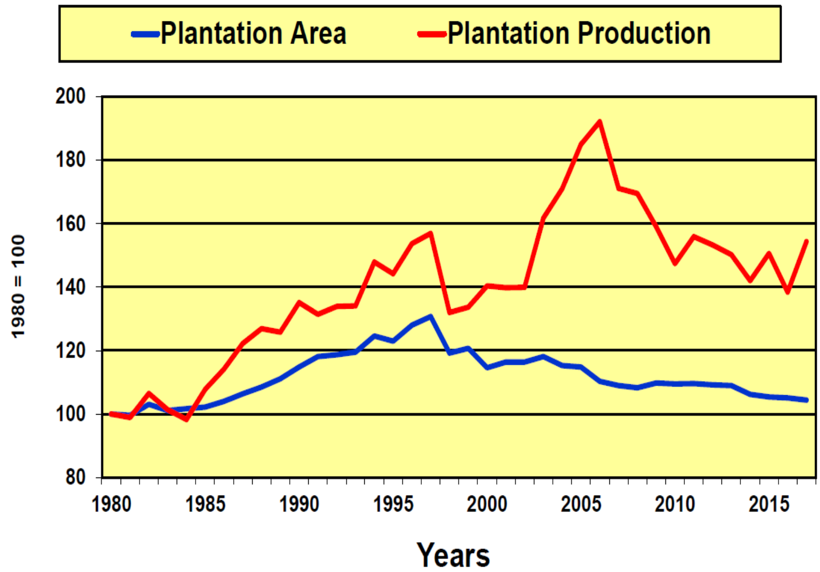


Figure 2.2: Index of round wood production vs plantation area from 1980 to 2017 (Godsmark and Oberholzer, 2019)

Eucalyptus species are known for rapid growth with rotations between 8 to 15 years and relatively less intensive management requirements in comparison to *Pinus* species; however, its down side is a relatively high nutrient demand and potentially negative impact on the soil structural properties between the short successive rotations (Jones et al., 1999). It is particularly imperative to consider the fact that plant growth is highly dependent on site conditions; however, silviculturists can manipulate site conditions through a variety of practices that can influence plant growth. For example, fertilizer application at planting and at mid-rotation can counteract nutrients lost through harvesting and harvest residue slash burning, while soil tillage can be used as a remedy for damaged soil structure to maintain the site in more sustainable and productive condition.

To a large extent, current forest management practices influence soil nutrient dynamics and hence, site productivity and sustainability. Du Toit (2003), noted that certain management practices might result in a decline in nutrient pools (burning and harvesting), while the others may have a positive input on the nutrient fluxes (fertilization). For this reason it is critical to monitor stocks of Nitrogen, Phosphorus and Carbon and the base cations essential for plant growth and survival.

Implementation of disc harrowing during site preparation and at mid-rotation is practiced in South Africa for both silvicultural purposes and fire management. Madeira (2012) states that findings from his experiments yielded positive results, such as improved soil friability, aeration and incorporate residues into the soil possibly improving tree growth. Karer et al. (2013) also mentioned bio charcoal application as an efficient soil rehabilitation remedy for both physical and chemical properties. In the context of this study, the term bio charcoal is used to refer to the remaining charred material from harvesting resides after slash burning.

2.2. Forest Fuel and Fire Management Strategies

Occurrences of uncontrolled wildfires that destroy plantation forests and natural ecosystems are among the biggest threat commercial plantation forests are vulnerable to. To manage wildfires (de Ronde, 2004), various strategies and techniques have been investigated and implemented for both small and large scale practices; this is termed integrated fire management. The principles of fire management are mainly based on three components: prevention, protection and suppression. This chapter presents research findings with specific focus on the "protection" component.

Research findings presented by various scientists suggest that in order for a wildfire to exist, it requires three of the fundamental environmental components: heat, oxygen and fuel. These are commonly referred to as the fire triangle (Trollope, de Ronde & Geldenhuys, 2004) presented in Figure 2.3. Fuel remains the only aspect that fire managers can potentially manipulate as an attempt to manage wildfire related risks.

Figure 2.3: Fire triangle (NOVA SCOTIA, 2013)

Forest fuels strongly impact fire behaviour: ignition, intensity, the rate of spread, and flame height (Teie, 2009). The extent to which the fuels will influence the fire behaviour is related to the generic fuel characteristics of shape and size, compactness, fuel loading, horizontal continuity, and vertical arrangement (fuel ladder). However, fire behaviour is not entirely dependent on fuels, but is also influenced by weather and topography as well (Bradstock et al., 2012).

Shape and size: The time it will take for fuels to ignite when presented to a heat source is mainly determined by its form and dimension. Woody fuel material of large dimensions with a rough surface requires more heat and takes more time to ignite, as opposed to fine fuels of smaller diminutions. Fuel shape and size also determines the amount of time it will take the material to either gain or lose moisture to be in equilibrium with ambient atmosphere (Wade & Lunsford, 1989). Fuel shape and size also influence the amount of heat required for ignition as well as the duration of the exposure, thus influencing fire intensity. The small fine woody fuel lose or gain moisture rapidly in comparison to thick heavy fuel which requires lengthy periods of exposure and a high amount of heat. Hence fine and coarse fuels classes highly impact fire rate of spread. Schlobohm & Brain (2002) better explains the impact of fuel size and shape on fire behaviour and moisture content using fuel time lag classes presented in Table 2.1. Hollis et al. (2016) states that 1 hour and 10 hour fuel class make up the largest proportion of the available fuels and are the most active fuel classes influencing fire behaviour in Eucalypt forest fires.

Table 2.1: Fuel time lag classes (Schlobohm & Brain, 2002)

Time lag	**Fuel diameter**	**Description**
1 hour	< 0.6 cm	Fine fuels moisture content fluctuate rapidly in response to weather conditions. Temperature, humidity and cloudiness.
10 hour	0.6 - 2.5 cm	Monitored from observation time temperature, humidity, and cloudiness. Also by using fuel sticks that are weighed for fire weather observation.
100 hour	2.5 - 7.6 cm	Observed from 24 hours average conditions. Day length, hours of rain, daily temperature, and humidity ranges.
1000 hour	7.6 - 20.3 cm	Observed over 7 days average conditions. Day length, hours of rain, daily temperature, and humidity ranges.

Compactness: Woody fuel material that is tightly arranged does not ignite and burn easily when presented to heat because compactness eliminates oxygen, the third component of the fire triangle. Conversely, loosely arranged fuel material provides access for oxygen to circulate freely, resulting in ease of fuel ignition and increased fire rate of spread (Wade & Lunsford, 1989).

Fuel Loading: The amount of available fuels in an area (t ha^{-1}) significantly influences the intensity of the fire. Fire intensity takes into account the amount of heat released by the fire over a given area within a duration of time (Teie, 2009). High accumulation of available fuels in an area results in highly intense fires with great damage to the environment. Fire intensity is linked to fire rate of spread. The more material available to burn, the longer the fire will take to consume woody fuels; thus high fuel loading produces a fire with enormous heat energy released in one area over a relatively lengthy period of time (Wu, He, Liu, & Liang, 2013).

Horizontal Continuity and Vertical Arrangement: Fire moving laterally on the land surface is entirely dependent on the horizontal continuity of the available fuels. Similarly, the vertical arrangement of fuel may cause a surface fire to develop into a crown fire (Fernandes et al., 2011). Horizontal continuity and vertical arrangement directly affect the fire rate of spread. Fire burning in sparse, patchy fuels will move much slower than when burning in an area with continuous dense available fuel on a horizontal plane. Also the presence of dry fuel ladder increases danger for surface fires becoming crown fires.

2.2.1. Structure of the forest floor fuel strata

Fuels in various ecosystems are broadly categorised into ground fuels, surface fuels, and aerial fuels. Ground fuels are all buried dead logs and root material, surface fuels are those fuels laying on top of the soil surface includes all dead and live material up to 2 m above the soil. Fuels above 2 m height are classified as aerial fuels (Teie, 2009). Surface fuels, both live material with diameter of <2.5 cm and dead material contributes significantly to the damage caused by wildfires and greatly impacts the fire behaviour (Fernandes et al., 2011).

Figure 2.4: Section of undisturbed forest floor with carefully cleared outer perimeter

The nature of this study necessitates a thorough understanding of the forest floor structure, functions and its generic characteristics concerning fire behaviour. Forest floor refers to all the dying, dead, and partially decomposed accumulation of flora and fauna organic material on top of the mineral soil in a forest ecosystem (Ross & du Toit, 2004). Figure 2.4 presents a typical forest floor structure that can be expected in an intensively managed and mature *Eucalypt* stand. The horizontal continuity, mass, and bed depth of the forest floor are dependent on decomposition and litter deposition rates. Morris (1995) reported that there is a correlation between site type and forest floor accumulation, and sites at high altitude were observed to have a relatively high forest floor mass. However, litter accumulation can also be influenced by silviculture activities, fires and the abundance of animal life in a particular ecosystem (Nadel, Scholes, & Byrne, 2007).

The forest floor plays significant roles in the forest ecosystem such as regulating water infiltration, thereby preventing excessive run off and erosion. The forest floor (Fisher & Binkley, 2000) was reported to be one of the major nutrient pools in a forest ecosystem. Du Toit (2006) presented strong evidence that manipulation of forest floor material has implications on the sites' long-term productivity in Eucalypt forest plantation systems. The forest floor also serves as an insulation mechanism with a direct impact on the soil microclimate and temperature, moister, and oxygen during adverse weather conditions.

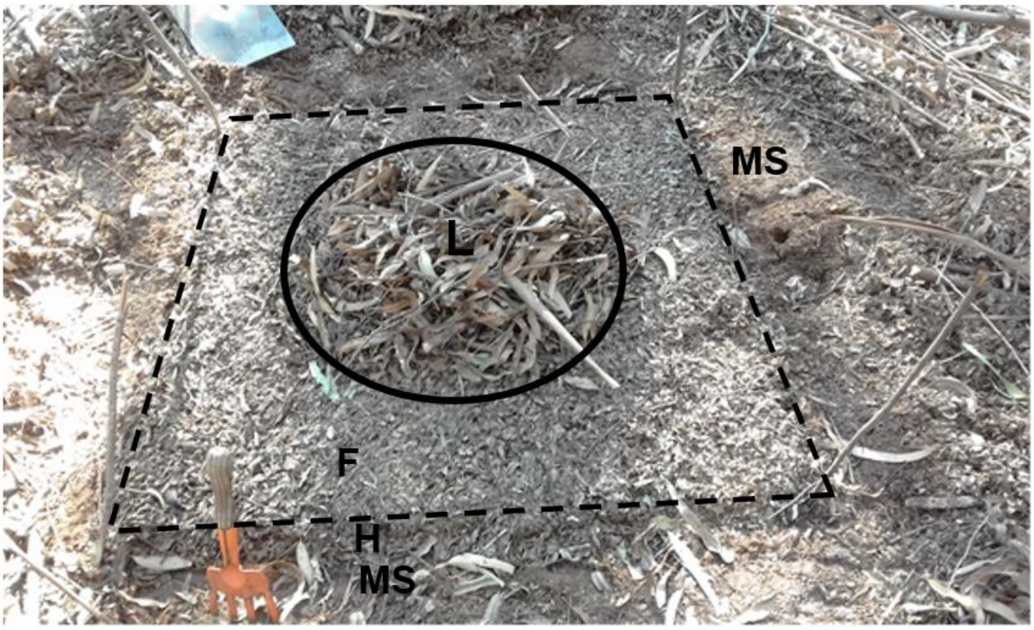


Figure 2.5: Categorised forest floor strata material assortments

Several layers in the forest floor strata exist, namely, the litter (L), fermented (F), and humus (H) layer on top of the mineral soil (MS) layer (Ross & du Toit, 2004). Figure 2.5 shows the aforementioned forest floor layers in a managed Eucalyptus plantation forest system. The material is labelled L - MS depicting the manner in which it would appear when observed on a transversal view from a horizontal direction.

The L layer is the first stratum consisting mainly of fresh dead bark, branch, and foliage material (Figure 2.5). This stratum constitutes significant amounts of available fuels and carries the majority of fire hazard because it is mostly concentrated with 1 and 10 hour fuel class characteristic of high fire receptiveness (De Ronde, 1990). The F layer is the second stratum comprised of partially decomposed material with its form still in a recognisable state; here fungi and bacteria exist. This stratum is between L and H in Figure 2.5 when observed in a cross section in a horizontal direction, even though it was challenging to demarcate it in this photograph. The H layer is where the decomposition process is in its peak; here the form of organic material is no longer recognisable (Figure 2.5). Lastly in Figure 2.5, the MS is the final stratum of the forest floor. A dark colouring appears in the interface between the mineral soil and humus layer. This is totally decomposed organic material mixed with the mineral soil and is an indication of carbon rich soil and various other nutrients elements. The layers L, F, and H account for the largest quantity of nutrient elements locked in the forest floor (Fisher & Binkley, 2000). These layers greatly influence the behaviour of surface fires. The L layer mostly impacts the ignition process, flame length, and the fire rated of spread, depending on the type of fuel class present on site. Conversely, the humus layer impacts the intensity of the fire as well as the degree of damage to the mineral soil (De Ronde, 1990). The humus layer consists of fine material that is characteristic of high fuel compactness. The amount of oxygen present in this layer allows for smouldering. Smouldering occurs at a much slower rate over a lengthy duration period, resulting in high fire intensity and soil damage.

2.2.2. Fuel load management techniques

A thorough knowledge of the aforementioned forest fuel characteristics, fire behaviour patterns and forest floor structure enables fire managers to understand the effectiveness of the particular fuel management technique in reducing the risk of wildfire damage. Rummer (2010) states that certain techniques completely remove or consume burnable material from site, thereby eliminating wildfire occurrence. The other methods, however, only alter important fuel characteristics, thus inhibiting and retarding erratic fire behaviour.

Partial Fuel Removing: Operations such as target grazing and browsing, chipping for bio energy, and firewood collection can be implemented to partially remove excess organic material that later becomes a fire hazard in forest ecosystems. Prescribed live stock is a strategically planned grazing or browsing operation in predetermined areas to accomplish fuel loading and fire hazard reduction (Browsing Academy, 1999; Lovreglio et al., 2014; Strand et al., 2014). According to the Browsing Academy (1999), prescribed livestock grazing can be implemented to create and maintain green/live fire breaks and to manage understory vegetation. Nader et al. (2007), states that prescribed herbivory reduce fire hazards by altering the following fuel characteristics: fuel bed depth, fuel loading, horizontal continuity, and vertical arraignment (ladder fuels). Target grazing and browsing effectiveness is only limited to fine 1 hour and 10 hour fuel classes (Strand et al., 2014). Livestock impact fuels either by ingestion: feeding on grass (fire breaks and buffer zones in grassland vegetation) and on understory vegetation (weeds, shrubs, twigs and branches); or physically: trampling over the forest floor fuel bed, rubbing posts, and “pruning” (breaking lower branches) (Lovreglio et al., 2014).

Nader et al. (2007) reported that prescribed herbivory (goats grazing on California Mountainous *Pine* and *Eucalyptus* forests) application over a period of three years resulted in reduction of vegetation cover ranging from 20 to 80%, a decline in understory vegetation of about 46% and 82% at a height of 50.8 cm and 1.5 m respectively, and a decrease of litter bed depth from 7.4 cm to 5.1 cm.

Altering Fuel Characteristics: One technique for managing fuel is to retain organic material on site while altering fuel traits that exacerbate erratic fire behaviour. This practice can be done using mechanical fuel load management techniques such as chopper rolling, mulching and disc harrowing. Graham et al. (2004) mentioned that chipping and mulching operations are effective in reducing fuels into fine compact material that becomes difficult to ignite and characteristic of a very slow rate of fire spread, making fire easy and safe to control and suppress. However, these operations do not reduce fuel loading. Mulching is efficient for fire risk reduction, but mulch layer prevents water infiltration and sun penetration; thus decomposition is hindered, resulting in microbial organisms consuming the available nitrogen required for plant growth (Rummer, 2010). Ryan et al. (2011), sustains the effectiveness of mulching in wildfire risk reduction, especially when implemented as a follow-up operation after pruning and thinning operations. Contrary to Rummer (2010) findings, Ryan et al. (2011), in this trail reported no impact in the soil microclimate and nitrogen following the treatment. This is due to a shallow fuel bed depth of the mulch material and the sparse broadcast distribution of the material from the mastication head of the machine.

Jones et al. (1999) mentioned disc harrowing as an effective alternative in fuel loading reduction through incorporation of organic material into the soil. This practice significantly and effectively addressed both fuel loading reduction and horizontal continuity with improved decomposition. Madeira et al. (2012) affirms that disc harrowing was effective on fuel loading reduction when implemented at mid-rotation of *Eucalyptus grandis* stand for fire risk reduction. Ximenes et al. (2017) and Hugget et al. (2008) state that there is an increasing demand for alternative efficient fuel load reduction methods to substitute the application of controlled burning. This is primarily due to climate change presenting a limited window of ideal weather conditions for burning, the urban and forest interface raising social and health issues (concern over smoke pollution), and increased record of runaway fires from controlled burn. Campbell & Ager (2013), also add the question of carbon stocks to the list. Furthermore, Fernández et al. (2013) substantiates that mechanical fuel load reduction is an efficient alternative when managing wildfire risk in a landscape with vegetation that is highly sensitive to fires.

Prescribed Burning: Partial combustion of fuels through prescribed burning practice has historically been conducted to accomplish fuel load reduction in one of several burning techniques: burning open areas, block burning, slash burn, under canopy burn, and firebreaks (de Ronde, 1982; de Ronde et al., 2004; Bradstock et al., 2012; Fernández et al., 2013; Campbell & Ager, 2013; Wu et al., 2013; Bird & Scholes, 2005). Fire intensity in this regard becomes of critical importance as it greatly impacts both the soil's physical and chemical properties, as well as tree survival after fire.

De Ronde (1990), reported that various fire intensities will alter the forest floor structure differently: with reference to Figures 2.4 and 2.5, fires with high intensity consume all of the forest floor material down to mineral soil (MS), as opposed to medium intensity fires that consume only the litter layer (L) and a small portion of the humus layer (H). On the contrary, low intensity fires are only limited to the litter layer (L). Prescribed burning is careful implementation of a pre-planned fire under ideal weather conditions to achieve a low to medium fire intensity that will consume all the excess woody fuels on the forest floor, but leave the humus layer protecting the mineral soil from the burn (Goldammer and de Ronde, 2004). Table 2.2 presents guidelines to evaluate and categorise the effectiveness of a prescribed burn when implemented on fuels of various vegetation types (Fernandes & Botelho, 2003).

This technique addresses the majority of the fuel characteristics that may result in erratic fire behaviour and intense damage. This has been reported as one of the most effective methods to reduce fuel loading. Graham et al. (2004), mentions reduction of both fine and coarse fuel classes, duff layer, horizontal and vertical continuity, and increase fuel compactness, thereby inhibiting fire ignition and rate of spread. Hollis et al (2016), states that a proper prescribed burn consumes an average of 31% of the forest floor as opposed to wildfire consuming an average of 51%. Bird & Scholes (2005), in support of Hollis et al. (2016), also reported 15, 30 and 60% fuel consumption from a low, medium and high fire intensity burns respectively. This was an under canopy prescribed burn on a *Pinus patula* stand, and fuel load results were: 16.7, 14.8, 12.0, and 14.0 t ha^{-1} for control treatment, low, medium and high fire intensity.

Table 2.2: Classification of the effectiveness of a prescribed burn (Fernandes & Botelho, 2003)

Effectiveness class	Reduction (%)		
	Litter	Slash	Shrub
Very good	>50	>75	>75
Good	25 - 50	>75	25 – 75
Fair	<25	25 - 75	<25
Poor	Unburned	<25	Unburned

De Ronde (2012) also highlight the importance of incorporating fuel loading when compiling a fire management plan by performing fuel appraisal and fire hazard mapping of the area based on fuel availability, as well as identifying buffer zones.

Systematic planning should be done in order to consider the following operations that will take place. Factors like machine access to sites, soil sensitivity, negative environmental site impacts, the types of fuels to manage, and cost of operations should be considered before deciding on a specific fuel management strategy.

2.3. The Effect of Bio Charcoal on Soil Nutrients and Tree Growth

When fire occurs on the forest floor, it combusts, and to a certain degree, consumes the existing fuel, depending on the intensity of the fire (determined by fuel characteristics, weather and topography), leaving white ash bed layer and some charred partially combusted material (Pietikainen, Kiikkila, & Fritze, 2016). They further explain that fire burning with high intensity will consume all the organic matter in fuels and leave only the inorganic compounds in a form of white ash. This is in contrast to cool burns with low to moderate intensity, resulting into partially burnt material with a charring characteristic of black carbon or bio charcoal. This is the case with the common practice of prescribed fires for harvest residue slash burning during site preparation and under canopy burning for fuel load reduction.

Bio charcoal has become of interest over the past decades as it has been observed to potentially alter soil properties, resulting in positive benefits for plant growth and yield (Karer, 2013). Bio charcoal is formed when organic material is incompletely combusted during a natural fire or fire conducted under controlled pyrolysis conditions (DeLuca et al., 2006). Wróbel-Tobiszewska (2014) points out that it is of paramount importance to note that bio charcoal should be distinguished from mining coal used as heat generating fuel. To be clear, bio charcoal refers to charred material from organic biomass that is deliberately applied into the soil with the sole purpose of improving soil properties and bringing about ideal plant growing conditions.

Bio charcoal in the soil has been observed to influence soil moisture, soil nutrient reactivity and availability to various degrees pending on the soil type as its effects are site-specific (Kolb, Fermanich, & Dornbush, 2009). Table 2.3 illustrates responses of different soils to biomass application. In support of bio charcoal influence on soil, Drake et al. (2015) also points out positive benefits of bio charcoal, which are: improved soil physical properties; induces a slow release of phosphorus and nitrogen, thereby increasing soil nutrient availability; an increase in carbon stock; and an increase microorganism biomass in the soil.

2.3.1. Description of bio charcoal physical and chemical properties

According to Wróbel-Tobiszewska (2014), the physical and chemical properties of bio charcoal vary considerably and are highly dependent on biomass type and pyrolysis conditions. Bio charcoal characteristics are determined by temperature, resident time, and amount of available oxygen during pyrolysis of material. The type of feedstock used to produce bio charcoal will influence to a greater extent the characteristics of bio charcoal produced. Typical biomass material used includes animal waste (poultry litter and cow manure), municipal waste (sewage sludge and domestic biodegradable products), and agriculture and wood residues (straws, thinning and harvesting residues, and macadamia shells) Wróbel-Tobiszewska (2014).

Bio charcoal has been reported and recommended as an effective tool that has been used over many decades for soil rehabilitation remedy, fertilization and growth stimulus in forestry nurseries (Wrobel-Tobiszewska et al., 2012; Águas et al., 2018 & Carter et al., 2018). The fundamental characteristics that make its use a success in all these aspects include prolonged chemically active resident time in the soil, its physical form (micro pores and a relatively large surface area), and most importantly, its negatively charged surface area, making it to be highly adsorptive (Carter et al., 2018).

2.3.2. Alteration on soil physical properties

Incorporation of bio charcoal into the soil remarkably modifies moisture content, soil water retention capacity, and soil bulk density as far as the physical properties are concerned. In a study conducted by Karer (2013) bio charcoal was applied at various rates. At an application rate of 72 t ha^{-1} on contrasting sites with different soil types, water holding capacity increased by 57.8% for cambisol and 49.4% for chernozem; while the plant available water increased by 20.1% for cambisol and 26.4% for chernozem.

According to FAO (1988), chernozem are soils characteristic of a mollic A horizon with a moist chroma of 2 or less to a depth of <15 cm; calcic or petrocalcic horizon or concentrations of soft powdery lime within 125 cm of the surface. Cambisols are soils that have a cambic B horizon and no diagnostic horizon other than an ochric or an umbric A horizon or mollic A horizon overlying a cambic B horizon (FAO, 1988). In the South African soil classification system context chernozems and cambisols soils are equivalent to melanic and cumulic soil groups (Fey, 2010).

Similar findings were produced by (Rhoades et al., 2017) in a study using bio charcoal and mulched residue material for soil amendment, where volumetric water content increased by 1.4% and 1.5% respectively for the treatments, in comparison to the control treatment. This effect is associated with the bio charcoal structural composition of having relatively high amounts of micro pores that trap and retain water, making it available to plants for a relatively lengthy period of time.

2.3.3. Alteration on soil chemical properties

The application of bio charcoal in the soil has been observed to alter the most important soil chemical properties, both directly and indirectly. Soil chemical properties by bio charcoal can be amended directly through sorption of essential elements, preventing them from leaching and thereby improving nutrient status of the soil. Indirectly, bio charcoal may bring about ideal conditions for microbiological organisms dwelling in the soil that contribute significantly in various soil microbial activities which include nitrification (Kolb et al., 2009). The act of bio charcoal adsorbing organic compounds to its surface was perceived to increase microorganism biomass and respiration in the soil, which suggests that the microbial activities associated with these microorganism will increase as well, thus enhancing fertility and nutrition of the particular soil (Pietikainen et al., 2016).

Bio charcoal has been observed to have a liming effect: it tends to raise soil pH after being applied, due to its high adsorption ability attracting significant amounts of cations. In support of this rationale, Rhoades et al. (2017), also mentions that the structural features of bio charcoal, like its large negatively charged surface area which enable it to attract and keep nutrient elements on its surface, thereby increasing soil pH and enhancing nutrient status of the soil in question. Micropores of bio charcoal are essential for trapping and storing water for lengthy periods of time, making it available for plants and also preventing excessive leaching of the essential nutrient elements required by plants for growth.

DeLuca et al. (2009), in favour of the above-mentioned statements regarding high adsorption potential of bio charcoal, points out that it adsorbs a significant amount of organic compounds into its surface; and based on this feature, it is also used for water purification purposes.

Rhoades et al. (2017) reported changes in total soil carbon and nitrogen, and pH when bio charcoal was applied in combination with wood mulch in comparison with control untreated soil. The amount of total C and N (g kg^{-1}), and pH on the control sites was 17.4, 0.8, and 5.3 respectively, in contrast to 24.5, 1.0 and 5.7 at the treated sites.

On the other hand, DeLuca et al. (2009) confirmed that bio charcoal influences processes that alter soil chemical properties. From experimenting with incubated soil samples under controlled laboratory conditions, were bio charcoal from naturally occurred fire was applied on the soil samples and then the rate of nitrification was studied by measuring the amount of nitrate in the soil. The results indicated that addition of bio charcoal increased the rate of nitrification in contrast to control treatments where bio charcoal was not applied.

However, since the incubated soils were sampled from sites with different time period since the previous fire event, it was noted that the most recently burned site of 4 years did not show any statistically significant variation, and sites of 26, 47, 89 and 94 years demonstrated the greatest increase on the rate of nitrification.

The research publications on the available literature has produced positive findings regarding the application of bio charcoal or residual bio charcoal from naturally occurring wildfire. In relation to a positive effect on soil chemical properties and chemical processes, Carter et al. (2018) recently reported an increase in microbial activities after bio charcoal application. It is suggested that this is associated with the bio charcoal's ability to increase soil pH to levels closer to ideal conditions for microorganisms thriving in the soil. During its long resident life in the soil, bio charcoal actively adsorbs all the phytotoxic elements that might interfere with the microbial activities, this increases the rates of mineralization and nitrification in the soil.

Table 2.3: Soil nutrient response to bio charcoal application in different soil types

Nutrient element and analysis	**Effect**	**Comment**	**Soil Type**	**Source**
Colwell P (mg kg^{-1})	45.6 - 58.7	Increase	Podzol	Drake et al. (2015)
Nitrate N (mg kg^{-1})	61.0 - 63.6	Increase	Podzol	Drake et al. (2015)
Ammonium N (mg kg^{-1})	47.6 - 58.4	Increase	Podzol	Drake et al. (2015)
Total C (%)	4.1 - 4.2	Increase	Podzol	Drake et al. (2015)
Total N (%)	0.3 - 0.3	Increase	Podzol	Drake et al. (2015)
Total C (%)	7.8 - 7.9	Increase	Podzol	Rovira et al. (2009)
Total N (%)	4.0 - 4.2	Increase	Podzol	Rovira et al. (2009)
CAL P (mg kg^{-1})	70.3 - 77	Increase	Cambisol	Karer et al. (2013)
CAL P (mg kg^{-1})	55 - 61	Increase	Chernozem	Karer et al. (2013)
Ammonium N (mg N kg^{-1})	1.6 - 1.2	Decrease	Alfisol	Rhoades et al. (2017)
Nitrate N (mg N kg^{-1})	0.4 - 0.5	Increase	Alfisol	Rhoades et al. (2017)
Total N (g N kg^{-1})	0.8 - 0.7	Decrease	Alfisol	Rhoades et al. (2017)
Total C (g N kg^{-1})	17.4 - 19.3	Increase	Alfisol	Rhoades et al. (2017)

2.4. Pros and Cons of Burning or Retaining Harvest Residue and Its Impact on Fuel Loading

Site preparation prior to re-establishment is one of the most critical practices that ensures a high initial survival and growth of a newly planted stand. Activities that are encompassed in this operation greatly impact long-term site productivity and nutrient status as it involves manipulation of harvesting residues and forest floor litter layer in varying management approaches. While striving for sustainable forest management practices, it is imperative to note that harvest slash residues contribute a significant amount of nutrients into the soil and hence soil fertility (Rocha et al., 2016). However, harvest slash residues also considerably contribute to forest fuel loading and risk of uncontrolled wildfire damage.

To minimise the impact on soil, various alternatives for managing harvest residue from the previous rotation have been studied in order to select the most suitable and appropriate method for the specific site in question (du Toit & Scholes, 2002; Nzila, Bouillet, Laclau, & Ranger, 2002; du Toit, 2003; de Ronde et al., 2004; and Corbeels et al., 2005).

Harvest slash residues can be managed by: spreading and retaining the material on the forest floor; by broadcast and burn; by burning in slash piles; or through complete removal of material for firewood collection or bio energy (du Toit, 2003). Fires and harvest slash residue management methods have a significant impact on the sites' long-term productivity (du Toit and Scholes, 2002). The available slash management options will influence soil nutrients dynamics to various magnitudes. Figure 2.6 presents findings reported by du Toit et al. (2008) on the top soil (0 - 10 cm) nutrient changes over time following different slash management treatments in a Eucalyptus stand. Treatment were: all harvest residue removed (BL_0), harvest residue broadcasted and retained on site (BL_2), harvest residue from BL_0 added onto this site (BL_3), and slash burn with medium fire intensity (SB).

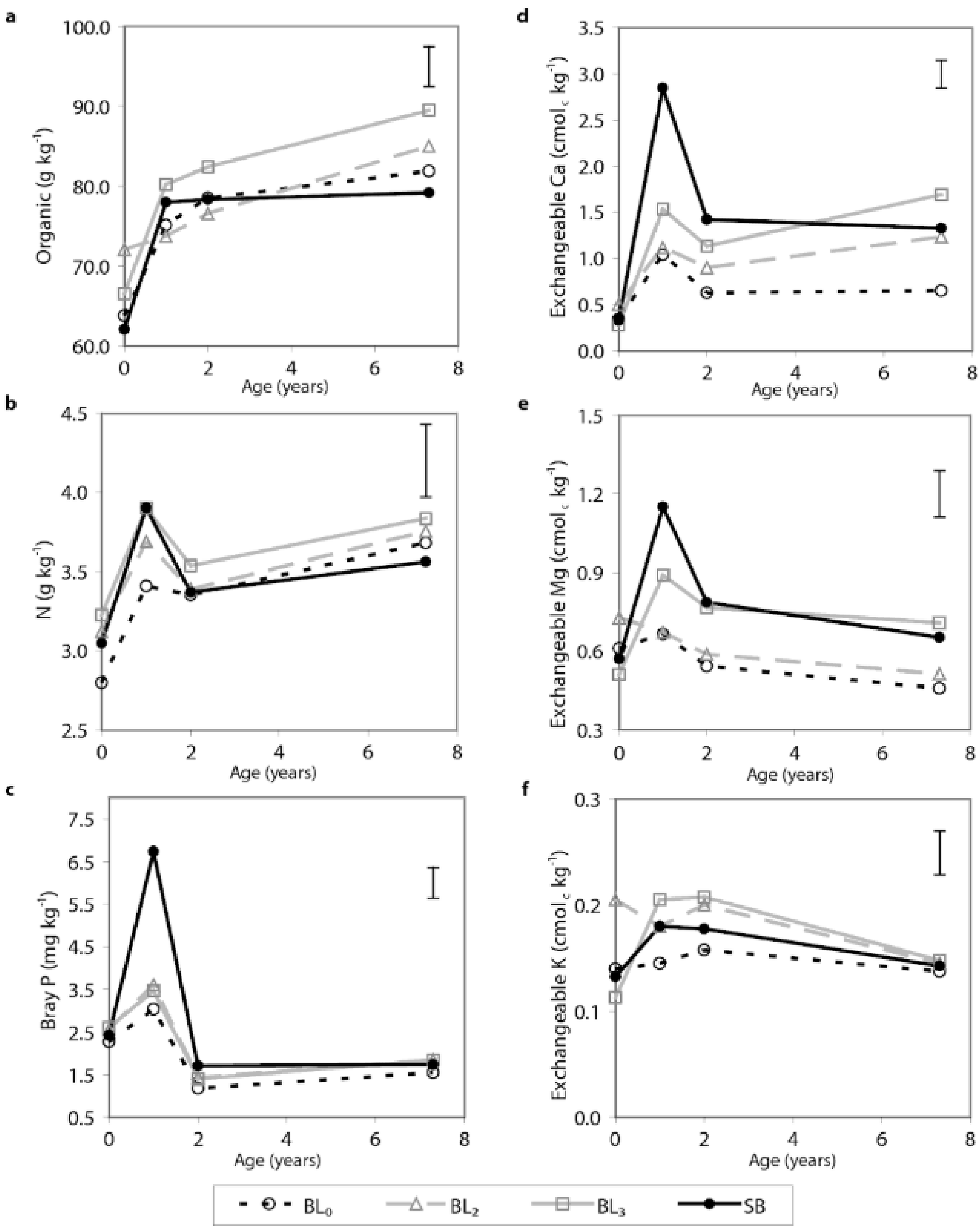


Figure 2.6: Changes in ECEC and selected soil properties and nutrient levels over time following different slash management practices (du Toit et al., 2008).

2.4.1. Retention of harvest slash residue

From the stand's establishment until rotation end, trees depend on the soil for growth essential nutrient elements and take them up in large quantities. In the long-term, site fertility diminishes, leading to poor and less productive sites after numerous successive rotations (Mendham et al., 2003). Foliage, bark, and branches were observed to have a high quantity of nutrients. Hence, harvesting only the bole and retaining harvest slash residues on site may reduce the impact and sustain soil fertility or even potentially improve the soil nutrient status (Corbeels et al., 2005). Numerous research publications point out that the bark, branches and foliage contain relatively large amount of the essential nutrients N, P, K, Ca and Mg. In a study of short rotation eucalypt stands in the KwaZulu Natal Midlands, these pools amounted to 68, 54, 70, 80 and 82% in relation to the above ground biomass, and, therefore this suggests that slash retention be considered (du Toit, 2003).

However, from a management perspective, harvest slash retention also presents some challenges concerning access during pitting and actual planting, creating a potential breeding ground for pests and pathogens, and more especially, a huge fire hazard. During the early stages of development, small seedlings are vulnerable and at high risk of motility. According to Mendham et al. (2003) slash retention further exacerbates growth suppression of small seedlings and saplings.

2.4.2. Harvest slash residue burning

Burning harvest slash residue is an available alternative to managing for slash during site preparation, which can significantly reduce fire hazard and risk of uncontrolled wildfires. This practice can minimise damage if fire does occurs. However, this practice has been looked upon with disfavour from a sustainability view point in that numerous scientific research studies have reported a negative impact on soil nutrient status following the implementation of this practice (Fernández et al., 2009) and (Gonçalves et al., 2007) .

Fire burning on a landscape, ignites and burns woody plant material that it comes into contact with; however, the extent to which woody fuels are combusted depends on the intensity of the fire which is influenced by fuel characteristics and other environmental factors (Pietikainen et al., 2016). Uncontrolled and unplanned fires are predominantly characteristic of high intensity, thereby resulting in substantial negative environmental implications like total vegetation cover removal, excessive erosion, damage to soil physical properties and immediate nutrient losses through volatilisation and oxidation as well as post-fire nutrient losses by excessive leaching (Rhoades, 2017).

For the purpose of soil nutrient sustainability and the application of prescribed fires, it becomes essential to understand the average oxidation inception temperature (Table 2.4) of the individual nutrient element. This could be linked to the most suitable fire intensity at which the intended burn should be aimed to minimize soil nutrient depletion. Low intensity surface fires commonly burn at temperatures not exceeding 600 ˚C, which means that oxidation losses of N does occur but most of the P, and base cations are not oxidised.

Table 2.4: Average oxidation inception temperature of nutrient elements

Nutrient element	**Oxidation temperature**	**Source**
N	200 °C	White & Thompson et al. (1973)
P	774 °C	Raison et at. (1985)
K	774 °C	Raison et at. (1985)
Mg	1107 °C	De Bano (1991)
Ca	1484 °C	Raison et at. (1985)
Organic material	**Threshold temperature**	**Source**
Organic matter	100 °C	Hosking (1938)

Prescribed fires which are characteristic of low to medium intensity have been reported to be an effective tool to manage for harvest slash residues with limited immediate negative implications but with even greater positive response of soil nutrients (Nzila et al., 2002). This was affirmed by (du Toit and Scholes, 2002) findings from the Karkloof case study using the index of nutritional sustainability to evaluate the long and short-term site resilience under various management practices at different intensities; particularly harvest slash residue management when it was burned at a low to moderate fire intensity, which resulted in nutrient losses that were within the proposed index of nutritional sustainability.

Amongst many other positive potential benefits that come with the application of fire on the wild environment is the alteration of undesirable soil chemical conditions such as allopathy (Águas et al., 2018). The thermal effect from fire volatilises toxic elements that interfere with plant growth, and the remaining bio charcoal adsorbs most of the toxic element into its surface, thereby alleviating growth stress and improving plant survival.

2.4.2.1. Burning conditions

Low to moderate intensity fires by far result in relatively low damage to the soil's physical and chemical properties, contrary to high intensity fires (Norris, 1993). This may be linked to the fact that low to moderate fires result in a partial combustion of the humus layer protecting the actual mineral soil; its temperature is normally below the volatile temperature threshold of certain nutrient elements (de Ronde et al., 1990 and Table 2.4). This is the case in controlled prescribed fires applied under favourable weather conditions in forest plantations for various management purposes.

Table 2.5 presents guidelines indicating ideal and safe conditions for conducting a prescribed burn. To successfully achieve an effective prescribed burn for slash management purpose special attention with regards to temperature, wind, relative humidity, and fuel moisture is required (de Ronde et al., 2004). There is an inverse proportional relationship between temperature and relative humidity. The daily temperatures tend to be much cooler in the early hours of the day with a high relative humidity accompanied by gentle wind and slightly moist fuels (Wade & Lunsford, 1989). This presents an ideal situation to initiate and control a prescribed burn safely with much ease. Contrary to the late afternoon hours when relative humidity is usually at its lowest, temperature at the peak with high speed wind gust rapidly drying out the fuel totally. Caution to be taken when conducting a prescribed burn under these conditions or prevented all together (Teie, 2009).

Table 2.5: Safe conditions for prescribed burn

Elements	Condition	Sources
Temperature	5 - 15 %	de Ronde (2004)
Relative humidity	25 - 45 %	Teie (2009)
Wind speed $_{\text{inside stand}}$	<4 Km hr^{-1}	Wade & Lunsford (1989)
Wind speed $_{\text{outside stand}}$	12 - 16 Km hr^{-1}	Wade & Lunsford (1989)
Fuel Moisture	10 - 20 %	USDA (2009)

2.5. Influence of Soil Tillage (Disc Harrowing) on Soil Properties and *Eucalyptus Spp* Growth

Soil tillage prior to planting is a common practice for positivity altering soil properties as a means of ensuring plant survival and good growth. Karuma et al. (2014) points out other potential benefits obtained from a proper tillage operation, such as: eases plant root penetration; improves soil water retention and infiltration; controls weeds from competing with the intended crop; and incorporates organic residue material into the soil, thereby hastening the decomposition process and plant nutrient availability.

Madeira et al. (2012) adds to the list of potential benefits from disc ploughing, such as reducing soil bulk density, improving soil aeration, and possibly improving tree growth and volume. He adds that disc harrowing at mid-rotation is a common practice executed with intentions to eliminate understory vegetation, alleviating interspecific competition between trees and weeds, and to reduce fuel loading as part of forest fire management strategies to reduce risk of uncontrolled wildfires.

2.5.1. Soil structure

The various soil tillage methods used in commercial forestry plantation during site preparation, and sometimes at mid-rotation, have a huge impact on soil physical properties. According to Madeira et al. (1989), the implementation of disc harrowing at site preparation prior to planting on a *Eucalyptus globulus* stand in Mediterranean conditions resulted in a reduction of soil bulk density. At a depth of 0 - 10 cm, surface disc harrowing was observed to significantly reduce bulk density compared to 75 cm deep ripping. Soil bulk densities were 1.37 g cm^3 for surface tillage, 1.59 g cm^3 for deep ripping, and 1.54 g cm^3 for the control treatment.

Soil tillage at site preparation contributes significantly to altering soil structure by mechanically converting compacted soil into friable soil with improved aeration that is much more ideal for plant growth. Dedecek et al. (2007) affirms that soil tillage positively alleviates soil compaction. This was observed by measuring soil penetrometer resistance on ripped soils and comparing it to soils that were not ripped; the results exhibited a high penetrometer resistance on soils that were not ripped Soils that have a high penetrometer resistance indicated a great degree of compaction that might be linked to limited plant root length density and growth.

Madeira (1989) reported an increase in porosity of 48.3%, a rate of 18.0% water infiltration, and 23.4 cm ha^{-1} aeration for surface treatment; 40.0% increase in porosity, a rate of 6.7% water infiltration, and 10.7 cm ha^{-1} aeration for deep ripping; and 41.9% increase in porosity, a rate of 16.4% water infiltration, and 11.7 cm ha^{-1} aeration for control treatment.

2.5.2. Tree growth and survival

Different soil tillage methods applied on various soil types have been observed to yield significantly positive growth responses. Smith, Little, & Norris (2001), experimented with different tillage practices that are applicable at site preparation for planting *Eucalyptus grandis, Eucalyptus dunnii, Eucalyptus grandis x camaldulensis,* and *Acacia mearnsii* in KwaZulu-Natal in South Africa. A positive type two growth response was observed in the study findings for final survival, basal area and volume growth. Variation growth response was measured in terms of basal area, where surface harrowing was applied (19.0 m^2 ha^{-1}) in comparison to control treatment which was pitting alone (17.6 m^2 ha^{-1}). A slight difference was also observed when comparing growth responses from sites where ripping was applied (20.8 m^2 ha^{-1}) and sites where there was no rip application (19.1 m^2 ha^{-1}). All this positive growth can be associated with the breakdown of the compacted topsoil surfaces through surface disking and removal of soil depth impending layer through rip application. These soil amelioration methods form part of a sound site preparation practice during reestablishment under the above-mentioned soil conditions to achieve good soil structure, tree survival and growth.

Alteration of soil structure attained through tillage (for example, alleviation of compacted soil into a friable and well aerated soil) can be a positive benefit on the below ground tree growth. This was observed by Gonçalves et al. (2004), where he examined root length density of *Eucalyptus grandis x nitens* under various penetrometer resistances. His findings showed a negative correlation between root growth and penetrometer resistance, where root length density declined with about 71% with an increase in penetrometer resistance from 0.4 to 4.2 MPa. The available literature only reports soil tillage practices conducted at site preparation prior to planting and at mid-rotation; no studies have been conducted on the implementation of disc harrowing throughout the stand rotation.

2.6. Literature Review Conclusion

Wildfires are a serious threat to commercial forest plantations in South Africa and worldwide. Thorough knowledge of how forest fuels characteristics influence fire behaviour and increase the risk of wildfires is essential when constructing a strategic fire management plan. Fuel management remains the only fire environment component that fire managers can potentially manipulate in an attempt to effectively reduce fuel loading and fire related risks. Long-term effects on site productivity, efficiency and effectiveness of the fuel load management practices, as well as physical possibility should be considered when selecting a fuel management method for a particular site. Of the various fuel management techniques, it is important to identify those most effective and efficient when implemented prior to planting or during stand rotation.

Prescribed burning to reduce fuel loading is an option when practiced under favourable conditions in order to achieve a cool burn with minimal negative impact on the site and optimal results on fuel loading reduction. This practice on Pine stands is effective and efficient when applied both prior to planting (slash burning) and during rotation (under canopy burning), but requires more preparatory input and cost when using it in eucalypt stands (especially the gum bark types).

Mechanical options such as disc harrowing can be implemented as an alternative to burning applications for managing forest fuel with negligible impact of site productivity and tree growth. Disc harrowing has potential to significantly reduce fuel loading, to improve soil bulk density and aeration, as well as soil water retention and infiltration. The extent to which these processes applicable in South African sites and conditions have not been quantified. Most international research publications report on disc harrowing studies conducted either prior to planting or at mid-rotation only. The application of disc harrowing throughout the rotation has also not been investigated and published.

3. METHODS AND MATERIALS

3.1. Site Description

This study was conducted in Iswepe area near Piet Retief in Mpumalanga province, South Africa. Iswepe is located in the high altitude region at 1 444 m above sea level in a warm temperate climatic zone. Weather data for the site was attained from the South African Sugarcane Research Institute from Mondi Office Iswepe weather station located approximately 16.7 km from the study site (Figure 3.1). Figure 3.2 presents monthly mean rainfall from July 2016 to July 2019. The site is within a summer rainfall region, with relatively dry, cold winter and wet, warm summer. December receives the highest mean rainfall of 192 mm and June receives the least rainfall of 0.20 mm. The mean annual precipitation is 858.2 mm (Note this data was a record of only three years). Both monthly mean minimum and maximum temperatures are presented in Figure 3.3. May was the hottest month averaged at 26 °C and July was the coldest month averaged at 12 °C.

Figure 3.1: Site location map

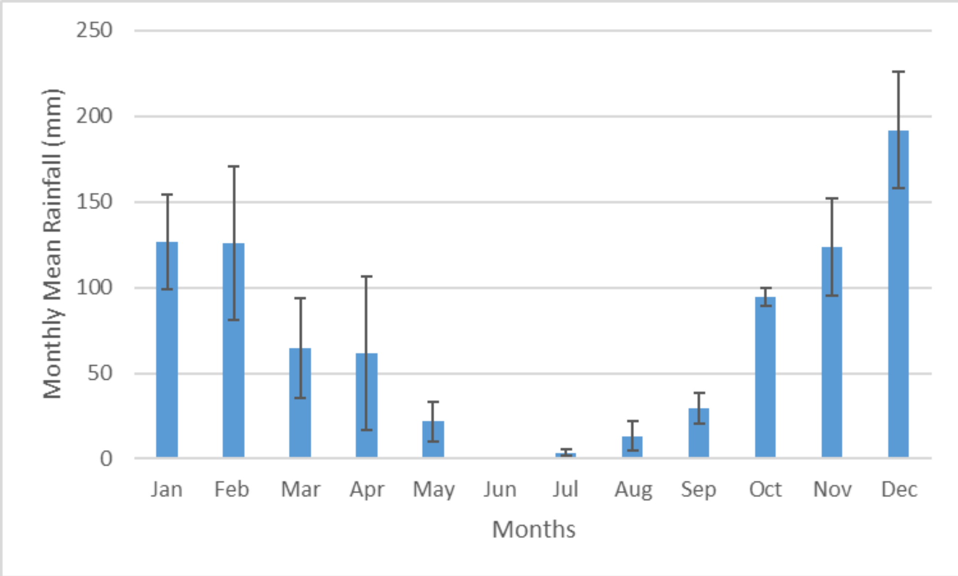


Figure 3.2: Mean monthly rainfall over 3 years

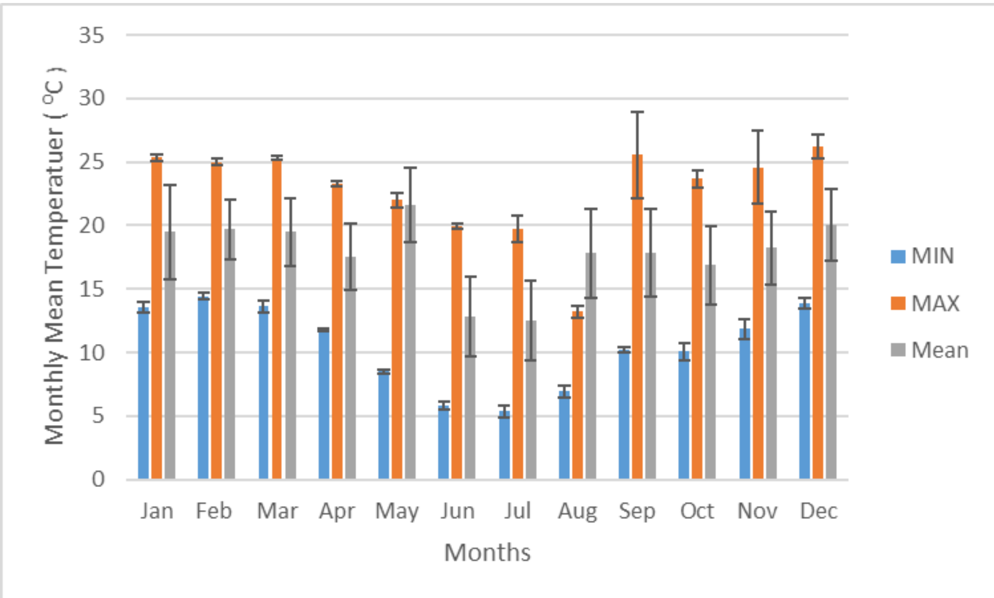


Figure 3.3: Mean monthly temperatures over 3 years.

This research was conducted on two *Eucalyptus grandis x nitens* stands grown for pulpwood production. One was an 11 year old coppiced regenerated stand and the other a 9 year old replanted stand. The two compartments had been established on two contrasting soil types; Magwa for the replanted compartment and Kranskop for the coppiced compartment, but under similar climatic conditions. At a depth of approximately 40 cm in Block 1 and 25 cm in Block 2 there was a broken stony impeding layer of about 15 to 20 cm in thickness (Figures 3.4 & 3.5). This layer had a great limiting effect mostly on roots of large diameter, but with minimal effect on fine roots as they were still observed beyond the stony layer depth throughout the soil profile during the root count. The soil profile of the study area to a depth of 100 cm is presented in Figures 3.4 & 3.5.

Figure 3.4: Soil profile from Block 1 study site

Figure 3.5: Soil profile from Block 2 study site

3.2. Study Design Methodology

A fence line study design method was used for the purpose of this research using as illustrated in Figure 3.6. The treatments were nested in two blocks; the blocks were a combination of regeneration method and site characteristics.

Block 1: Replanted regeneration method on a south facing aspect on a Magwa soil type.

Block 2: Coppiced regeneration method on a north facing aspect on a Kranskop soil type.

It was important that the treatments be investigated on the two blocks (approximately 1 km apart) in order to test for the universal applicability of this practice. This is due to slight differences between the sites that might influence the response of the site to treatment. Firstly, the regeneration method and subsequent coppice reduction might possibly influence forest floor litter accumulation during the stand rotation, resulting in greater fuel loading in Block 2. Secondly, geographical position of the site influences the amount of fuel loading and the type of fuel classes present in a particular site; south facing aspects are typical of dense and heavy fuel class, thus Block 1. Geographical position also influences mean annual temperature (MAT) and mean annual precipitation (MAP) of the site. According to the company’s information system, the two blocks fall on the transition zone between two warm temperate (WT) climatic classes: Block 1 is classified as a WT5 site type and Block 2 is a WT2 site type. Site type WT2 has a MAT within the range of 16 -17 °C and MAP within 850 - 950 mm, while WT5 site type has a MAT 17 - 18 °C and MAP within 875 - 975 mm (Louw & Smith, 2012). Lastly, certain soil types respond differently to treatments and might have higher nutrient content and ECEC than another.

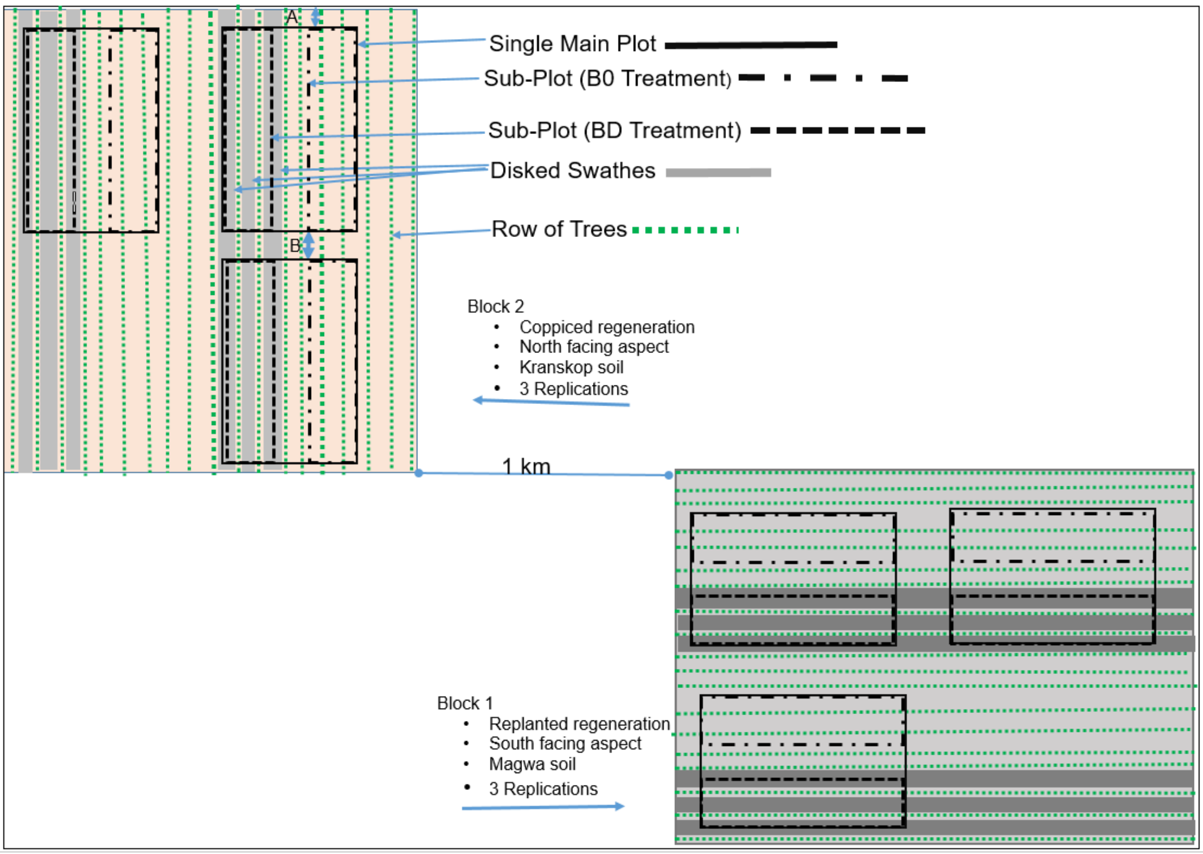


Figure 3.6: Schematic demonstration of the two blocks showing disked swathes within each replication, nested within one of two blocks.

Two slash and fuel load management treatments were investigated:

B0 – Slash was burned during site preparation with no disc harrowing operation during the stand rotation.

BD – Slash was burned during site preparation and the stand was repeatedly disc harrowed, at least once a year throughout the rotation for purposes of fuel loading reduction.

The treatments were investigated on the two blocks. Block 1 consisted of three main plots; each plot had a total area of 2 400 m^2 (12 m x 200 m). These plots were laid out in the form of two transects spanning the length of the block, i.e., 6 sub-plots of 1 200 m^2 (6 m x 200 m) each. Of the two transects, one was for the B0 treatment and the other for the BD treatment as illustrated in Figure 3.6. The plot length in Block 1 was reduced due to compartment boundary limitations.

Similarly for Block 2, a single main plot had an area of 3 600 m^2 (12 m x 300 m), then split into two transects forming sub-plots of 1 800 m^2 (6 m x 300 m) each. One of the two transects was for the B0 treatment and the other for the BD treatment. Each block had three treatment replications, making six replications in total. To prevent the edge effect, plots were placed 20 m from the compartment boundary (see Figure 3.6 point (A)) and 40 m apart spanning the length of the block (see Figure 3.6 point (B)). Figure 3.7 illustrates a schematic diagram of a section of a single main plot with the two treatments. A distance of 6 m between the two treatments was demarcated using two rows of trees as "guard rows" to maintain constant distance between the treatments (Figure 3.7 point (F)). Figure 3.8 demonstrates the actual situation of plantation forest when the treatment is implemented.

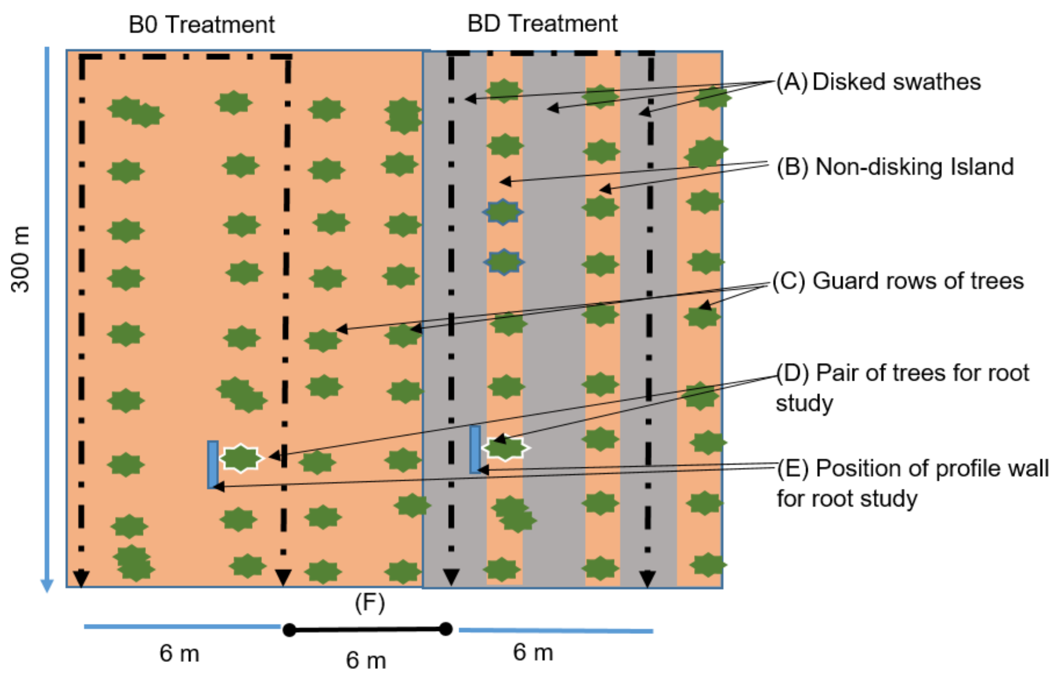


Figure 3.7: Section of a single plot layout: the inner measurement plot of trees is thus located between the boundaries marked with the line - • - - • - in the figure.

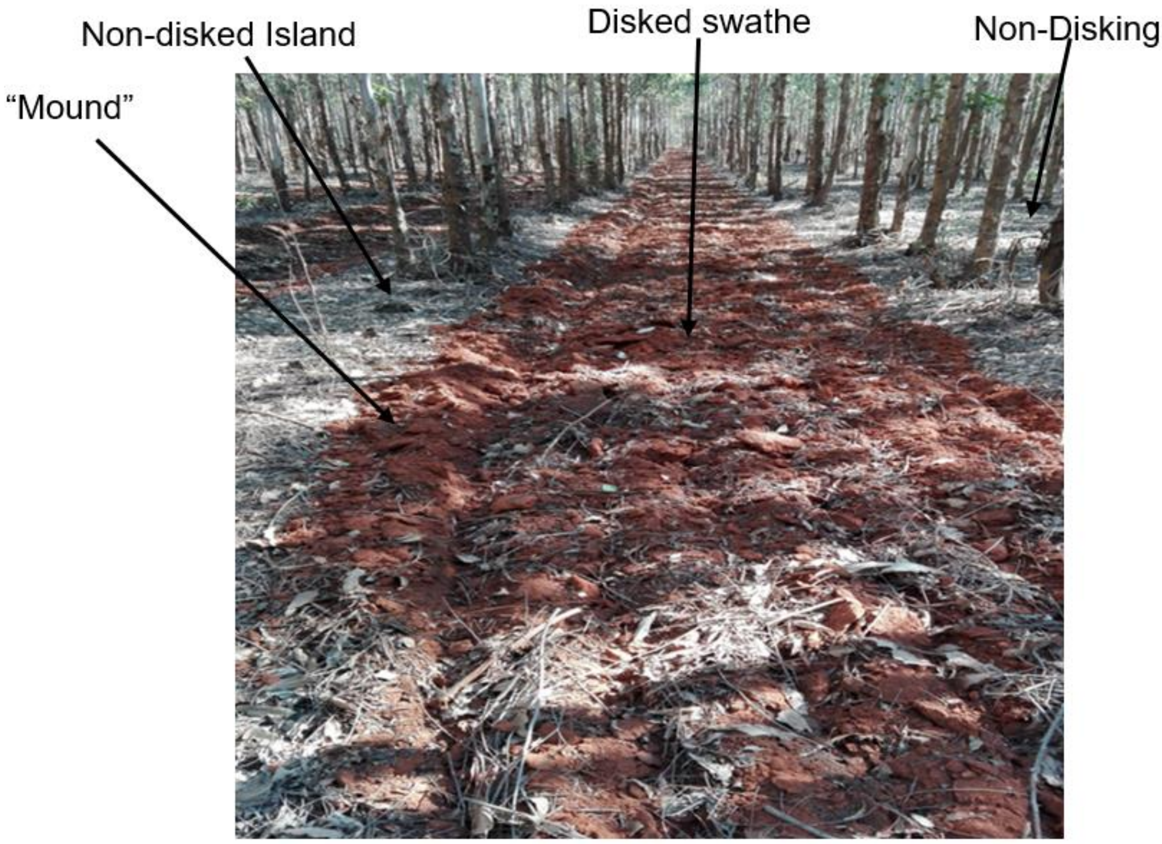


Figure 3.8: Photograph of a single plot layout

3.3. Data Collection

3.3.1. The above ground plant growth

Tree diameter at breast height (DBH) was measured on all the trees in each of the plots using manual callipers. Thirty DBH height pairs were also measured to generate a height regression equation for estimating heights of all the trees in the plot. Hypsometer vertex and transponder were used for measuring tree heights. During data collection, dead, dying and missing trees were noted for the purpose of analysing stand density and survival for the two treatments. The effect of repeated disc harrowing on the aboveground plant growth was examined through measuring and comparing differences between various growth-related variables: (a) at the individual tree level: stand density (Stems ha^{-1}), and (b) at the stand level: basal area m^2 ha^{-1}, volume (m^3 ha^{-1}), and plant biomass (t ha^{-1}) for the B0 treatments in contrast to the BD treatments in the fence line study. Stand density was evaluated both on the single stem and individual stump basis.

For single stem, all the stems in the plot were regarded as an individual tree irrespective of two or three stems originating from the same stump. For individual stumps, only the stumps were counted and regarded as an individual tree with disregard to the number of shoot or stems per stump. This was essential to understand the potential effect of regeneration method (coppicing versus planting) on stand density in this study.

3.3.2. Below ground growth: root distribution patterns

Twelve trees were identified for the purpose of analysing the effect of repeated disc harrowing on root distribution pattern. This was done by contrasting root distribution patterns of the selected trees from the B0 treatments to the BD treatments. The tree population in Block 1 had a mean DBH of 15.7 cm and a standard deviation of 3.8. The corresponding values for Block 2 were 14.9 cm and 3.5. It was therefore decided to select sample trees from three distinct size classes in the population, namely 10, 15 and 20 cm classes. Of the selected trees, three pairs were from Block 1 and the other three pairs from Block 2. The pairs were selected with one tree in the B0 treatment and the other in the BD treatment within one main plot (Figure 3.7 & 3.9).

The root distribution pattern of below ground tree growth was investigated following the profile wall root study method (Böhm, 1979). This was done by digging a trench at a distance of 50 cm from the tree under study, then placing a 1 m x 1 m frame against the profile wall to be studied as shown in Figures 3.4, 3.5 & 3.9. The trench was dug using manual handpick and spade. After the profile wall was dug according to the required specification, the actual wall under study was scrubbed with both wire brush and nylon/plastic brush. The wall was then sprayed with pressured water from a conventional firefighting knapsack, making the roots clearly visible for counting. Roots protruded from the profile wall with a minimum length of 5 mm.

The frame housed 100 boxes within a 10 cm x 10 cm grid. Roots visible in each grid were counted horizontally and summed. The depth of each horizontal row increased by 10 cm, with the last row being 1 meter. A graphic paper was used to record root count and map the root distribution pattern as it appeared on the profile wall. The roots found on the vertical face of the profile wall were classified according to various class categories based on diameter: class A, < 2 mm regarded as fine roots; class B, 2 to 5 mm as small; class C, 5 to 10 mm being medium; class D, 10 to 20 mm, large; and class

E, > 20 mm, very large (Böhm, 1979). A small handheld calliper was used to measure root diameter for root classification.

Figure 3.9: Profile wall root study method

3.3.3. Forest floor and litter characterisation

A number of litter samples were collected for the purpose of determining the impact of the above-mentioned treatments on *Eucalyptus grandis x nitens* stand forest floor dynamics. Difference in forest floor structure and fuel loading of various fuel classes and chemical content of the actual forest floor material under study were analysed.

Six litter samples were collected from each of the 6 main plots = 36 samples. Six litter samples were collected from each plot: three samples from the B0 treatments and three from the BD treatments, totalling 36 collected samples. This was done using a 1 m x 1 m custom built wooden sampling frame, then collecting all the material within the sampling point. Figure 3.10 shows some of the steps followed during the sampling procedure: randomly selecting a sampling point by throwing a hatchet over the shoulder; placing the sampling frame on the selected point; carefully removing all the material around the sampling point using secateurs and small pruning saw; and then clearing the perimeter of the sampling point using a spade. The actual litter within the sampling frame was then collected down to the humus layer; then the humus was collected until the mineral soil appeared. Humus was collected by gently scraping with a small garden fork and placing the material in a paper bag. The litter material was placed in packaging paper bags separate from the humus material.

As it appears in Figure 3.7, the undisturbed forest floor on the B0 treatment is homogeneous; sampling was done randomly throughout the transects. In contrast, the BD treatments had a heterogeneous forest floor, where one-third of transect within the tree rows was not disked. These rows had partial incorporation of soil material displaced by the disc harrow from the disked swathe onto the so-called island, forming some sort of a bedding. For this reason one of the tree sampling points with BD treatments was intentionally placed on the island within the row of trees as a representative sampling procedure.

Figure 3.10: Infield litter collection technique using a custom built frame of 1x1 m.

3.3.3.1. Laboratory

For purposes of fire behaviour modelling, litter and fuel loads are categorized into four distinct fuel class sizes, namely the 1, 10, 100 and 1000 hour fuel classes (de Ronde, 1990; Teie, 2009; and Prell, 2016), shown in Table 2.1. The same classification was used in the current study with one modification, specifically that the 1 hour fuel class was split into (a) branch fraction with a thick end diameter of < 0.6 cm and (b) the leaves and bark fraction. This was done because branch fraction could practically be separated out, and because its nutrient content is likely to be different from that of the bark and leaf fraction. There were no branches with a diameter greater than 2.5 cm from all the sampled material (Figure 3.11).

The sites in which this study was conducted are subjected to intensive management, namely, clear-fell harvesting methods, slash burn during site preparation, and weed control of understory vegetation. Consequently, the forest floor is broadly limited to 1 hour and 10 hour fuel classes, as opposed to natural forest systems where up to 1 000 hour fuels are present on the forest floor. It was particularly important to focus attention on the most active fuel classes, which are the 1 hour and 10 hours fuels in influencing fire behaviour (ignition, rate of spread and intensity). A small handheld manual calliper was used to measure the thick diameter of the branch when separating the litter material into various fuel classes. Then all the 10 hour, 1 hour (branch fraction) and 1 hour (bark and leaf fraction) fuel classes were oven dried at 65°C to a constant weight and weighed separately. Mass was measured using a Delta Range Mettler PC 4400 scale. The final mass was scaled up into oven dry tonnes per hectare (t ha^{-1}); this was done to all the forest floor material samples that were collected from the field. The samples were further milled and sent to an accredited service provider laboratory (Bemlab) for (N, P, K, Ca, and Mg) analysis.

Figure 3.11: Litter sample separated according to fuel time lag classes

3.3.4. Sampling for soil physical and chemical properties

Soil samples for chemical analysis were collected using a Beater auger. This was done by first removing the litter layer, then inserting the auger in the actual mineral soil. Soil samples from the B0 treatments were collected from 10 randomly selected sampling points throughout the entire transect and then bulked into one sample representing the entire transect.

Sampling was slightly different in the BD treatments. For the specific purpose of chemical soil sampling on the BD treatment, three categories of soil samples were collected from: the actual disked swathe between the tree rows, and two samples from the non-disked island on the tree row. On the tree row, a sample was taken from the roughly mixed material "Mound" that had been deposited on top of the regular soil profile through the disc harrowing operation (Figures 3.7 & 3.8). This material consisted of partially decomposed forest floor material partly mixed with the displaced topsoil. A second sample was taken in the regular soil profile below the displaced material. On the actual disked swathe, 10 soil subsamples were collected from 10 randomly selected sampling points and then bulked to make one sample. The same procedure was done for collecting samples with partly mixed and displaced material as well as samples consisting of only mineral soil. Four samples were collected for a single main plot for the six plots: one from the B0 treatments and three from the BD treatments (one actual disc swathe, one with partly mixed material and one only mineral soil), making a total of 24 soil samples.

Soil samples from infield were then taken to the laboratory to measure total nitrogen (N), extractable phosphorus (P) and total organic carbon (C). Total N and total organic C were measured at high temperature combustion by means of Leco Truspec® C and N analyser. The amount of extractable P in the soil was measured following Bray II procedure (Hunter, 1974). Extractable topsoil cation quantities (K, Ca, Mg, and Na) were extracted with 0.2 M ammonium acetate solution at a pH 7. Extractable acidity was measured using titration with 0.05 M NaOH, after extraction with 1 M KCl. The effective cation exchange capacity (ECEC) was determined by adding the amount of extractable acidity to the sum of base cations charge at an unbuffered soil pH. The soil pH was analysed in 1 M KCl. Contents and quantities of the above-mentioned soil elementals were examined by performing an inductively coupled plasma optical emission spectroscopy (ICP-OES) for all the extracted solutions. The extractable P quantity was determined with Varian ICP-OES.

Soil sampling for contrasting differences in soil bulk density between the two treatments was done by knocking a core cylinder of a known dimension into the ground to collect an undisturbed soil sample as illustrated in Figure 3.12. This was done at a depth of 0 - 10 cm and 10 - 20 cm. In the laboratory, the samples were oven dried at 105°C to constant mass. The oven dried mass was divided by the volume of the cylinder to get the actual density. Delta Range Mettler PC 4400 scale was used to measure soil mass.

Figure 3.12: Soil sampling for bulk density at 10 - 20 cm depth

4. DATA ANALYSIS

Data from infield was captured and sorted using an Excel 2013 spreadsheet. The effectiveness of treatment was statistically evaluated by making use of SAS Enterprise Guide 7.1. The following procedure was followed:

- Distribution of data sets was analysed by performing normality test of residuals using Shapio-Wilk test at $p<0.05$.
- One-Way ANOVA was used to test for homogeneity performing Levene's $p<0.05$.
- Data was transformed using $\sqrt{Y+0.5}$ function if the aforementioned assumptions were not met and satisfied.
- Nested design: the treatments were nested in two blocks, then tested for significant difference between the two blocks and between the treatments within each block.
  - Nested design was appropriate because the blocks did not have replications and this prevented the application of factorial design.
- ANOVA linear model at $p<0.05$, where there was significant difference Bonferroni (Dunn) t-Test was used to follow up.

5. RESULTS

5.1. Fuel Loading and Forest Floor Structure

The undisturbed fuel build-up from slash burning (during the site preparation phase) until sampling for this study was recorded for Block 1 and Block 2. This serves as a benchmark for treatment effects. In Block 1, the humus fraction averaged to 19.0 t ha^{-1}, the 10 hour fuels averaged to 10.9 t ha^{-1}, 1 hour fuel (bark and leaf fraction) averaged to 11.8 t ha^{-1} and 1 hour fuel (branch fraction) had an average mass of 4.7 t ha^{-1}. The total forest floor mass averaged to 44.8 t ha^{-1}. In Block 2, the humus fraction averaged 18.9 t ha^{-1}, the 10 hour fuels averaged 5.2 t ha^{-1}, 1 hour fuel (bark and leaf fraction) averaged to 13.4 t ha^{-1} and 1 hour fuel (branch fraction) had an average mass of 3.9 t ha^{-1}. The total forest floor mass averaged to 41.4 t ha^{-1}.

1 hour fuel (branch fraction): Mean fuel loading of this fraction is presented in Figure 5.1. The repeated disk harrowing treatment resulted in a significant reduction of the 1 hour fuels (branch fraction), however, there was no significant difference between the two blocks for fuel class in this experiment (Table 5.1). In Block 1, the B0 treatments had a mass of 4.7 t ha^{-1} and the BD treatments had 1.8 t ha^{-1}. Similarly in Block 2, the B0 treatments amounted to 3.9 t ha^{-1} and the BD treatments to 1.6 t ha^{-1}.

Table 5.1: ANOVA results of the 1 hour fuel class (branch fraction)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	62.8537	31.4268	34.65	<0.0001
Blocks	1	1.6737	1.6737	1.85	0.1835
Treatment	1	61.1800	61.1800	67.46	<0.0001
Error	33	29.9279	0.9069		
Corrected Total	35	92.7816			

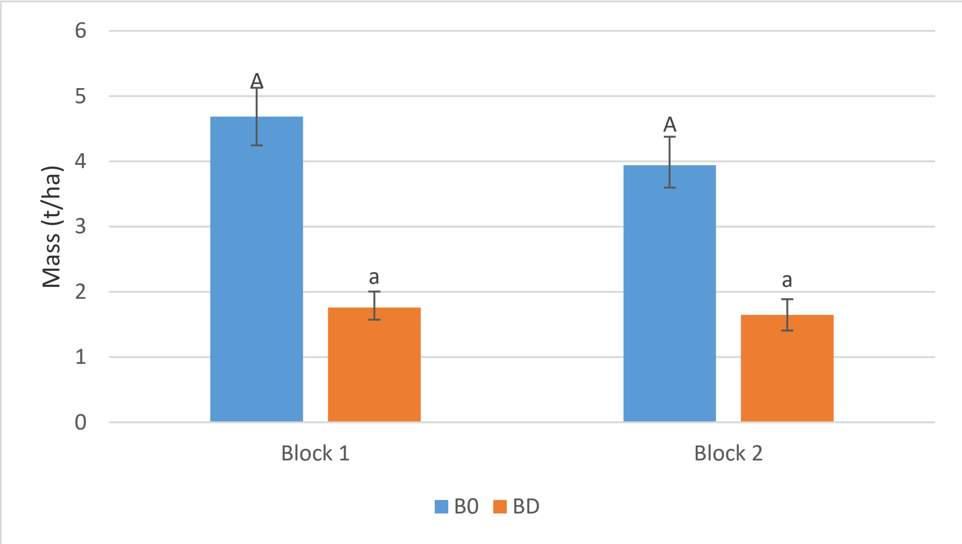


Figure 5.1: Fuel loading distribution for treatments of the 1 hour fuel class (branch fraction) (Aa) Letters with different cases indicate significant difference among the treatments at *p*<0.05

1 hour fuels (bark and leaf fraction): The data for this fraction is shown in Figure 5.2. Significant fuel load reduction in this fuel class was only brought about by treatment; there was no significant difference between the blocks (Table 5.2). Block 1 had a mass of 11.4 t ha^{-1} for the B0 treatments compared to 5.5 t ha^{-1} for the BD treatments. Block 2 was similar, with mass of 13.4 t ha^{-1} for the B0 treatments compared to 4.6 t ha^{-1} for the BD treatments.

Table 5.2: ANOVA results of the 1 hour fuel class (bark and leaf fraction)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	14.5384	7.2692	18.06	<0.0001
Blocks	1	0.0626	0.0626	0.16	0.6959
Treatment	1	14.4758	14.4758	35.97	<0.0001
Error	33	13.2804	0.4024		
Corrected Total	35	27.8188			

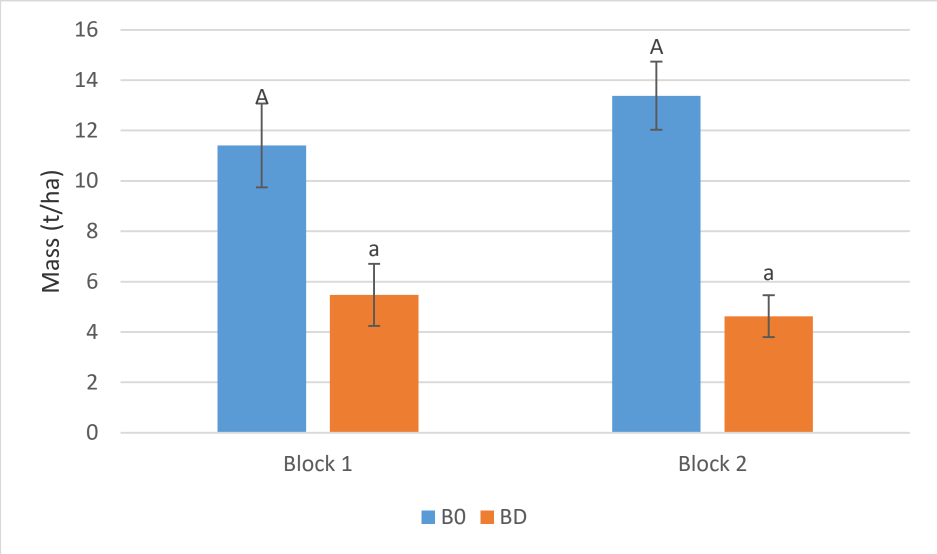


Figure 5.2: Fuel loading distribution for treatments of the 1 hour fuel class (bark and leaf fraction) (Aa) Letters with different cases indicate significant difference among the treatments at $p<0.05$

10 hour fuels: The values for the 10 hour fuel loading are shown in Figure 5.3. In this fuel class, significant differences in fuel loading were observed between the blocks and the treatments (Table 5.3). When the two blocks were combined, the BD treatments had an average mass of 3.8 t ha^{-1} and the B0 treatments had 8.1 t ha^{-1}, indicating that the BD treatment resulted in a significant reduction in fuel loading across both blocks. Furthermore, Block 1 had significantly higher fuel loading in comparison to Block 2 for both the BD and B0 treatments. For the B0 treatment, Block 1 had a dry mass of 10.9 t ha^{-1} in comparison to 5.2 t ha^{-1} for Block 2. Similarly, for BD treatment, Block 1 had fuel loading amounting to 4.6 t ha^{-1} in comparison to 2.9 t ha^{-1} for Block 2.

Table 5.3: ANOVA results of the 10 hour fuel class

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	285.5301	142.7650	18.19	<0.0001
Blocks	1	119.6537	119.6537	15.24	0.0004
Treatment	1	165.8764	165.8764	21.13	<0.0001
Error	33	259.0679	7.8505		
Corrected Total	35	544.5971			

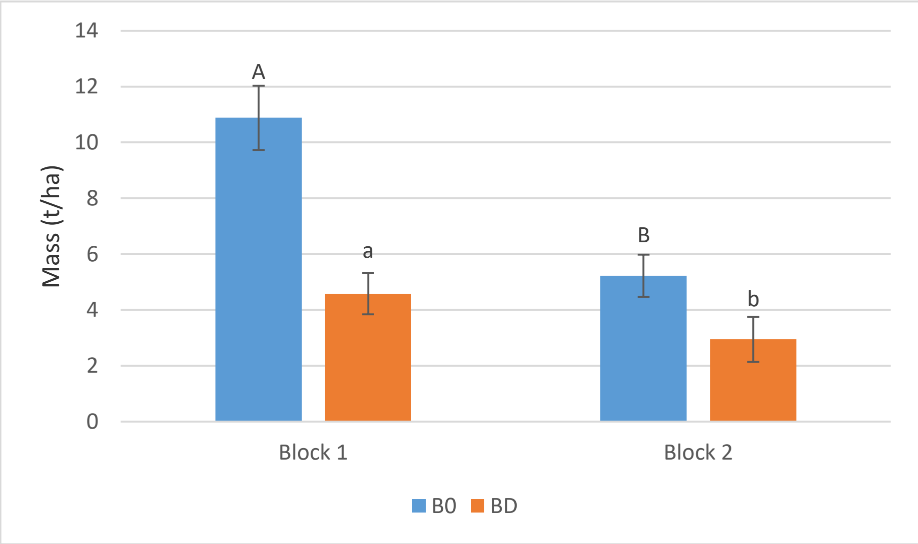


Figure 5.3: Fuel loading distribution for treatments of the 10 hour fuel class
(Aa) Letters with different cases indicate a significant differences among the treatments at p<0.05
(AB) Different letters indicate a significant difference among the blocks at p<0.05

Total forest floor mass: It is important to note that the total litter load consisted of only the 1 and 10 hour piece sizes, i.e., no pieces of litter were encountered in the 100 and 1000 hour fuel classes. Table 5.4 illustrates that repeated disc harrowing resulted in a significant reduction in total forest floor mass. The difference in total forest floor mass was non-significant between the two blocks. As shown in Figure 5.4, in Block 1 the B0 treatments had a significantly higher quantity at 44.8 t ha^{-1} while the BD treatments had a significantly lower total forest floor mass of 11.8 t ha^{-1}. Similarly in Block 2, the B0 treatments amounted to 41.4 t ha^{-1} over 9.2 t ha^{-1} for the BD treatments.

Table 5.4: ANOVA results for the total forest floor mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	9397.6813	4698.8407	95.95	<0.0001
Blocks	1	78.6586	78.6586	1.61	0.2142
Treatment	1	9260.6884	9260.6884	189.10	<0.0001
Error	32	1567.0957	48.9717		
Corrected Total	34	10964.7771			

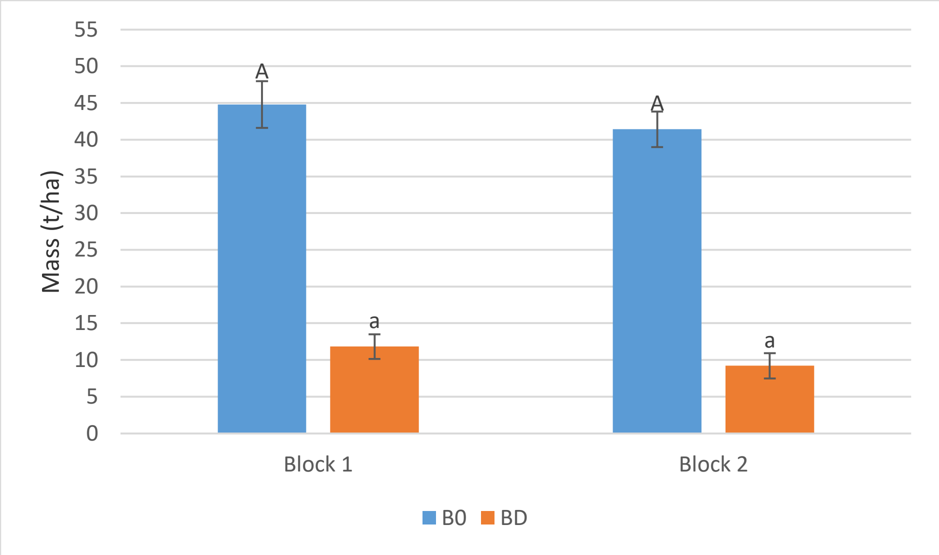


Figure 5.4: Total forest floor mass distribution for treatments
(Aa) Letters with different cases indicate a significant differences among the treatments at $p<0.05$

Block 1 and block 2 combined: The practice of repeated disc harrowing resulted in a significant decrease in fuel loading in the BD treatments in comparison to the B0 treatments for the combined sites (Block 1 and Block 2). This is illustrated in Figure 5.5. The mean values of fuel loading from the two treatments were significantly different for all the fuel classes and for the total forest floor mass (Tables 5.1 - 5.4). This section presents the magnitude of the difference in fuel loading among the treatments for the various fuel classes. The difference between the two treatments for humus was 19.0 t ha^{-1}; for 10 hour fuels, 4.3 t ha^{-1}; for 1 hour fuels (bark and leaf fraction), 7.3 t ha^{-1}; and for 1 hour fuels (branch fraction), the difference was 2.7 t ha^{-1}. The mean difference in total forest floor mass was 32.58 t ha^{-1}.

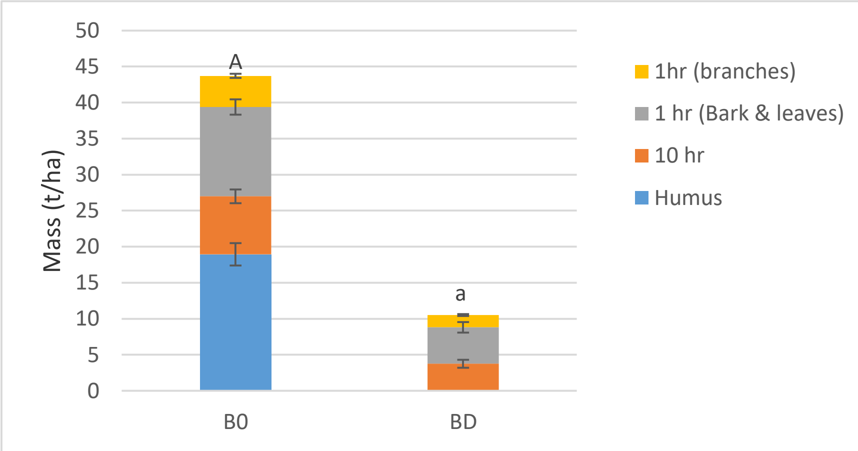


Figure 5.5: Combined fuel loading per size class across treatments
(Aa) Letters with different cases indicate significant differences among the treatments at $p<0.05$

Block 1: Differences in fuel loading for this block are presented in Figure 5.6. This site had slightly greater fuel loading than Block 2 for the same treatment. However, the difference in fuel loading between blocks was only significant ($p<0.05$) for the 10 hour fuel class; the differences for the other classes were all non-significant (Tables 5.1 - 5.4). For total fuel loading in the non-disking treatments, Block 1 had an average load of 44.8 t ha^{-1} in contrast to the 41.4 t ha^{-1} in Block 2. For the repeatedly disked treatments, the total fuel loading in Block 1 averaged 11.8 t ha^{-1} while Block 2 averaged at 9.2 t ha^{-1}. The magnitude the of difference in fuel loading between the two treatments for various fuel classes in Block 1 was measured, namely humus, 19.0 t ha^{-1}; 10 hour fuels, 6.3 t ha^{-1}; 1 hour fuels (bark and leaf fraction) 5.9 t ha^{-1} and 1 hour fuels (branch fraction), 3.2 t ha^{-1}. For the total forest floor mass, the difference was 33.0 t ha^{-1}. Tables 5.1 - 5.4 illustrate that the magnitude of difference in fuel loading and total forest floor mass observed between B0 and BD treatment was significant.

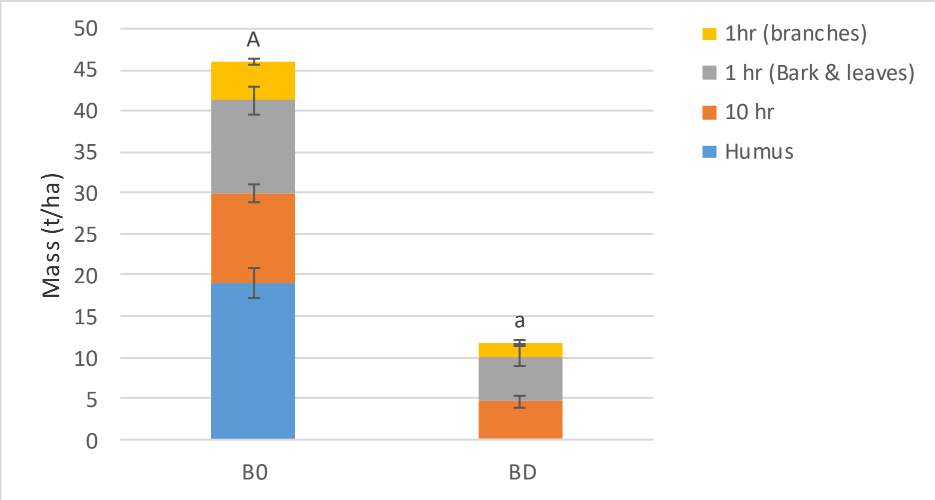


Figure 5.6: Block 1 fuel loading per size class across treatments
(Aa) Letters with different cases indicate significant differences among for the treatments at $p<0.05$

Block 2: This block had a slightly lower amount of fuel loading when contrasted to Block 1 for both treatments. However, the BD treatments within this block had a significantly lower quantity of fuel loading compared to the B0 treatments (Tables 5.1 - 5.4). Data showing means for fuel loading for the two treatments are presented in Figure 5.7. The magnitude in difference between the two treatments for humus was 18.9 t ha^{-1}; for 10 hour fuels, 2.3 t ha^{-1}; for 1 hour fuels (bark and leaf fraction), 8.8 t ha^{-1} and 2.3 t ha^{-1} for 1 hour fuels (branch fraction). The difference in the total forest floor mass averaged 32.2 t ha^{-1}. Difference in fuel loading following repeated disc harrowing was significant for all the fuel classes as well as the total forest floor mass (refer to Table 5.1 - 5.4).

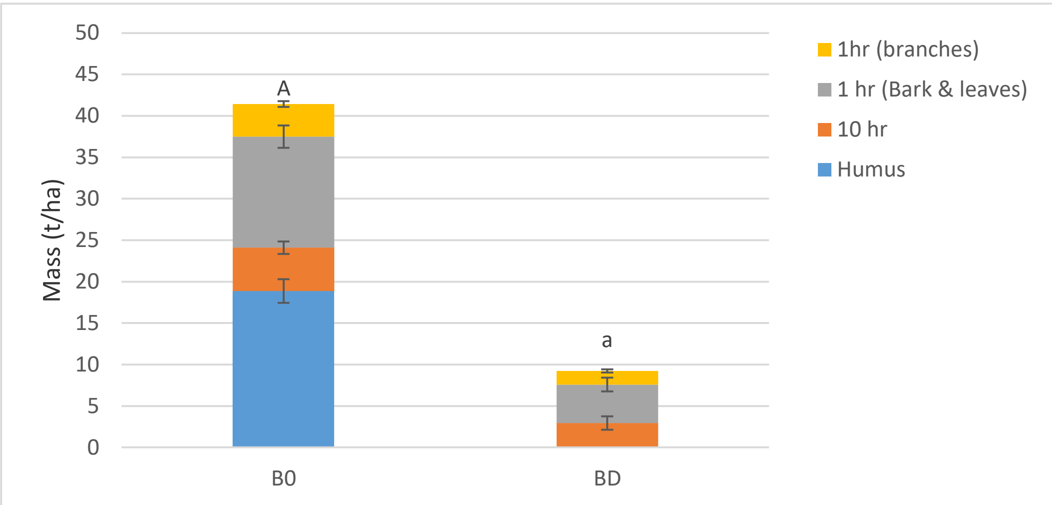


Figure 5.7: Block 2 fuel loading per size class across treatments
(Aa) Letters with different cases indicate significant differences among the treatments at $p<0.05$

Mean values showing differences in nutrient content of the forest floor material are indicated in Table 5.5. The nutrient distribution for the total forest floor material was significantly different for all elements among the treatments. The repeatedly disked treatments had the least amount of all the measured nutrient elements compared to the significantly higher quantities for the non-disking treatments across all blocks. Nitrogen was the only nutrient element that was significantly different among the blocks, Block 1 having the highest amount of N for both treatments.

Table 5.5: Forest floor material nutrient distribution

Kg ha^{-1}	**Forest Floor**		**N**		**P**		**K**		**Ca**		**Mg**	
Treat	B0	BD	B0	BD	B0	BD	B0	BD	B0	BD	B0	BD
Block 1	44780^{A}	11817^{a}	366^{A}	86^{a}	14^{A}	3^{a}	34^{A}	9.0^{a}	265^{A}	59^{a}	34^{A}	9^{a}
	(3185)	(1672)	(32)	(16)	(2)	(1)	(5)	(1)	(36)	(9)	(4)	(1)
Block 2	41419^{A}	9220^{a}	297^{B}	50^{b}	11^{A}	2^{a}	33^{A}	8^{a}	217^{A}	37^{a}	37^{A}	7^{a}
	(2419)	(1720)	(29)	(8)	(1)	(0)	(3)	(1)	(26)	(7)	(3)	(1)

(Aa) Letters with different cases in a row indicate significant differences among the treatments at $p<0.05$
(AB) Different letters in a column indicate a significant difference among the blocks at $p<0.05$
(1.8) Standard error values are presented in parenthesis below means

Figures 5.8A and B are photographs of the forest floor material captured infield before sampling in both treatments. Figure 5.8A depicts the non-disking treatments while Figure 5.8B portrays the repeatedly disked treatments. It is clear to see with the naked eye that the B0 treatment has dense, raised forest floor layers with a deep fuel bed. This indicates a greater accumulation of fuel loading over time. In contrast, the BD treatment (Figure 5.8B) shows a sparse forest floor layer where it is almost possible to see through to the mineral soil, indicating a significantly lower fuel loading scenario. All three generic forest floor strata were still present with non-disking treatment, as seen in Figures 5.8A. On the contrary, Figure 5.8B illustrates significant alteration in the forest floor structure following the application of repeated disc harrowing treatments. This resulted in L only present directly on top of the MS layer; both the F and H strata were not present in the disked swathes.

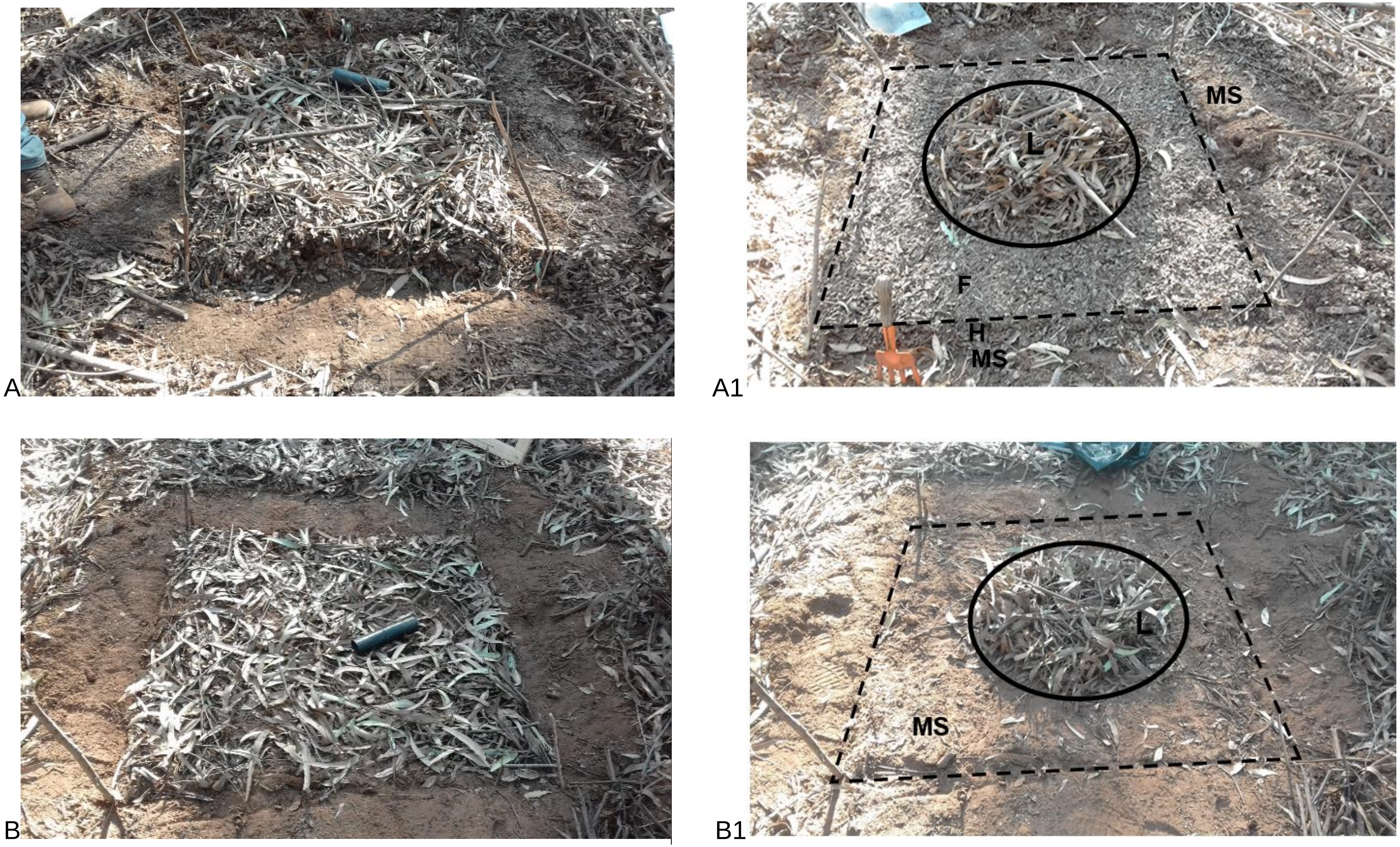


Figure 5.8: Infield photographs from Block 2 [the inner material is the untouched forest floor (A = B0 and B = BD) with carefully cleared outer perimeter]

5.2. Soil Chemical Properties

Soil samples were collected at a depth of 0 - 10 cm in both blocks for both treatments. Soil chemical property values presented in this section are applicable only to the topsoil layer. For base cations (K, Ca, Mg, and Na), the difference was only quantified in the exchangeable fraction, extractable fraction for topsoil P (Bray II), the total topsoil N and organic C fractions, and soil pH in KCl.

5.2.1. Exchangeable base cations (K, Ca, Mg, and Na) and ECEC

K: The exchangeable topsoil K ANOVA results are presented in Table 5.6. Differences in the topsoil exchangeable K fraction were significant between treatments within and between the blocks in this experiment. Mean values of topsoil exchangeable K quantity are shown in Figure 5.9. Block 2 had a significantly high topsoil exchangeable K compared to Block 1. The BD treatment in overall had the highest topsoil exchangeable K in contrast to the B0 treatment for both blocks. Within Block 2, the BD treatment had 0.108 $cmol_c$ kg^{-1} and the B0 treatment was 0.067 $cmol_c$ kg^{-1}. Block 1 had the least topsoil exchangeable K: the BD treatment was 0.073 $cmol_c$ kg^{-1} and 0,037 $cmol_c$ kg^{-1} for the B0 treatment.

Table 5.6: ANOVA of topsoil exchangeable K quantity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.0077	0.0038	9.01	0.0071
Blocks	1	0.0031	0.0031	7.33	0.0241
Treatment	1	0.0045	0.0045	10.68	0.0097
Error	9	0.0038	0.0004		
Corrected Total	11	0.0115			

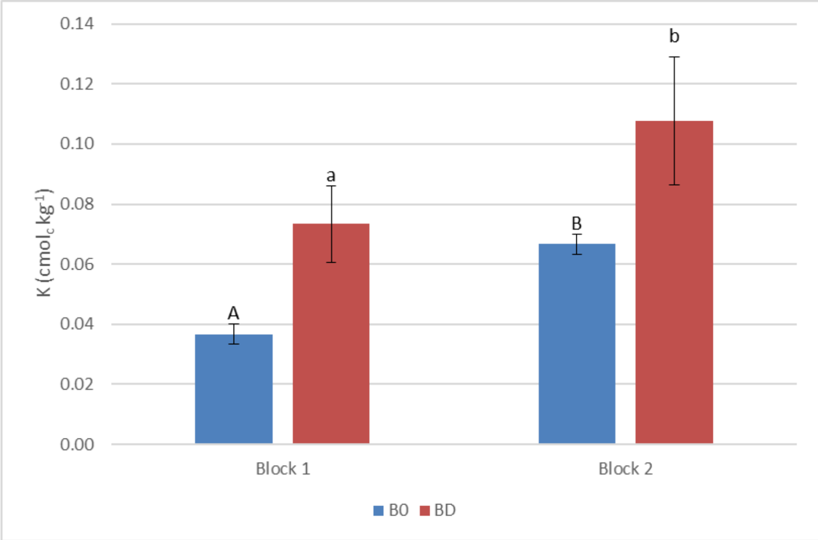


Figure 5.9: Topsoil exchangeable K values among treatments and blocks
(Aa) Letters with different cases indicate a significant differences among the treatments at p<0.05
(AB) Different letters indicate a significant difference among the blocks at p<0.05

Ca: Repeated disc harrowing treatment significantly contributed to the difference in topsoil exchangeable Ca quantities; however, the difference between the blocks was not significant (Table 5.7). Mean values of topsoil exchangeable Ca for both the blocks and the treatments are presented in Figure 5.10. This practice resulted in a significant increase in topsoil exchangeable Ca quantity in both blocks. In Block 1, topsoil exchangeable Ca was 0.83 $cmol_c\ kg^{-1}$ for the BD treatment and 0.48 $cmol_c\ kg^{-1}$ for the B0 treatment. Likewise, for Block 2, exchangeable topsoil Ca was 0.55 $cmol_c\ kg^{-1}$ for the BD treatment and 0.24 $cmol_c\ kg^{-1}$ for the B0 treatment. Even though Block 2 had a low topsoil exchangeable Ca compared to Block 1, Table 5.6 illustrates that the magnitude of difference was not significant.

Table 5.7: ANOVA results of topsoil exchangeable Ca quantity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.5411	0.2706	6.39	0.0187
Blocks	1	0.2011	0.2011	4.75	0.0572
Treatment	1	0.3400	0.3400	8.03	0.0196
Error	9	0.3811	0.0423		
Corrected Total	11	0.9222			

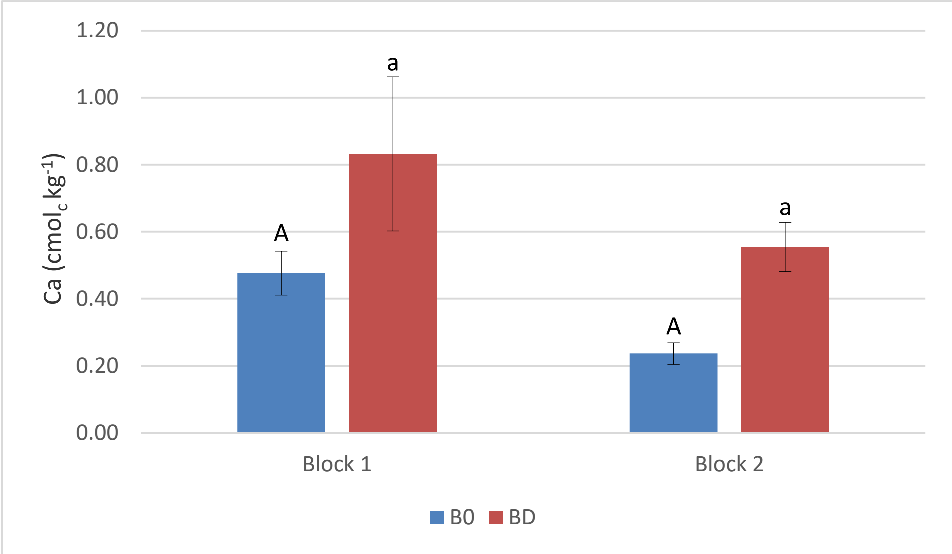


Figure 5.10: Topsoil exchangeable Ca values among treatments and blocks
(Aa) Letters with different cases indicate a significant differences among the treatments at *p*<0.05

Mg: Data showing the effect of repeated disc harrowing on the topsoil exchangeable Mg quantity is presented in Figure 5.11. Table 5.8 shows that the repeated disc harrowing treatment resulted in a significant increase in topsoil exchangeable Mg in this experiment, but there was no significant difference between the blocks. The BD treatment had the highest topsoil exchangeable Mg when compared to the B0 treatment for both blocks. Block 2 had a slightly greater topsoil exchangeable Mg with BD treatment of 0.42 $cmol_c$ kg^{-1} and B0 treatment of 0.25 $cmol_c$ kg^{-1}. In contrast, Block 1 had a lower topsoil exchangeable Mg: the BD treatment was 0.30 $cmol_c$ kg^{-1} and the B0 treatment was 0.23 $cmol_c$ kg^{-1}, Figure 5.11.

Table 5.8: ANOVA results of topsoil exchangeable Mg quantity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.0597	0.0298	7.36	0.0127
Blocks	1	0.0145	0.0145	3.57	0.0914
Treatment	1	0.0452	0.0452	11.16	0.0087
Error	9	0.0365	0.0041		
Corrected Total	11	0.0962			

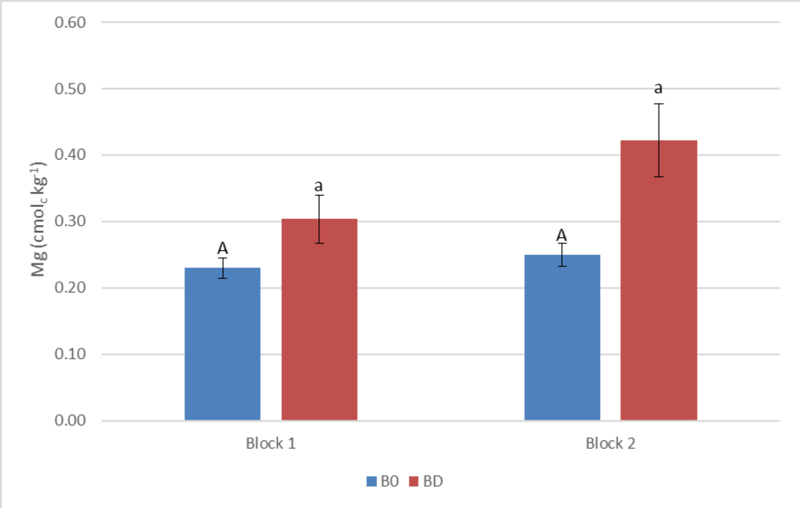


Figure 5.11: Topsoil exchangeable Mg values among treatments and blocks
(Aa) Letters with different cases indicate a significant differences among the treatments at *p*<0.05

Na: Table 5.9 indicates that both the blocks and the treatments had no significant effect on differences in the topsoil exchangeable Na quantities in this experiment; *p*-values were all greater than 5%. Data showing mean values is presented in Figure 5.12. Block 2 had topsoil exchangeable Na of 0.109 $cmol_c$ kg^{-1} for the BD treatment and 0.093 $cmol_c$ kg^{-1} for the B0 treatment. Similarly, in Block 1, the topsoil exchangeable Na was 0.088 $cmol_c$ kg^{-1} for the BD treatment and 0.083 $cmol_c$ kg^{-1} for the B0 treatment.

Table 5.9: ANOVA results of topsoil exchangeable Na quantity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.0010	0.0006	3.53	0.0738
Blocks	1	0.0007	0.0007	5.00	0.0522
Treatment	1	0.0003	0.0003	2.07	0.1845
Error	9	0.0013	0.0001		
Corrected Total	11	0.0023			

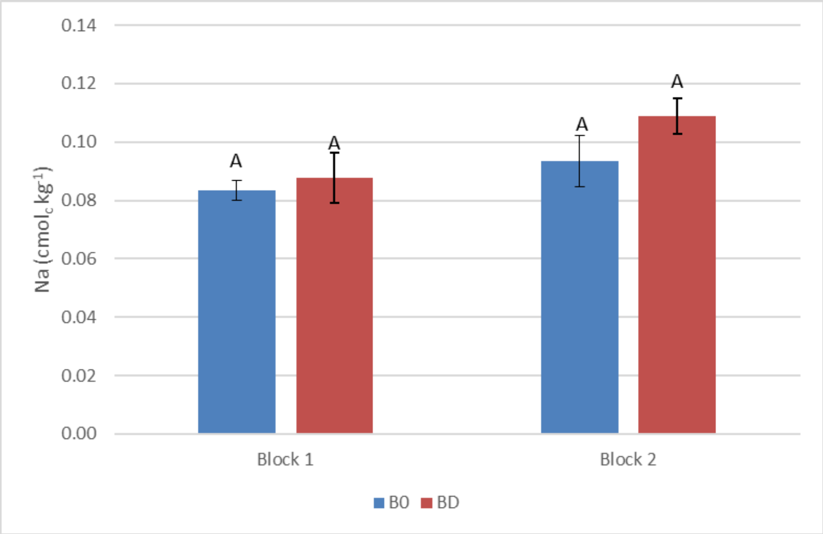


Figure 5.12: Topsoil exchangeable Na values among treatments and blocks
(AA) Letters with same cases indicate no significant differences among the treatments and the blocks at *p*<0.05

Table 5.10 is a summary of topsoil exchangeable cation content in kg per ha (1 ha • 0.1m). This data is essential to contextualize the differences between treatments in topsoil cation content on a stand level.

Table 5.10: Topsoil exchangeable cation content

Cation (kg ha^{-1})	**K**		**Ca**		**Mg**		**Na**	
Treatment	B0	BD	B0	BD	B0	BD	B0	BD
Block 1	19.4^{A}	36.1^{a}	129.0^{A}	210.1^{A}	75.5^{A}	92.9^{A}	25.9^{A}	25.4^{A}
	(1.8)	(6.2)	(17.8)	(58.0)	(5.0)	(10.9)	(1.0)	(2.5)
Block 2	35.7^{B}	46.2^{b}	65.0^{B}	124.3^{B}	83.2^{A}	113.4^{A}	29.4^{A}	27.3^{A}
	(1.8)	(8.8)	(8.7)	(25.3)	(5.8)	(17.8)	(2.8)	(0.4)

(Aa) Letters with different cases in a row indicate significant differences among the treatments at *p*<0.05
(AB) Different letters in a column indicate a significant difference among the blocks at *p*<0.05
(1.8) Standard error values are presented in parenthesis below means

ECEC: Figure 5.13 shows that the repeatedly disked treatments had a slightly higher ECEC for both blocks in comparison to non-disking. However, according to the ANOVA results (Table 5.11), the difference was not significant. Soil ECEC was only significantly different between blocks, as illustrated in Table 5.11. Block 2 had significantly higher ECEC in comparison to Block 1. Block 2 had an ECEC of 7.76 $cmol_c$ kg^{-1} for the BD treatments and 7.23 $cmol_c$ kg^{-1} for the B0 treatments. Conversely, Block 1 had a significantly lower ECEC of 6.35 $cmol_c$ kg^{-1} for the BD treatment and 5.84 $cmol_c$ kg^{-1} for the B0 treatment.

Table 5.11: ANOVA results of topsoil ECEC

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	667.4446	333.7223	8.60	0.0082
Blocks	1	587.5334	587.5334	15.15	0.0037
Treatment	1	79.91120	79.9112	2.06	0.1850
Error	9	349.1075	38.7897		
Corrected Total	11	1016.5521			

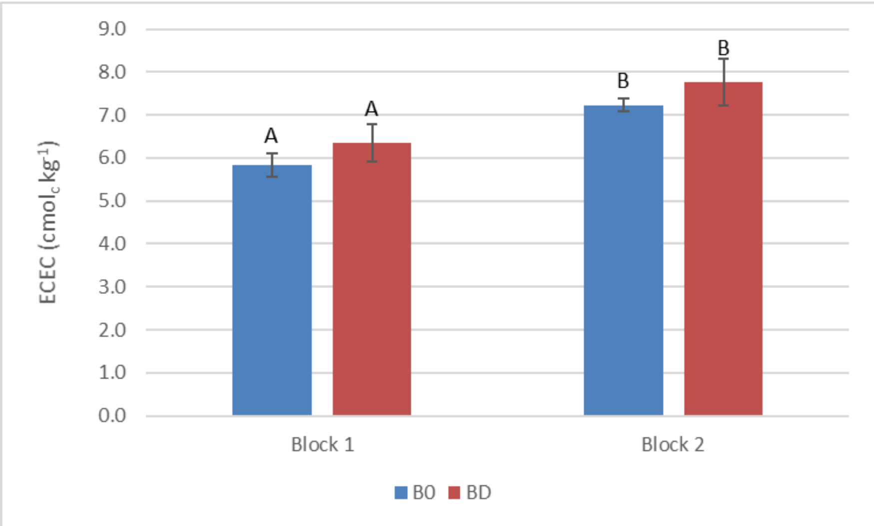


Figure 5.13: Topsoil ECEC values among treatments for the two blocks
(AB) Different letters indicate significant difference among the blocks at $p<0.05$

5.2.2. Topsoil pH, S-value, base saturation and acid saturation

pH: Soil pH (KCl) did not differ significantly among treatments or blocks (Table 5.12). In Figure 5.14, Block 1 had a pH value of 3.5 in KCl for both treatments. Similarly, the pH value of Block 2 was 3.6 in KCl for both the BD and the B0 treatments. Clearly the treatment had no significant effect on soil pH in this experiment.

Table 5.12: ANOVA results of topsoil pH in KCl

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.0093	0.0046	0.43	0.6646
Blocks	1	0.0093	0.0093	0.86	0.3791
Treatment	1	0.0000	0.0000	0.00	1.0000
Error	9	0.0974	0.0108		
Corrected Total	11	0.1067			

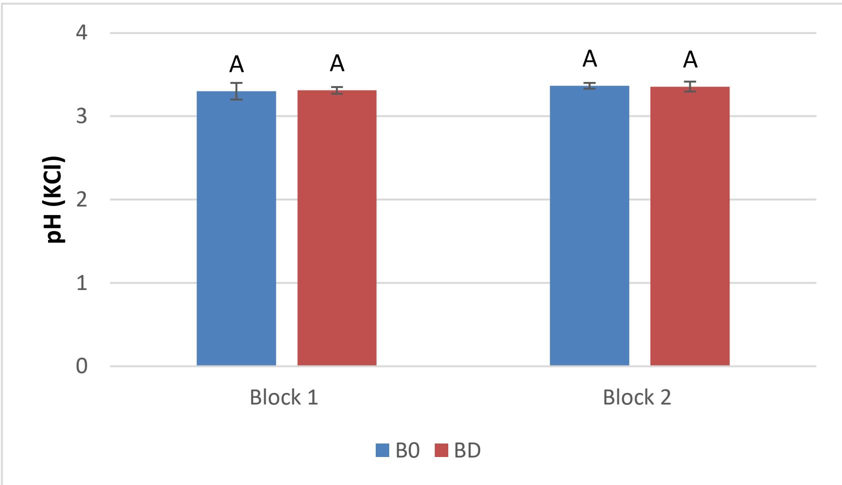


Figure 5.14: Topsoil pH in KCl values among treatments and blocks
(AA) Same alphabets indicate no significant differences for the treatments and blocks at $p<0.05$

S-value: S-value ANOVA results in Table 5.13 indicate that the differences in topsoil S-value were only significant in response to the treatments, but not significant among the blocks. The S-value mean values for the blocks and the treatments are presented in Figure 5.15. In Block 1, the BD treatment significantly increased topsoil S-value to 1.30 $cmol_c\ kg^{-1}$ in comparison to the B0 treatment at 0.83 $cmol_c\ kg^{-1}$. Similarly in Block 2, the BD treatment increased topsoil S-Value at 1.19 $cmol_c\ kg^{-1}$in comparison to the B0 treatment at 0.64 $cmol_c\ kg^{-1}$.

Table 5.13: ANOVA results of topsoil S-value

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	83.5417	41.7708	6.32	0.0193
Blocks	1	6.0208	6.0208	0.91	0.3647
Treatment	1	77.5208	77.5208	11.73	0.0076
Error	9	59.4564	6.6063		
Corrected Total	11	142.9981			

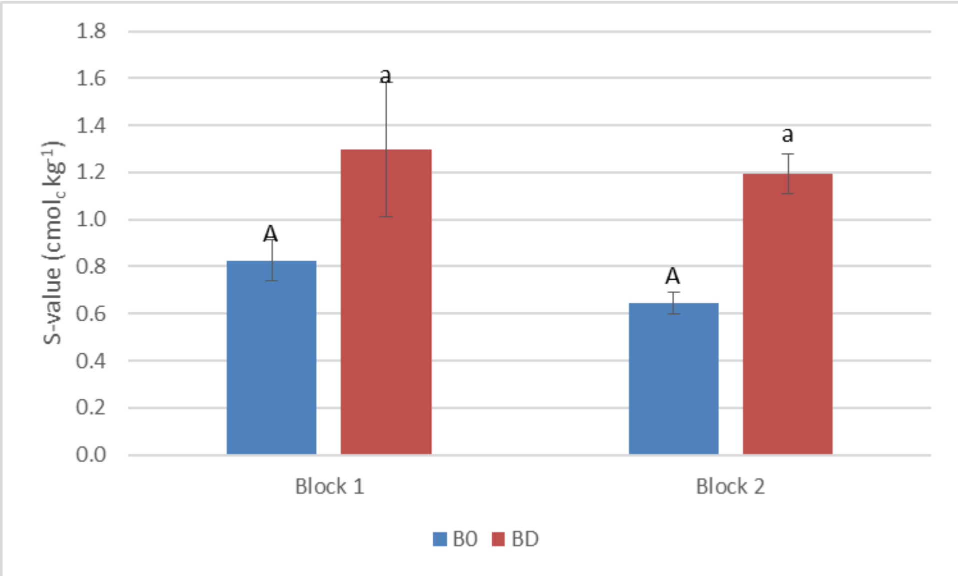


Figure 5.15: Topsoil S-value mean values among treatments and blocks
(Aa) Letters with different cases indicate a significant differences among the treatments at *p*<0.05

Base Saturation: There was a significant difference in base saturation percentage between blocks and treatments, as shown in Table 5.14. Block 2 had a significantly lower base saturation than Block 1, Figure 5.16. The repeated disc harrowing treatment significantly increased topsoil base saturation in comparison to the non-disking treatment. Block 1 had the highest base saturation, amounting to 19.3% for the BD treatment and 14.2% for B0 treatment. On the contrary, Block 2 had the least base saturation amounting to 14.9% for the BD treatment and 8.9% for the B0 treatment.

Table 5.14: ANOVA results of topsoil base saturation

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	163.5234	81.7617	9.82	0.0055
Blocks	1	70.4137	70.4137	8.46	0.0174
Treatment	1	93.1097	93.1097	11.19	0.0086
Error	9	74.9155	8.3239		
Corrected Total	11	238.4389			

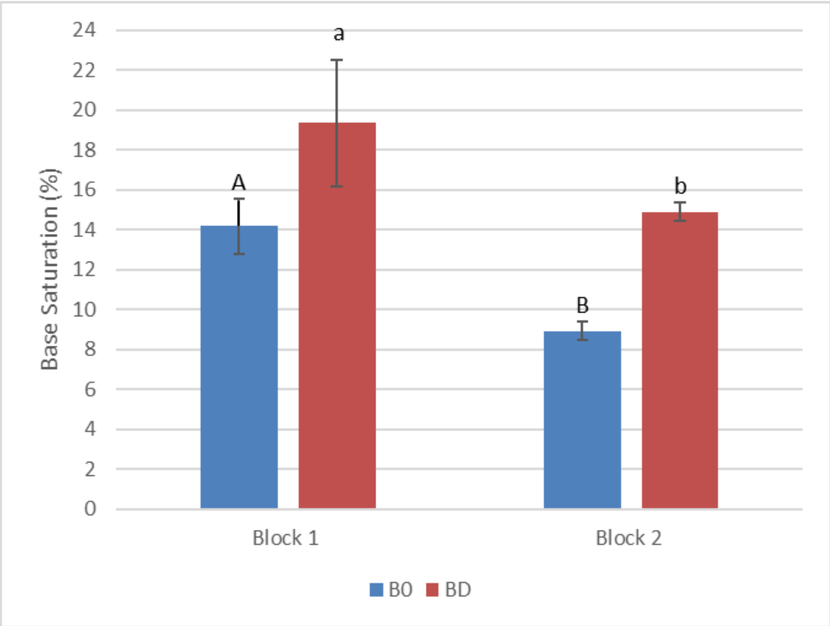


Figure 5.16: Topsoil base saturation values among treatments and blocks
(Aa) Letters with different cases indicate a significant differences among the treatments at $p<0.05$
(AB) Different letters indicate a significant difference among the blocks at $p<0.05$

Acid saturation: Topsoil acid saturation ANOVA results in Table 5.15 indicate a significant difference among the blocks and the treatments. In Figure 5.17, Block 2 had a significantly higher acid saturation in contrast to Block 1. The BD treatment in Block 1 significantly reduced acid saturation to 80.6% compared to 85.8% for the B0 treatment. Following the same trend in Block 2, the BD treatment was at 85.1% compared to the B0 treatment at 91.1%.

Table 5.15: ANOVA results of topsoil acid saturation

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	163.5234	81.7617	9.82	0.0055
Blocks	1	70.4137	70.4137	8.46	0.0174
Treatment	1	93.1097	93.1097	11.19	0.0086
Error	9	74.9155	8.3239		
Corrected Total	11	238.4389			

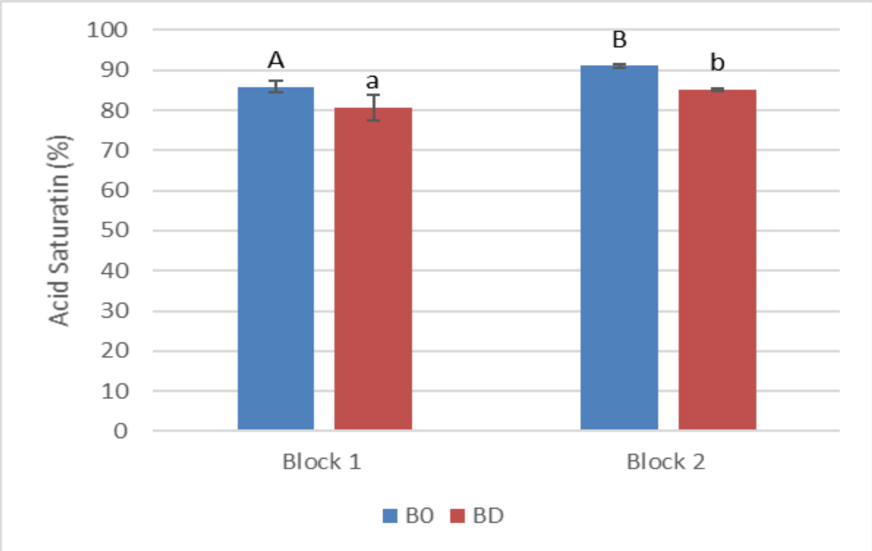


Figure 5.17: Topsoil acid saturation values among treatments and blocks
(Aa) Letters with different cases indicate a significant differences among the treatments at *p*<0.05
(AB) Different letters indicate a significant difference among the blocks at *p*<0.05

5.2.3. Soil N, P, and C response to treatments for the two blocks

Total N: From Table 5.16, the difference in topsoil total N percentage was only significant among the blocks, but not significant for the treatments. Mean values are presented in Figure 5.18. Block 2 had the highest topsoil total N content with no difference between the treatments at 0.16%. Block 1 indicated a significantly lower topsoil total N, with BD treatment at 0.11% and B0 treatment at 0.10%.

Table 5.16: ANOVA results of topsoil total N content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.0095	0.0047	20.24	0.0005
Blocks	1	0.0093	0.0093	39.47	0.0001
Treatment	1	0.0002	0.0002	1.01	0.3410
Error	9	0.0021	0.0002		
Corrected Total	11	0.0116			

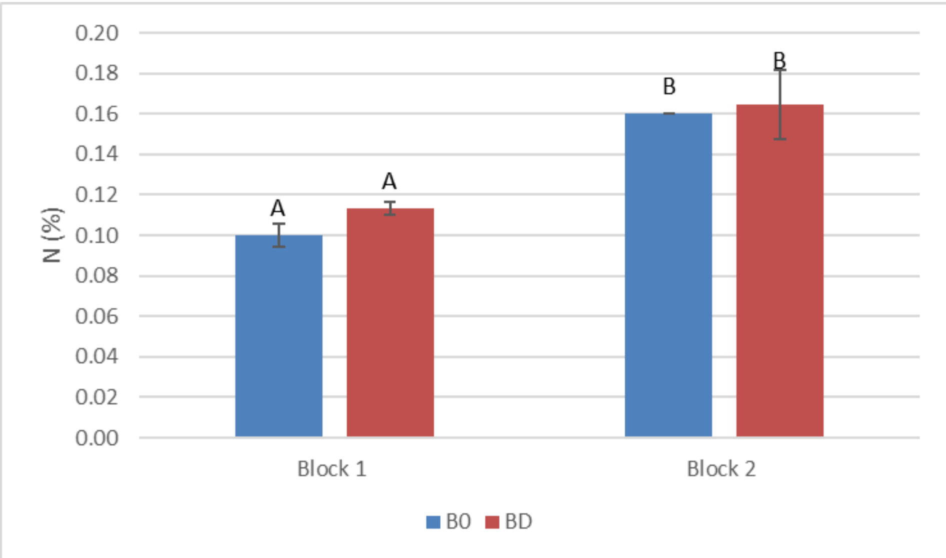


Figure 5.18: Topsoil total N values among treatments for the two blocks
(AA) letters with the same casing indicate no significant differences among the treatments at $p<0.05$
(AB) Different letters indicate significant difference among the blocks at $p<0.05$

P Bray II: The topsoil extractable P (Bray II) was not significantly different amongst both the blocks or the treatments in this experiment (see Table 5.17). Topsoil extractable P mean values are presented in Figure 5.19. In Block 1, BD treatment was 14.1 mg kg^{-1} and the B0 treatment was 14.4 mg kg^{-1} in comparison to Block 2 with BD treatment at 18.2 mg kg^{-1} and B0 treatment at 16.1 mg kg^{-1}.

Table 5.17: ANOVA results of topsoil extractable P Bray II content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	28.2884	14.1442	2.25	0.1614
Blocks	1	25.76447	25.76447	4.10	0.0737
Treatment	1	2.5239	2.5239	0.40	0.5422
Error	9	56.6075	6.2897		
Corrected Total	11	84.8959			

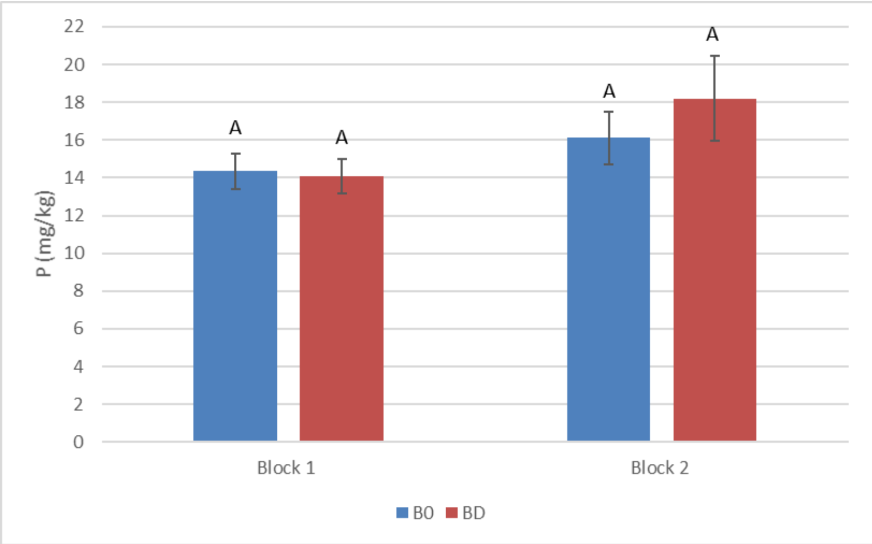


Figure 5.19: Topsoil extractable P values among treatments for the two blocks
(AA) letters with the same casing indicate no significant differences among the treatments at $p<0.05$

Total Organic C: Neither the blocks nor treatments had a significant effect on topsoil total C in this experiment, Table 5.18. Data presented in Figure 5.20 illustrates that the topsoil total C was similar in both blocks and treatments. Treatment did not have any effect on topsoil total C in Block 1; it remained at 2.4% for both the BD and B0 treatments. In Block 2, the BD treatment had 2.5% of soil C content and the B0 treatment at 2.4%.

Table 5.18: ANOVA results of topsoil total C content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.0213	0.0106	0.72	0.5121
Blocks	1	0.0169	0.0169	1.14	0.3126
Treatment	1	0.0044	0.0044	0.30	0.5979
Error	9	0.1327	0.0147		
Corrected Total	11	0.1540			

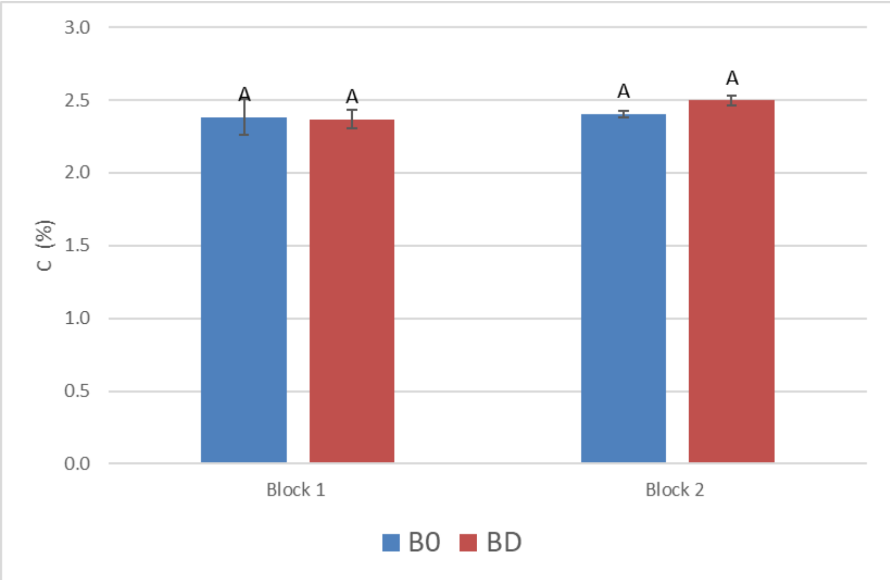


Figure 5.20: Topsoil total C values among treatments for the two blocks
(AA) letters with the same casing indicate no significant differences among the treatments at *p*<0.05

5.3. Soil Bulk Density

Concerning the soil physical properties, only soil bulk density was investigated in this study. Figure 5.21 shows means for soil bulk density data that was measured and contrasted between the two treatments and the two blocks. Sampling was done at depths of 0 - 10 cm (Figure 5.21A) and 10 - 20 cm depth (Figure 5.21B). Repeated disc harrowing significantly reduced soil bulk density in both blocks (see Table 5.19). The effect was also significant to the depth of 20 cm throughout all the blocks. However, there was no significant difference in soil bulk density between the blocks.

Table 5.19: ANOVA results of soil bulk density (A=depth 0-10 & B = depth 10-20 cm)

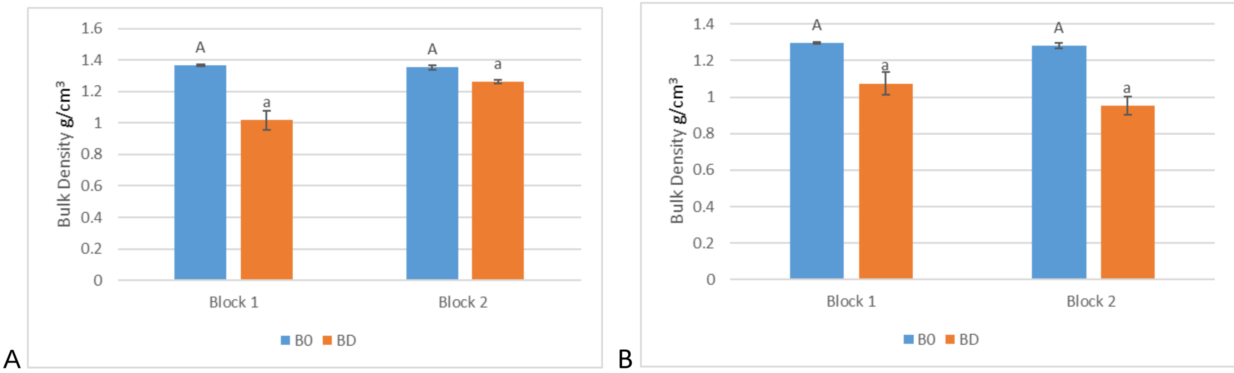
A

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.1845	0.0923	11.32	0.0035
Blocks	1	0.0406	0.0406	4.98	0.0526
Treatment	1	0.1439	0.1439	17.67	0.0023
Error	9	0.0733	0.0081		
Corrected Total	11	0.2578			

B

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.2406	0.1203	21.77	0.0004
Blocks	1	0.0141	0.0140	2.55	0.1446
Treatment	1	0.2265	0.2265	41.00	0.0001
Error	9	0.0497	0.0055		
Corrected Total	11	0.2903			

At a depth of 0 - 10 cm, the non-disking treatment had the highest soil bulk density (1.37 g cm^3) while the repeatedly disked treatment showed a significant reduction in soil bulk density (1.02 g cm^3) in Block 1 (Figure 5.21A). Correspondingly, Block 2 followed a similar trend in soil bulk density: non-disking treatment was at 1.35 g cm^3 and repeatedly disked treatment was at 1.26 g cm^3. This was similar for depth of 10 - 20 cm in Figure 5.21B. In Block 1, the non-disking treatment showed the highest soil bulk density at 1.29 g cm^3 in comparison to the repeatedly disked treatment at 1.07 g cm^3. Likewise in Block 2, the non-disking treatment had a higher soil bulk density at 1.28 g cm^3 and the repeatedly disked treatment had 0.95 g cm^3.



Depth: 0-10 cm

Depth: 10-20 cm

Figure 5.21: Soil bulk density response to treatment for the two blocks
(Aa) letters with different cases indicate significant differences among the treatments at $p<0.05$

5.4. Above Ground and Below Ground Plant Growth

The effect of repeated disc harrowing on the above ground tree growth is presented in Figures 5.22 - 5.26. The magnitude of difference was tested with ANOVA results seen in Tables 5.20 - 5.23. The effect of repeated disc harrowing on the above ground tree growth was examined by evaluating differences on various growth-related variables, including stand density (stems ha^{-1}), basal area (cm^2 ha^{-1}), volume (m^3 ha^{-1}), and plant biomass (t ha^{-1}).

5.4.1. Stand density

The effect of repeated disc harrowing throughout the stand rotation on stand density of *Eucalyptus grandis x nitens* was recorded and reported for both individual stump and single stem within blocks and treatments (detailed explanation in Methodology section 3.3.1). The magnitude of difference in stand density was tested with ANOVA results presented in Table 5.20. Mean values are shown in Figure 5.22.

Table 5.20: ANOVA results of stand density (A = Stump & B = Stem)

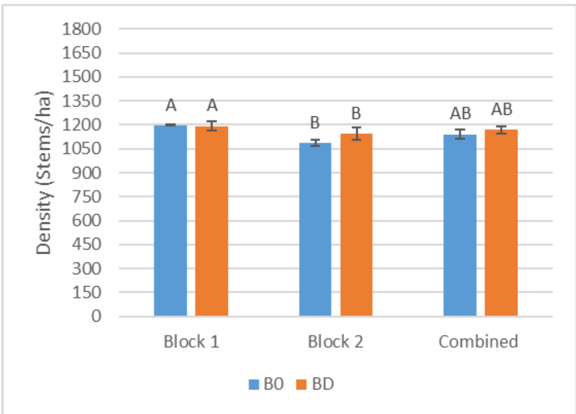
A

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	21185.6996	10592.8498	5.11	0.0329
Blocks	1	19022.6337	19022.6337	9.18	0.0143
Treatment	1	2163.0658	2163.0658	1.04	0.3336
Error	9	18649.6914	2072.1879		

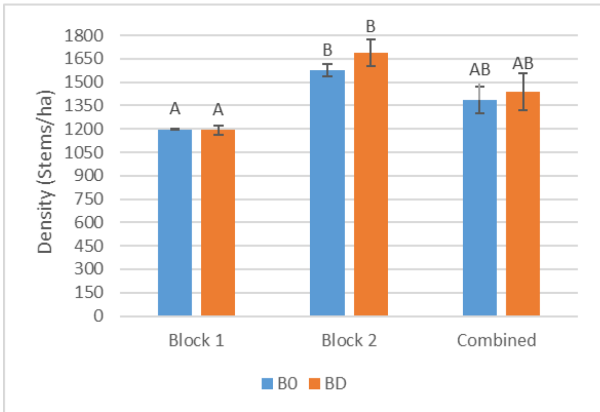
Corrected Total	11	39835.3901			

B

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	581360.5967	290680.2984	37.78	<0.0001
Blocks	1	573004.1152	573004.1152	74.47	<0.0001
Treatment	1	8356.4815	8356.4815	1.09	0.3245
Error	9	69246.3992	7694.0444		
Corrected Total	11	650606.9959			



A



B

Figure 5.22: Stand density for treatments. [(A) Individual stump and (B) single stem]

(Aa) Letters with same cases indicate no significant difference among the treatments at p<0.05
(AB) Different letters indicate a significant difference among the blocks at p<0.05

The following observations in stand density are based on individual stump (data shown in Figure 5.22A). Table 5.20A indicates no significant difference in stand density between the treatments. The difference in stand density was only significant between the blocks. Treatment B0 had an average of 1141 stems ha^{-1} and 1168 stems ha^{-1} on the BD treatments for the combined blocks. Block 1 had an average of 1197 stems ha^{-1} for the B0 treatments and 1192 stems ha^{-1} for the BD treatments. For Block 2, the B0 treatments had an average of 1085 stems ha^{-1} while the BD treatments averaged 1144 stems ha^{-1}.

When stand density was evaluated on a single stem basis, the results still followed the same trend (see Figure 5.22B). However, stand density in Block 2 increased dramatically for both B0 and BD treatments in contrast to using individual stump. This was not the case for Block 1. Table 5.19B indicates that there was a significant difference in stand density between the blocks, but no significance between the treatments. For the combined blocks, the B0 treatments, had 1388 stems ha^{-1}, thus being the lowest, while the BD treatments had 1439 stems ha^{-1}. In Block 1, the B0 treatments had 1197 stems ha^{-1} and 1192 stems ha^{-1} in the BD treatments. For Block 2, the B0 treatments was 1578 stems ha^{-1} and the BD treatments was 1687 stems ha^{-1}.

5.4.2. Stand basal area

Basal area in this study was used as a supplementary stand growth and productivity indicator; data is presented in Figure 5.23. Basal area was measured for both treatments and in two blocks. The ANOVA results in Table 5.21 show that there was no significant difference between the two treatments or between the two blocks. For Block 1, B0 treatments had a basal of 24.6 m^2 ha^{-1} and BD treatments, 23.5 m^2 ha^{-1}. Correspondingly the two treatments had a similar productivity with a basal area of 25.5 m^2 ha^{-1} in B0 compared to the BD treatment with a basal area of 24.9 m^2 ha^{-1} in Block 2. The magnitude of difference in stand productivity for the treatments was negligible at $p<0.05$ across all blocks.

Table 5.21: ANOVA results of stand basal area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	5.9733	2.9866	1.75	0.2280
Blocks	1	3.8755	3.8755	2.27	0.1661
Treatment	1	2.0978	2.0978	1.23	0.2963
Error	9	15.3581	1.7065		
Corrected Total	11	21.3314			

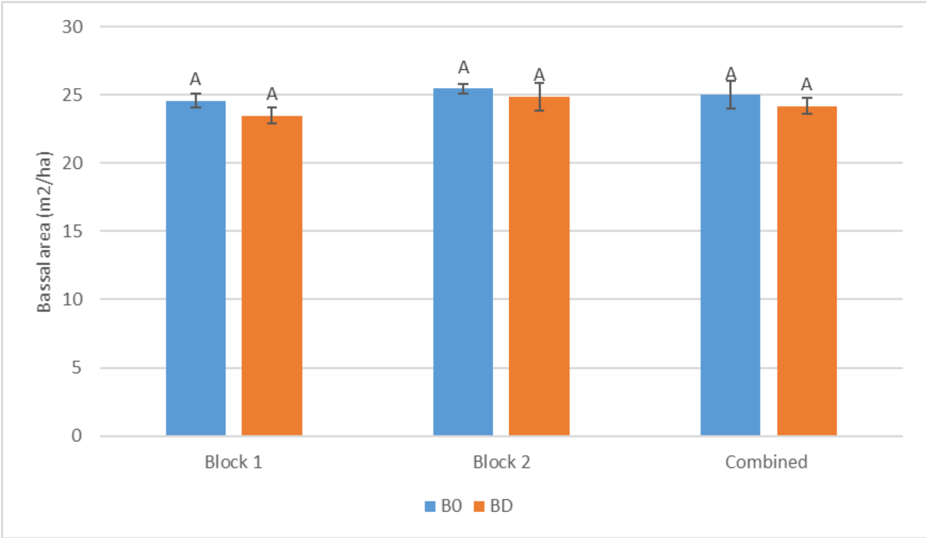


Figure 5.23: Basal area for the two treatments
(AA) Letters with same cases indicate no significant difference among the treatments at $p<0.05$
(AB) Different letters indicate a significant difference among the blocks at $p<0.05$

5.4.3. Stand volume

Stand volume was measured to quantify the effects of the repeated disk harrowing treatment on stand productivity by comparing it to the non-disking treatment; results are presented in Figure 5.24. The ANOVA results in Table 5.22 show stand volume was not significantly different as a function of either the blocks or the treatments. In Block 1, the B0 treatments had a slightly higher stand volume at 212.7 m^3 ha^{-1} in comparison to the BD treatments at 200.4 m^3 ha^{-1}. Similarly, in Block 2, the B0 treatments had stand volume of 212.4 m^3 ha^{-1} compared to the BD treatments at 205.0 m^3 ha^{-1}. The average stand volume for the combined blocks amounted to 212.6 m^3 ha^{-1} in B0 treatments and 202.7 m^3 ha^{-1} in BD treatments. The magnitude of the differences in stand volume between the two treatments was negligible across all the blocks, and the response followed a similar trend throughout.

Table 5.22: ANOVA results of stand volume productivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	307.7523	153.87612	1.50	0.2737
Blocks	1	13.8139	13.8139	0.13	0.7220
Treatment	1	293.9384	293.9384	2.87	0.1246
Error	9	922.3215	102.4802		
Corrected Total	11	1230.0738			

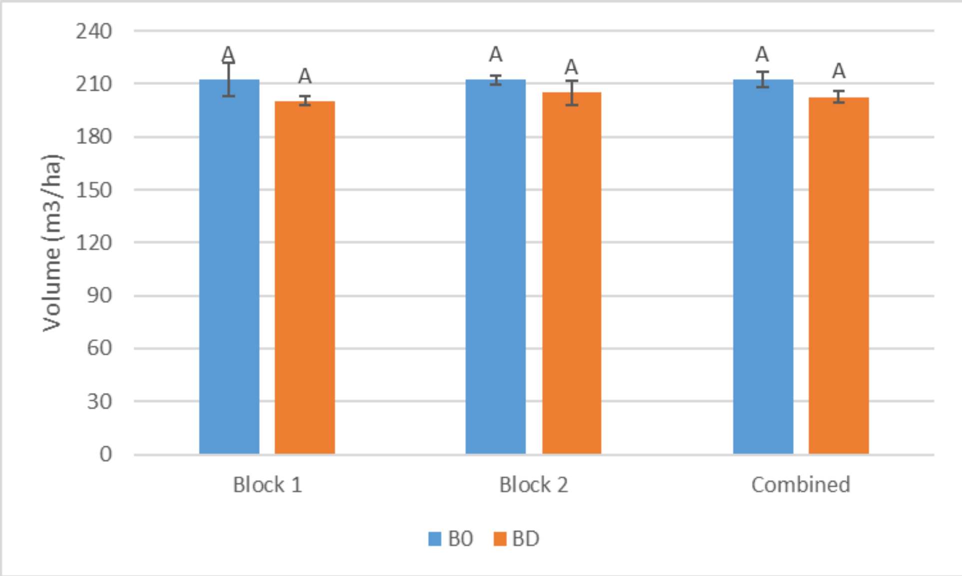


Figure 5.24: Average volume per hectare for the two treatments
(AA) Letters with same cases indicate no significant difference among the treatments at $p<0.05$
(AB) Different letters indicate a significant difference among the blocks at $p<0.05$

5.4.4. The above ground plant biomass

The above ground plant biomass was estimated to further quantify and evaluate the effect of repeated disc harrowing on stand productivity. Mean values are presented in Figure 5.25. Stem, bark, branches, and foliage making up the total aboveground plant biomass of *Eucalyptus grandis x nitens*. Stem wood contributed the most significant biomass amount towards the total aboveground plant biomass in relation to the other components across all sites and treatments. The ANOVA results in Table 5.23 confirm that neither the blocks nor the treatments had significant differences in aboveground plant biomass for the various components, with bark biomass being the only exception. Bark biomass estimates in Block 1 was significantly greater than that of Block 2.

Table 5.23: ANOVA results of stand above ground plant biomass

Total Above Ground Biomass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	146.0665	73.0333	1.31	0.3178
Blocks	1	0.1793	0.1793	0.00	0.9561
Treatment	1	145.8873	145.8873	2.61	0.1408
Error	9	503.5241	55.9472		
Corrected Total	11	649.5915			

Stem Biomass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	86.7665	43.3833	1.39	0.2980
Blocks	1	2.9372	2.9372	0.09	0.7660
Treatment	1	83.8293	83.8293	2.68	0.1357
Error	9	281.0274	31.2253		
Corrected Total	11	367.7939			

Bark Biomass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	12.7970	6.3985	11.64	0.0032
Blocks	1	12.5067	12.5067	22.74	0.0010
Treatment	1	0.2903	0.2903	0.53	0.4859
Error	9	4.9492	0.5499		
Corrected Total	11	17.7463			

Branches Biomass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2.2711	1.1356	1.65	0.2454
Blocks	1	0.9372	0.9372	1.36	0.2734
Treatment	1	1.3349	1.3339	1.94	0.1974
Error	9	6.1982	0.6887		
Corrected Total	11	8.4693			

Foliage Biomass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.5279	0.2639	1.26	0.3287
Blocks	1	0.1324	0.1324	0.63	0.4467

Treatment	1	0.3955	0.3955	1.89	0.2023
Error	9	1.8818	0.2091		
Corrected Total	11	2.4097			

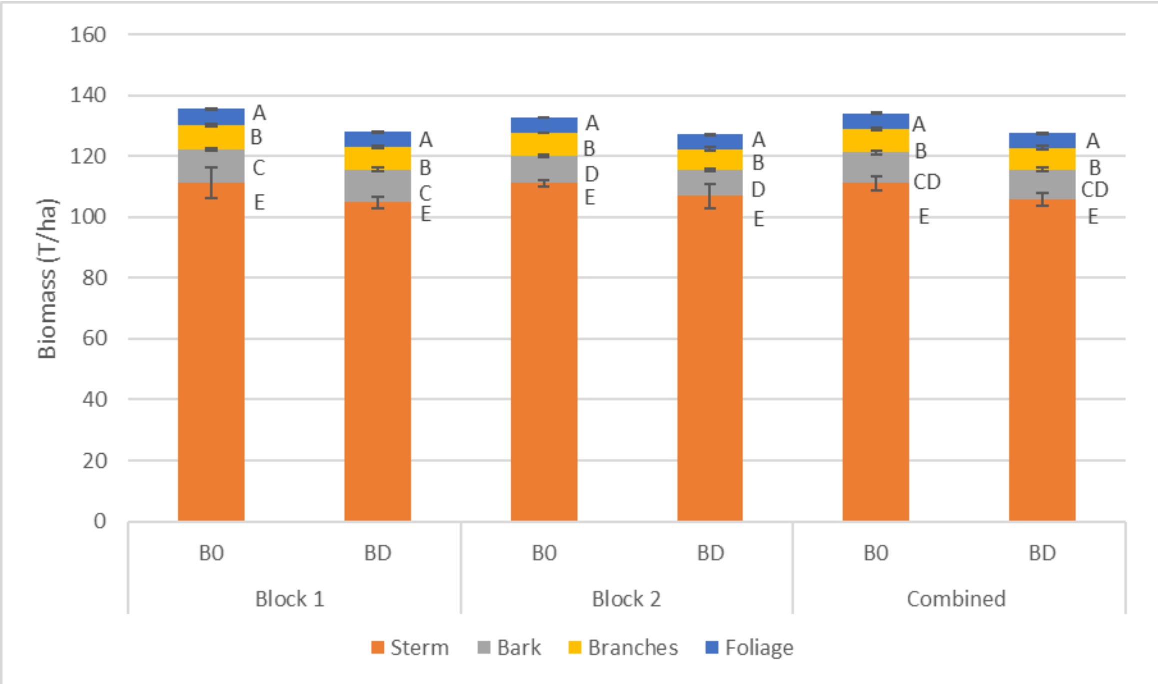


Figure 5.25: Distribution of the above ground plant biomass

(AA) letters with same cases indicate no significant difference among the treatments at $p<0.05$
(CC DD) Different letters indicate significance difference among the blocks at $p<0.05$

The total above ground tree biomass was similar between treatments across the blocks. For Block 1, the B0 treatments was at 135.2 t ha^{-1} and the BD treatments at 127.0 t ha^{-1}. In Block 2, the B0 treatments had 133.7 t ha^{-1} and 120.0 t ha^{-1} for the BD treatments. When the two blocks were combined, the B0 treatments had an average of 134.4 t ha^{-1} and the BD treatments had an average of 127.5 t ha^{-1}. The differences in the aboveground biomass was not significant between the two treatments at ($p< 0.05$). From the aboveground biomass components, only bark biomass showed a significant between the blocks ($p<0.05$).

5.4.5. Below ground growth: root distribution pattern

Data presented in this section is specifically focused on fine roots distribution patterns (class A, <2 mm diameter). Fine roots are feeder roots with significant contribution to tree growth. A thorough understanding of changes in fine root distribution patterns became particularly important for interpreting above ground growth differences in the two treatments. The effect of repeated disc harrowing on the below ground tree growth was investigated and quantified by assessing variation in fine root distribution patterns of the trees under study. In Figure 5.26 and Figure 5.27, the root distribution patterns in the non-disking treatments were used as benchmark for changes in root distribution patterns in the repeatedly disc harrowed treatments. The profile wall root study methodology was used. The results are presented in a profile wall mapping in Figure 5.26 and Figure 5.27. To demonstrate an increase or decline in the number of root counted per grid box, a colour intensity gradient was used. Root count is directly proportional to darkness of shading, as indicated by the key next to the profile wall map.

For every 10 cm depth, form 0 - 100 cm, the magnitude of difference in root distribution patterns between the two treatments was measured. Table 5.24 presents the ANOVA results for root count per 10 cm depth for the treatments and blocks. At the 5% confidence level, there was no significant difference in the abundance of fine root distribution patterns between the two treatments in any of the soil horizons. There was a slight trend, (only very weakly significant at the 11% level), showing greater root abundance at 10 - 20 cm in the BD treatment. Between the two blocks, evidence of significant difference in rooting count per horizon was only recorded at a depth of 20 - 30 cm. The remaining soil horizons had no significant differences in root distribution patterns following the repeated disc harrowing treatments between Block 1 and Block 2.

Results in changes of *Eucalyptus grandis x nitens* root distribution pattern for the two treatments are also presented using an exponential decay function in Figures 5.28, 5.29 and 5.30. Variation in root distribution pattern between B0 treatments and BD treatments is demonstrated by the changes on the curvature of the root distribution pattern curve and a shift in position of the root distribution curve. In Tables 5.25 - 5.28, equations were fitted to the curves to quantify changes on the curvature and shift in the position of the curve. This was done for B0 treatments and BD treatments for three discrete tree diameter classes (10, 15 and 20 cm) in both Block 1 and Block 2.

Repeated disc harrowing had an influence on the root distribution patterns of *Eucalyptus grandis x nitens* trees, even though the effect was non-significant. In Figures 5.26 and 5.27, this practice resulted in a slight reduction of root colonisation on the top 10 cm depth of the soil profile in BD treatments. The B0 treatments had a slightly higher root count in the first 10 cm depth in both blocks and all trees, with an exception for the 10 cm class tree in Block 2 (Figure 5.27). From 50 - 100 cm, the BD treatments indicated a greater root count when contrasted with the B0 treatments in all occasions. The BD treatments had a higher total root count than the B0 treatments throughout all the blocks and tree classes; however, the contrary was observed for the 10 cm class trees in Block 1 (Figure 5.27).

Table 5.24: ANOVA results of root count per 10 cm depth

Depth 0 - 10 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2984.6667	1492.3333	1.14	0.3619
Blocks	1	1008.3333	1008.3333	0.77	0.4029
Treatment	1	1976.3333	1976.3333	1.51	0.2503
Error	9	11777.0000	1308.5556		
Corrected Total	11	14761.6667			
Depth 10 - 20 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2520.1667	1260.0833	1.64	0.2473
Blocks	1	140.0833	140.0833	0.18	0.6796
Treatment	1	2380.0833	2380.0833	3.09	0.1124
Error	9	6922.7500	769.1944		
Corrected Total	11	9442.9167			
Depth 20 - 30 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	650.6667	325.3333	2.92	0.1054
Blocks	1	645.3333	645.3333	5.79	0.0395
Treatment	1	5.3333	5.3333	0.05	0.8317
Error	9	1003.0000	111.4444		
Corrected Total	11	1653.6667			
Depth 30 - 40 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2408.8333	1204.4167	1.16	0.3555
Blocks	1	2268.7500	2268.7500	2.19	0.1730

Treatment	1	140.0833	140.0833	0.14	0.7215
Error	9	9321.4167	1035.7130		
Corrected Total	11	11730.2500			

Depth 40 - 50 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2714.1667	1357.0833	1.04	0.3912
Blocks	1	2054.0833	2054.0833	1.58	0.2404
Treatment	1	660.0833	660.0833	0.51	0.4942
Error	9	11702.7500	1300.3056		
Corrected Total	11	14416.9167			

Depth 50 - 60 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1912.3333	956.1667	0.88	0.4480
Blocks	1	867.0000	867.0000	0.80	0.3952
Treatment	1	1045.3333	1045.3333	0.96	0.3525
Error	9	9789.33333	1087.7037		
Corrected Total	11	11701.6667			

Depth 60 - 70 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1333.6667	666.8333	0.92	0.4328
Blocks	1	800.3333	800.3333	1.10	0.3206
Treatment	1	533.3333	533.3333	0.74	0.4131
Error	9	6519.0000	724.3333		
Corrected Total	11	7852.6667			

Depth 70 - 80 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	780.0000	390.0000	1.07	0.3828
Blocks	1	12.0000	12.0000	0.03	0.8600
Treatment	1	768.0000	768.0000	2.11	0.1805
Error	9	3279.0000	364.3333		
Corrected Total	11	4059.0000			

Depth 80 - 90 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F

Model	2	481.6667	240.8333	1.21	0.3424
Blocks	1	161.3333	161.3333	0.81	0.3914
Treatment	1	320.33333	320.3333	1.61	0.2364
Error	9	1791.0000	199.0000		
Corrected Total	11	2272.6667			

Depth 90 - 100 cm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10.8333	5.4167	0.04	0.9569
Blocks	1	10.0833	10.0833	0.08	0.7804
Treatment	1	0.7500	0.7500	0.01	0.9393
Error	9	1100.0833	122.2315		
Corrected Total	11	1110.9167			

B0 DBH 10 cm	10	20	30	40	50	60	70	80	90	100	Count	%
0	15	12	21	23	19	22	29	21	27	16	205	31
10	8	10	6	7	5	13	15	8	11	7	90	13
20	8	6	7	9	12	9	10	11	8	9	89	13
30	6	9	7	5	3	4	6	5	7	8	60	9
40	11	8	13	10	20	9	16	11	12	5	115	17
50	1	5	3	5	3	0	2	7	6	4	36	5
60	0	4	5	1	2	0	2	2	1	1	18	3
70	0	1	3	0	0	0	2	3	3	2	14	2
80	1	5	0	0	1	1	3	2	0	6	19	3
90	0	4	1	0	3	0	2	0	7	4	21	3
100											667	100

B0 Treatment for the 10 cm tree

BD DBH 10 cm	10	20	30	40	50	60	70	80	90	100	Count	%
0	11	14	12	9	12	15	13	11	12	16	125	20
10	11	12	14	9	9	10	8	11	6	5	95	15
20	3	7	6	5	9	6	9	4	5	9	63	10
30	3	6	4	7	6	5	7	8	4	7	57	9
40	4	6	7	13	11	5	5	6	8	11	76	12
50	9	7	12	8	10	9	13	9	6	7	90	14
60	5	3	0	3	2	6	4	4	3	2	32	5
70	4	6	1	5	3	5	7	5	4	21	61	10
80	2	0	1	2	2	2	2	2	1	1	15	2
90	4	0	1	2	4	5	7	1	2	1	27	4
100											641	100

BD Treatment for the 10 cm tree

Key

0
1 to 2
3 to 4
5 to 6
7 to 8
9 to 10
11 to 12
13 to 14
>15

B0 DBH 15 cm	10	20	30	40	50	60	70	80	90	100	Count	%
0	21	18	13	15	17	14	12	18	23	12	163	30
10	6	4	8	12	8	9	6	5	9	7	74	14
20	5	8	6	11	9	10	5	4	8	3	69	13
30	2	1	0	2	4	2	6	5	7	5	34	6
40	3	6	5	4	2	3	3	5	2	2	35	6
50	5	4	7	2	2	6	3	5	8	12	54	10
60	2	4	6	7	3	2	5	4	2	13	48	9
70	0	2	4	3	2	1	3	4	14	1	34	6
80	0	0	6	0	0	0	2	3	6	1	18	3
90	1	2	0	2	1	0	0	2	2	3	13	2
100											542	100

B0 Treatment for the 10 cm tree

BD DBH 15 cm	10	20	30	40	50	60	70	80	90	100	Count	%
0	23	19	20	25	18	15	13	16	15	12	176	26
10	13	18	8	10	9	11	10	14	11	13	117	18
20	4	8	5	8	11	6	6	2	8	12	70	11
30	8	3	6	5	3	2	5	7	7	6	52	8
40	7	2	3	3	7	8	2	2	4	8	46	7
50	5	8	2	2	6	5	13	7	9	4	61	9
60	6	7	6	5	4	12	4	9	7	4	64	10
70	6	3	7	4	3	6	5	5	5	4	48	7
80	3	2	4	2	2	1	2	4	1	1	22	3
90	2	1	0	1	0	0	1	0	0	5	10	2
100											666	100

BD Treatment for the 10 cm tree

Key

0
1 to 2
3 to 4
5 to 6
7 to 8
9 to 10
11 to 12
13 to 14
>15

B0	DBH 20 cm										Count	%
0	21	13	18	21	14	17	19	17	25	25	190	32
10	7	11	11	7	10	10	10	8	8	8	90	15
20	9	8	9	7	5	11	11	5	7	6	78	13
30	3	5	4	15	12	4	12	7	3	1	66	11
40	2	3	6	5	5	3	5	5	3	1	38	6
50	6	8	3	9	6	3	3	4	6	5	53	9
60	3	2	7	2	1	4	1	3	2	4	29	5
70	1	3	9	1	2	4	1	5	1	3	30	5
80 / 90	1	0	3	0	0	1	0	1	1	2	9	2
90	0	1	3	0	0	3	0	2	2	1	12	2
100	10	20	30	40	50	60	70	80	90	100	595	100

B0 Treatment for the 10 cm tree

BD	DBH 20 cm										Count	%
0	16	8	11	14	17	17	18	16	18	12	147	22
10	7	8	10	7	7	7	9	5	14	10	84	12
20	11	8	7	4	4	6	9	4	6	7	66	10
30	6	6	6	10	9	8	5	9	22	22	103	15
40	5	8	7	5	8	6	3	5	6	14	67	10
50	8	6	5	1	6	12	13	9	5	5	70	10
60	6	5	7	4	4	6	8	3	5	16	64	9
70	3	6	2	4	5	2	9	5	3	5	44	6
80	3	5	1	0	3	2	4	2	3	8	31	5
90	0	2	1	0	0	3	0	0	0	0	6	1
100	10	20	30	40	50	60	70	80	90	100	682	100

BD Treatment for the 10 cm tree

Key

Key
0
1 to 2
3 to 4
5 to 6
7 to 8
9 to 10
11 to 12
13 to 14
>15

Figure 5.26: Profile wall root mapping for Block 1 (B0 left and BD right)

B0	DBH 10 cm										Count	%
0	20	23	20	14	19	18	23	18	20	15	190	19
10	11	7	10	8	12	7	11	13	8	10	97	10
20	7	8	6	5	9	11	9	5	15	11	86	9
30	17	9	10	18	23	14	11	19	16	18	155	16
40	8	6	10	8	9	10	11	21	15	18	116	12
50	6	9	10	12	10	13	13	9	10	18	110	11
60	11	6	15	10	6	19	12	11	10	3	103	10
70 / 80	3	8	9	8	6	8	6	7	3	5	63	6
90	1	1	4	7	4	3	3	4	3	4	34	3
100	0	4	5	5	0	2	2	2	5	2	27	3
	10	20	30	40	50	60	70	80	90	100	981	100

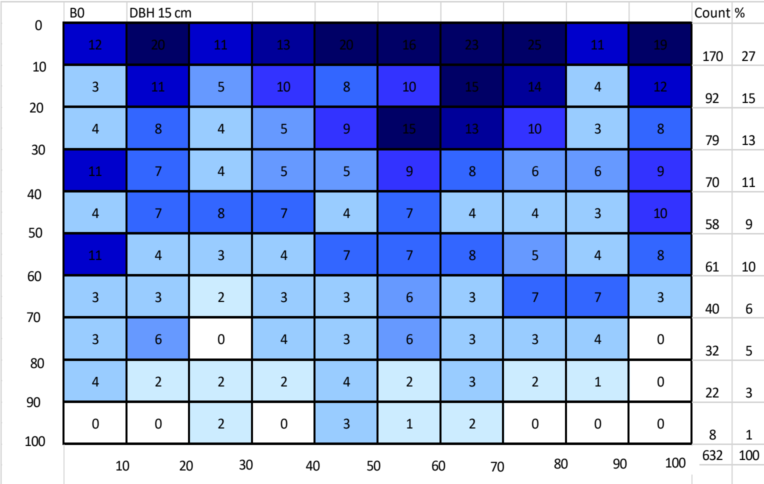
B0 Treatment for the 10 cm tree

BD	DBH 10 cm										Count	%
0	25	21	18	25	30	28	29	23	27	22	248	22
10	15	15	11	7	17	20	19	25	29	12	170	15
20	8	11	10	8	8	6	11	8	13	18	101	9
30	6	5	5	7	6	5	6	8	12	9	69	6
40	18	13	16	18	16	22	16	10	11	14	154	13
50	14	18	13	14	23	22	15	13	5	12	149	13
60	9	9	7	11	9	13	14	6	7	7	92	8
70	5	8	6	8	13	6	4	6	10	8	74	6
80	7	3	10	7	6	6	6	5	7	2	59	5
90	5	1	7	4	3	2	2	2	4	1	31	3
100	10	20	30	40	50	60	70	80	90	100	1147	100

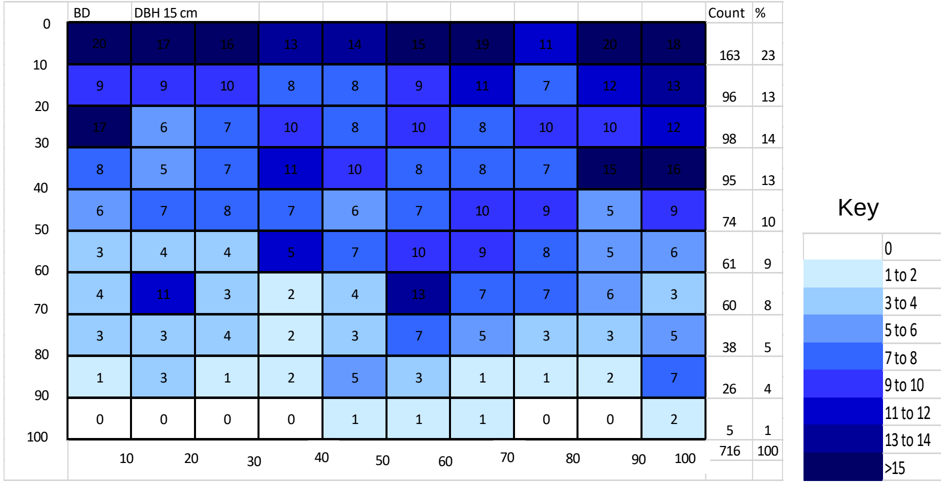
BD Treatment for the 10 cm tree

Key

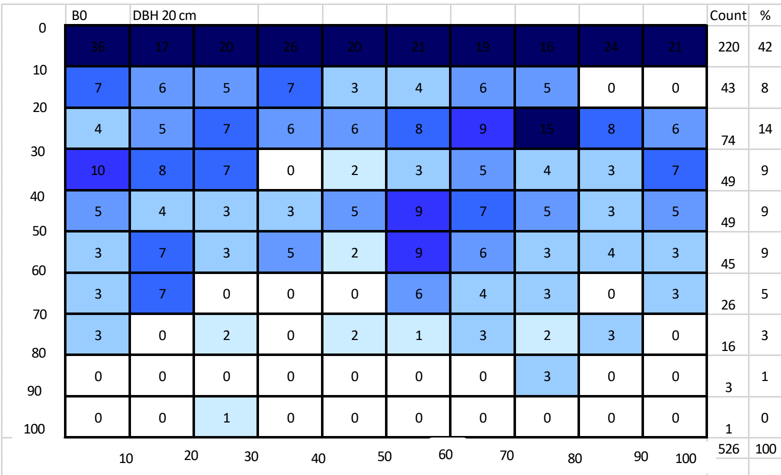
Key
0
1 to 2
3 to 4
5 to 6
7 to 8
9 to 10
11 to 12
13 to 14
>15



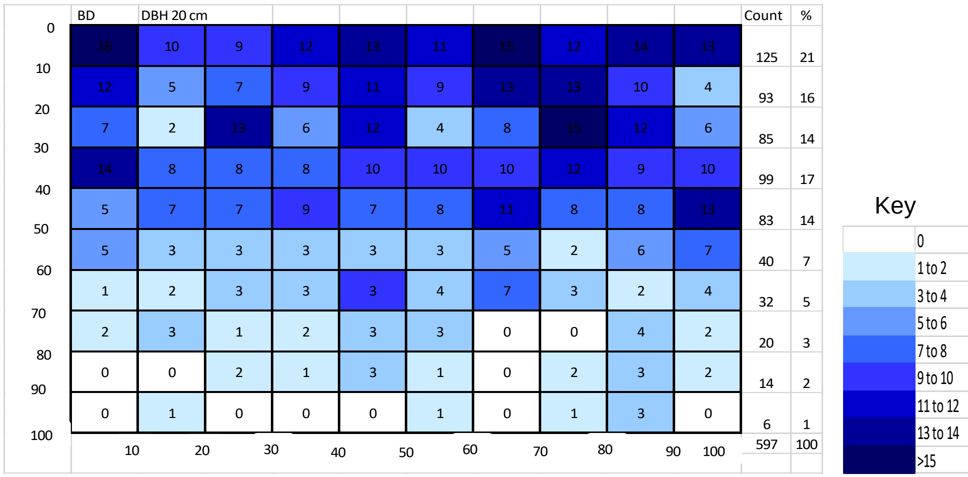
B0 Treatment for the 10 cm tree



BD Treatment for the 10 cm tree



B0 Treatment for the 10 cm tree



BD Treatment for the 10 cm tree

Figure 5.27: Profile wall root mapping for Block 2 (B0 left and BD right)

Table 5.25: Exponential models for root distribution patterns for 10 cm class trees

Site	BDH (cm)	B0 Treatment		BD Treatment	
Block 1	10	$y = 208.33\ e^{-0,028(d)}$	$R^2 = 0.8032$	$y = 140.59\ e^{-0,017(d)}$	$R^2 = 0.6386$
Block 2	10	$y = 213.12\ e^{-0,017(d)}$	$R^2 = 0.6718$	$y = 240.47\ e^{-0,016(d)}$	$R^2 = 0.6551$

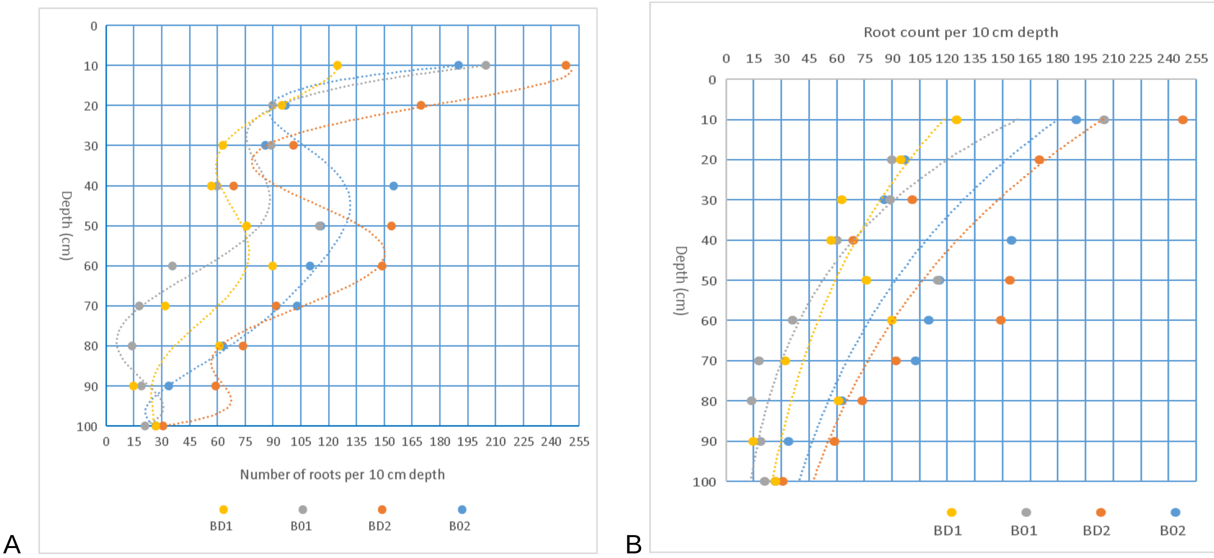


Figure 5.28: Root distribution pattern for a tree with 10 cm diameter (A, actual distribution depicted with a moving average and, B, fitted exponential distribution)

Eucalyptus grandis x nitens roots were observed to diminish exponentially as a function of depth in both the B0 treatments and BD treatments (Figures 5.28B - 5.30B). The repeatedly disked harrowing also had an influence on the curvature and shift in the position of the root distribution curve. In Table 5.25, the first group of numbers of the equation (y = 208.33) describes the position of the root distribution curve for Block 1. The greater this figure, the greater the indication of a high root count at the initial topsoil value of the distribution curve. This occurs just below the surface of the mineral soil profile, at 0 - 10 cm soil depth in actual forestry ecosystems. A low value indicates a lower topsoil root count, which will cause a shift in the position of the curve. The exponent describes the curvature of the root distribution curve. A large value of k is an indication of an abrupt decline in root count as a function of depth, resulting in a strong curvature for increasing depth (Figure 5.29B). On the contrary, a low value of k demonstrates a fairly modest decline in root count as a function of depth, resulting in a gentle curvature (Figure 5.29B).

Figure 5.28B illustrates a difference in both the position and curvature of the root distribution curve of 10 cm diameter class trees. For 10 cm diameter class trees, Table 5.25 shows a difference in curvature as well as a shift in the position of the root distribution curves in Block 1. The B0 treatment was $y = 208.33\ e^{-0.028(d)}$, while the BD treatment was $y = 140.59\ e^{-0.017(d)}$. In Block 2, there was a shift in the position of the curve, but the curvature remained relatively unchanged for the two treatments: for B0 treatment, $y = 213.12\ e^{-0.017(d)}$ and for BD treatment, $y = 240.47\ e^{-0.016(d)}$. Trees from Block 2 demonstrated a relatively higher root count in both treatments when contrasted with trees from Block 1.

For 15 cm diameter class trees, Figure 5.29B shows a relatively high number of roots in the BD treatment compared to roots counted In the B0 treatment. Figure 5.30B also indicates that a shift occurred in the position of the curve in both blocks. However, the curvature remained relatively similar for the treatments. The equations are shown in Table 5.26 for Block 1 with the B0 treatment of $y = 136.06\ e^{-0.021(d)}$ and the BD treatment of $y = 187.27\ e^{-0.023(d)}$. Likewise, in Block 2, B0 treatment was $y = 207.03\ e^{-0.026(d)}$, and BD treatment was $y = 255.06\ e^{-0.028(d)}$. Trees from Block 1 had a relatively lower root count in both treatments in contrast to trees from Block 2.

Table 5.26: Exponential models for root distribution patterns for 15 cm class trees

Site	**BDH (cm)**	**B0 Treatment**		**BD Treatment**	
Block 1	15	$y = 136.06\ e^{-0.021(d)}$	$R^2 = 0.7775$	$y = 187.27\ e^{-0.023(d)}$	$R^2 = 0.7766$
Block 2	15	$y = 207.03\ e^{-0,026(d)}$	$R^2 = 0.886$	$y = 255.06\ e^{-0.028(d)}$	$R^2 = 0.7659$

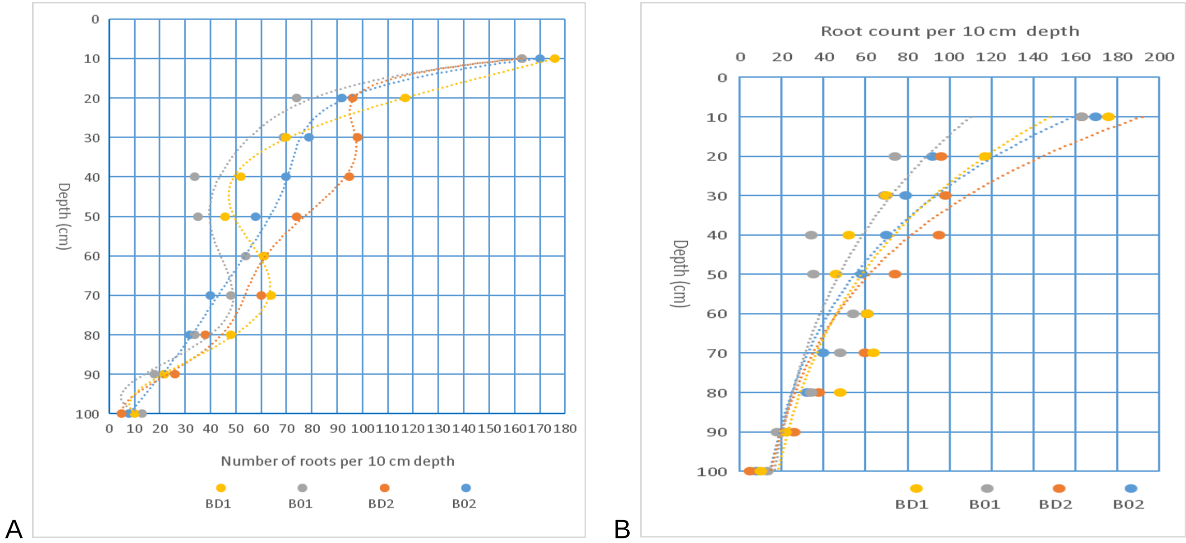


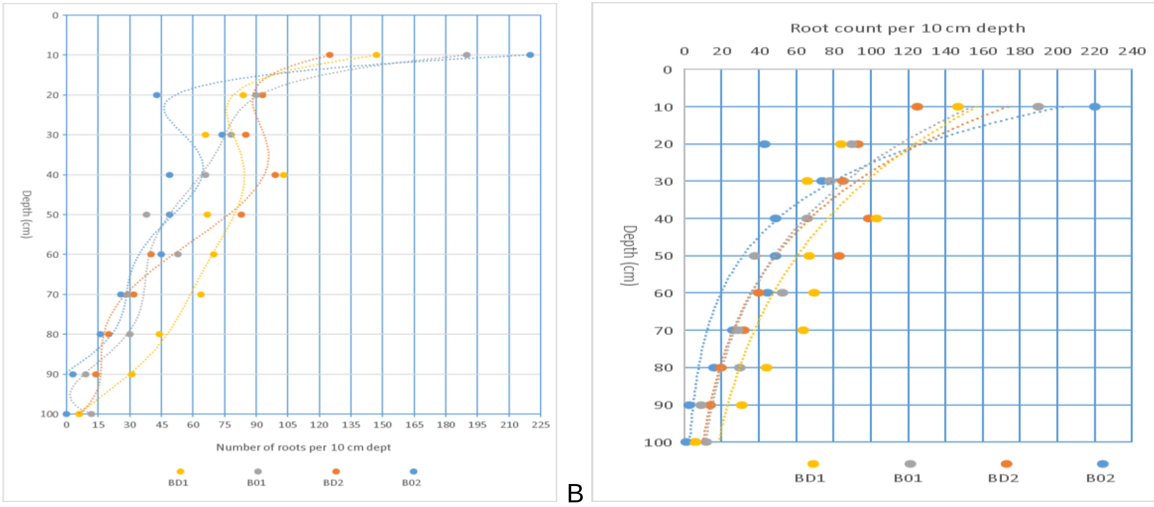
Figure 5.29: Root distribution pattern for a tree with 15 cm diameter (A, actual distribution depicted with a moving average and, B, fitted exponential distribution)

Trees in the 20 cm diameter class were observed to have the least total root count overall for the experiment (Figure 5.30). Block 1 had a greater root count in comparison to Block 2 in the B0 treatments; the contrary occurred in the BD treatment. In Table 5.27, there were slight changes in both the position and the curvature of the root distribution curve between the two treatments in Block 1: for the B0 treatment, $y = 206.74\ e^{-0.029(d)}$; and, for the BD treatment, $y = 198.87\ e^{-0.024(d)}$. Block 2 had pronounced changes in both the shift in position of the curve and curvature for the two the treatments: for the B0 treatment, $y = 323.33\ e^{-0.047(d)}$; and, for the BD treatment, $y = 237.72\ e^{-0.031(d)}$.

Table 5.27: Exponential models for root distribution patterns for 20 cm class trees

Site	BDH (cm)	B0 Treatment		BD Treatment	
Block 1	20	$y = 206.74\ e^{-0,029(d)}$	$R^2 = 0.9022$	$y = 198.87\ e^{-0.024(d)}$	$R^2 = 0.6667$
Block 2	20	$y = 323.33\ e^{-0.047(d)}$	$R^2 = 0.7945$	$y = 237.72\ e^{-0.031(d)}$	$R^2 = 0.8945$

A



B

Figure 5.30: Root distribution pattern for a tree with 20 cm diameter (A, actual distribution depicted with a moving average and, B, fitted exponential distribution)

In Table 5.28, the changes in the root distribution curves for the two treatments are summarized. Results from the exponential decay function graphs and equations used to quantify changes in root distribution patterns indicate no particular trend when evaluated for individual trees. However, when using the mean of all the trees per treatment, irrespective of tree size and blocks, the following equation was formulated: for B0 treatments, $y = 215.77\ e^{-0.028(d)}$ and $y = 210.00\ e^{-0.023(d)}$ for BD treatments. Overall, repeated disc harrowing resulted in a shift of the distribution curve: decline on root count at a depth of 0 - 10 cm. It also altered curvature: nearly even root declined as a function of depth from 0 - 100 cm.

Table 5.28: Summary of exponential models for root distribution patterns

Site	**DBH (cm)**	**B0 Treatment**		**BD Treatment**	
Block 1	10	$y = 208.33\ e^{-0.028(d)}$	$R^2 = 0.8032$	$y = 140.59\ e^{-0.017(d)}$	$R^2 = 0.6386$
Block 1	15	$y = 136.06\ e^{-0.021(d)}$	$R^2 = 0.7775$	$y = 187.27\ e^{-0.023(d)}$	$R^2 = 0.7766$
Block 1	20	$y = 206.74\ e^{-0.029(d)}$	$R^2 = 0.9022$	$y = 198.87\ e^{-0.024(d)}$	$R^2 = 0.6667$
Block 2	10	$y = 213.12\ e^{-0.017(d)}$	$R^2 = 0.6718$	$y = 240.47\ e^{-0.016(d)}$	$R^2 = 0.6551$
Block 2	15	$y = 207.03\ e^{-0.026(d)}$	$R^2 = 0.886$	$y = 255.06\ e^{-0.028(d)}$	$R^2 = 0.7659$
Block 2	20	$y = 323.33\ e^{-0.047(d)}$	$R^2 = 0.7945$	$y = 237.72\ e^{-0.031(d)}$	$R^2 = 0.8945$

Mean	$y = 215.77$	$e^{-0.028(d)}$	$R^2 = 0.8059$	$y = 210.00$	$e^{-0.023(d)}$	$R^2 = 0.7329$
Std. Error	±24.59	±0.00423	±0.0340	±17.50	± 0.00241	±0.0402

6. DISCUSSION

6.1 Fuel Loading and Forest Floor Structure

The accumulation of forest floor is a balance between the amount of litter-fall and the rate of decomposition. Morris (1995) mentioned several factors that can potentially influence the rate of decomposition in a particular forest ecosystem, including climate and altitude (this is elaborated in the literature review, section 2.2.1). This current study is located 1 444 meters above sea level and is characterised by moderately cool conditions; therefore, the rate of decomposition is relatively low while the litter accumulation is average, resulting in a moderate fuel loading of approximately 43 t ha^{-1} (Figure 5.5).

In fire management it is essential to view the litter layer as a single unit comprised of several components separated into fuel time lag classes. This is important because the fuel ignition process, fire rate of spread, fire intensity, and fire behaviour are strongly influenced by fuel characteristics such as fuel size and shape, amongst various other factors (Morvan & Dupuy, 2001). In Figure 5.5 (where averaged data across blocks are presented), the humus layer contributed greatly to the forest fuel loading in these sites as it made up an average of 19.0 t ha^{-1}. The 1 hour fuel (bark and leaf fraction) had the second largest proportion at 12.4 t ha^{-1}, followed by the 10 hour fuels at 8.1 t ha^{-1}, and the 1 hour fuels (branches) at 4.3 t ha^{-1}, making the smallest contribution to the total mass. These treatments represent the actual situation of the plantation as a whole where slash was burnt before stand reestablishment, and disc harrowing was not done to reduce and incorporate fuel into the mineral soil. Thus, the results are estimates of the net amount of fuel that will accumulate over a rotation in the absence of fuel reduction measures during the life of the stand (where net amount refers to litter-fall minus litter decomposition).

In contrast, the BD treatments had a total forest floor mass only amounting to 10.5 t ha^{-1} on average (Figure 5.5). The humus layer was not present in these treatments. The 1 hour fuel (bark and leaf fraction) accounted for the greatest proportion at 5.1 t ha^{-1}, followed by the 10 hour fuels at 3.8 t ha^{-1}, and 1 hour fuels (branches) at 1.7 t ha^{-1} making up for the remainder. These plots are representative of the average quantity of fuel in the repeatedly disc harrowed swathes between the tree rows and in the non-disked island within the tree rows that forms part of this treatment.

The application of repeated disc harrowing throughout the rotation of *Eucalyptus grandis x nitens* significantly reduced fuel loading (Tables 5.1 - 5.4). From Figures 5.1 - 5.8, the BD treatments had a lower quantity of fuel loading when compared to the B0 treatments in all fuel classes for all sites. The reduction in fuel loading reported in this study is comparable to findings presented by Madeira (2012), where disc harrowing at mid-rotation of *Eucalyptus globulus* stand in Mediterranean conditions reduced fuel loading from 8.19 t ha^{-1} for control to 5.91 t ha^{-1} for the disc harrowing treatment 30 months after treatment. However, the difference was not significant in Madeira's (2012) experiment, hence the author suggested that disc harrowing be done continually during stand rotation. This is the case with the current study and explains the significant difference of fuel loading recorded among treatments.

The disc harrowing action crushes and break the branches into relatively small dimensions. In the process, organic material is constantly incorporated into the mineral soil, which hastens the decomposition process (Madeira, 2012). Therefore, the discernible change in forest floor structure and fuel loading in the BD treatments is probably due to the combined effect of litter maceration and soil incorporation.

It was shown in Figures 5.6 and 5.7 that Block 1 had a slightly greater fuel loading than Block 2. However, Tables 5.1, 5.2 & 5.4 indicate that the difference was non-significant in all fuel classes except for in the 10 hour fuels (Table 5.3). The significant difference in fuel loading for the 10 hour fuel class fuel between the two blocks can be attributed to site type (aspect) and the regeneration method. As illustrated in Figure 3.4, Block 1 was located on a southerly aspect. South facing slopes in middle and high latitudes of the Southern Hemisphere characteristically have relatively lower temperatures, slightly lower evapotranspiration rates, and usually denser and heavier fuel loads, in contrast with north facing slopes (Teie, 2009). Block 2 was located on the northerly aspect. It is well documented that north facing slopes are typical of relatively warmer temperatures, with sparse and lighter fuels, in contrast with southerly aspect (Teie, 2009).

Stand density is another factor that may have contributed to the significant differences in 10 hour fuel loads among blocks. The ANOVA results in Table 5.20 illustrate a significant difference in stand density among the blocks. Block 1 has a significantly lower stand density (Figure 5.22B). It is well documented that branching intensity and branch thickness increase with a reduction in stand density (Mäkinen & Hein, 2006).

Less dense stands typically have numerous heavier branches. The contrary occurs in dense stands, as seen in Block 2 of this study. The significantly greater accumulation of the 10 hour fuel class in Block 1 could partly be explained by this phenomenon.

Repeated disc harrowing throughout the rotation of *Eucalyptus grandis x nitens* caused significant alterations of the forest floor structure. Infield photographs of the two treatments captured before sampling (Figures 5.8A and B) show the difference in forest floor structure following the implementation of repeated disking. The non-disking sites in Figure 5.8A had a dense forest floor structure with all generic forest floor layers (L, F and H) easily discernible. (Note that although the F layer was visible infield, it is indiscernible in Figure 5.8A.) In contrast, repeated disc harrowing in Figures 5.8B significantly altered the forest floor structure, reducing it to only a sparse L layer directly on top of the MS layer. The F and H strata were not present in the disked swathes due to repeated harrowing constantly mixing the organic material into the MS layer.

H layer build-up contributed a significant portion of 19.0 ha^{-1} out of 43.1 t ha^{-1} (i.e., 44%) of fuel loading in these sites. The H layer strongly impacts fire intensity, degree of damage to the mineral soil and may bring about challenges during fire suppression "intensive mop up" (De Ronde, 1990). Therefore, alterations of the forest floor structure through disking reduces the aforementioned negative implications in case of a fire.

Section 2.2 of the literature review mentioned that, within the three components of the Fire Triangle, fuel remains the single component that can be manipulated to manage wildfires. The results presented in this manuscript indicate that repeated disc harrowing was effective in significantly altering the fuel horizontal continuity and reducing fuel loading of the 1 hour and 10 hour fuel classes. The disked swathes serve as an internal break in fuel horizontal continuity inside the compartment. Repeated disc harrowing supplements the practice of fire break placement on plantation boundaries. This practice further creates fire breaks within the compartment between the standing trees, thus reinforcing the firebreak network. Reduced fuel loading and a break in fuel horizontal continuity were reported to inhibit erratic fire behaviour of surface fires. This creates a possible reduction in the fire rate of spread and fire intensity as well as presents an opportunity to control and suppress the fire with more ease and safety (de Ronde, 1990).

6.2. Soil Nutrient Distribution

The knowledge of nutrient pools in the ecosystem forms the basis of understanding the nutrient input-output budgets in a forest ecosystem. Nutrients within the forest ecosystem move around the three major pools of soil, standing biomass, and litter and slash residues (du Toit, 2014). Trees will take up nutrients in large quantities from the mineral soil through their roots. These nutrients are stored in different locations, namely roots, stem, bark, foliage and fruits/flowers (du Toit, 2003). The nutrients are returned back into the mineral soil through stem flow, through fall, and litter fall (Fisher and Binkley, 2000). Litter and dead roots have been identified as the major pathways for returning these nutrients back into the soil.

The litter material and harvest slash residue in the forest ecosystem significantly contribute to the soil nutrient cycle (du Toit and Scholes, 2002). This was also observed in the current study. The significant decline on forest floor nutrient quantities presented in Table 5.5 and the increased mineral soil nutrient quantities in Figures 5.9 - 5.21 following disc harrowing indicates that this practice resulted in large scale nutrient translocation from the forest floor to the mineral soil.

Humus colloids are characteristic of two major qualities: a large surface area and abundance of negative charge per unit mass, which improve soil cation exchange capacity, depending on soil pH (Brady & Weil, 2010). Figures 5.9 - 5.12 illustrate that repeated disc harrowing significantly increased the quantity of the topsoil exchangeable base cations (K, Ca, and Mg), and caused a non-significant increase in Na. This indicates that disc harrowing incorporates the organic forest floor material into the topsoil which might have possibly increased the quantity of humus colloids. Therefore this practice enriches the soil nutrient status of the site in question. Disc harrowing at site preparation of a *Eucalyptus globulus* stand resulted in a significant decrease in organic carbon and sum of base cations 18 months after treatment in Madeira's (1989) study. In Madeira's (2012) study, the control treatment had total organic carbon values averaging 1.82%, and sum of base cation was 3.13 mmol/100g compared to 1.25% organic carbon and 2.36 mmol/100g for the sum of base cations in the disking treatment.

In Figure 2.6, du Toit et al. (2008) reported a slash burning treatment in *E. grandis*, KwaZulu Natal to significantly increase the topsoil ECEC and the exchangeable base cations quantities over time when contrasted to various other slash management practices. In their experiment a low to moderate fire intensity was applied. A similar fire intensity during slash burn at site preparation on the present study was implemented. The significant increase base cation quantities in BD treatment in this experiment follow a similar trend to du Toit’s et al. (2008) observation.

Bio charcoal by Rhoades et al. (2017) has been observed to have a slight liming effect: it tends to raise soil pH after being applied, due to its high adsorption ability attracting significant amounts of cations. In a six months greenhouse trial he reported a significant increase in soil pH_{KIC} (4.5 - 4.9), K (23.6 - 30.5 mg/L), Mg (16.6 - 18.7 mg/L) and Ca (99.5 - 112.2 mg/L). The incorporation of bio charcoal from slash burning during site preparation in the current study can partly explain the significant increase in base cation quantity recorded in BD treatments of this experiment. Amalgamation of bio charcoal in the repeatedly disked sites may have possibly increased the negatively charged surface area of the site, thus improved adsorption of the high base cation quantities translocated to the mineral soil in these treatments.

In Figure 5.13, the incorporation of organic material in the topsoil through disc harrowing resulted in a non-significant increase in topsoil ECEC. Block 2 had significantly higher levels of exchangeable base cations and ECEC compared to Block 1, except for Ca that was significantly higher in Block 1. The high levels of exchangeable base cations and ECEC recorded for Block 2 might have been influenced by soil and site types. Furthermore, coppice reduction practice may have contributed to the results. Coppice reduction in Block 2 added more organic material on the forest floor, which was later incorporated into the soil through disc harrowing. This may have contributed to higher base cation and ECEC levels. Plantation forestry in South Africa is generally practiced in sites with relatively low soil pH value (Louw and Smith, 2012). The fast growing species that are planted in these plantation forests have adapted and are now able to grow in these acidic soils. The soil pH values of 3.6 and 3.5 in KCl recorded in this experiment are typical to soil pH values identified by Louw and Smith (2012) for forestry sites. The negligible difference in soil pH (Table 5.12) following repeated disc harrowing treatment presented in this manuscript is in line with Madeira et al., (2012) findings when comparing disc harrowing (pH_{KIC} 3.60), fertilizing (pH_{KIC} 3.84) and non-disking (pH_{KIC} 3.82) in a Eucalyptus stand.

As presented in Tables 5.16 - 5.18, the disc harrowing practice did not have a significant effect on topsoil total N, total organic C and extractable P (Bray II) content in this study. Data presented in Figures 5.18 - 5.20, show similar average topsoil N, P and C values between the two treatments. Among the blocks, only the total N content was significantly higher in Block 2. The higher N, P and C content can be attributed to slightly raised pH in Block 2, soil type, and site type. In addition, the organic material from coppice reduction may have contributed to the topsoil nutrient status of Block 2.

Soil bulk density was the only physical property that was measured in this study. Repeated disc harrowing significantly reduced bulk density of 0 - 10 cm and 10 - 20 cm topsoil; this effect was similar to Madeira's (1989) findings. He reported disc harrowing reduced soil bulk density to 1.37 g cm^3 18 months after treatment and 1.36 g cm^3 30 months after treatment, compared to 1.54 g cm^3 for the control treatment at a depth of 0 - 10 cm. Likewise, for 10 - 20 cm depth, bulk density of the control was 1.77 g cm^3 in contrast to 1.49 g cm^3 18 months after treatment and 1.44 g cm^3 30 months after treatment.

The current study was conducted on very gentle slopes which limited the ability to investigate and quantify possible effects of repeated disc harrowing on soil erosion. This potential impact still needs to be investigated in further studies.

6.3. Above Ground Stand Growth

The implementation of repeated disc harrowing throughout the rotation of *Eucalyptus grandis x nitens* stand as shown in Table 5.20 - 5.23 had no significant impact on any of the tree growth and stand productivity measures. Related variables include stand density, basal area m^2 ha^{-1}, volume m^3 ha^{-1}, and above ground plant biomass t ha^{-1}. The non-significant growth difference between treatments reported in this study agrees with results presented by Madeira et al. (2012); he reported harrowing and fertilization at middle rotation had no significant effect on *Eucalyptus globulus* growth. Growth response was measured for control, fertilization, and disc harrowing treatments in Madeira's study: basal area was 21.83 m^2 ha^{-1}, 22.76 m^2 ha^{-1}, 25.38 m^2 ha^{-1} and volume was 219.5 m^3 ha^{-1}, 228.5 m^3 ha^{-1}, and 264.9 m^3 ha^{-1} respectively. Madeira et al. (2012) reported that a single, mid-rotation disc harrowing operation slightly increased tree growth, contrary to the non-significant growth reduction reported in the current study with repeated disking operations. However, the changes in growth observed in this study are negligible compared to the intended benefits of effective and efficient fuel load reduction.

Stand density measurements are explained in detail in the Methods and Materials Section 3.3.1. Rotation end stand density was contrasted with the intended initial stand density to monitor tree survival through the rotation. The repeated disc harrowing treatment had a non-significantly higher stand density, possibly indicating slightly better plant survival (Figure 5.22). Similarly, Mhando et al. (1993) reported 88, 93, and 97% survival for complete tillage 20 cm deep, strip tillage 15 cm deep, and strip tillage 25 cm deep respectively. These treatments were implemented during site preparation of *Eucalyptus saligna* and had no significant effect on survival. Stand density for Block 2 was significantly lower than Block 1 for all treatments when evaluated for individual stump (Figures 5.22 and 5.23). This indicated a possibility that there was a low initial stump survival from the previous rotation that remained in the current stand in Block 2. However, this was countered by leaving a relatively higher number of stems (two stems per stump next to open gaps caused by stump mortality) during coppice reduction to make up for the dead stumps. This resulted in Block 2 having significantly higher stand density based on the single stem evaluation.

Figure 5.24 shows that even though the repeatedly disked treatments had a slightly higher stand density over the no-till treatments, they exhibited a slightly lower volume than the no-till treatments. Both blocks had a similar volume for the B0 treatments, and Block 2 had a slightly higher volume than Block 1 for the BD treatments, but the effect was not significant. This indicates that leaving two stems per stump during coppice reduction allows for more volume to be carried per stump. Throughout the experiment the repeated disc harrowed treatments had a non-significantly lower stand productivity. The action of disc harrowing during the multiple passes cuts and disturbs tree roots in the top 0 - 20 cm depth (more details on the next sub-section 6.4). This may result in trees being under some stress and thus explain the small (5%) reduction in tree growth and stand productivity.

6.4. Below Ground Growth: Root Distribution Pattern

Figures 5.26 and 5.27 show that the majority of fine roots were concentrated in the top 10 cm depth of all the profile walls that were studied in both blocks and treatments. Grant et al. (2012) studied Eucalypt roots and found that about 30% root count was concentrated in the top 10 cm soil depth. Table 5.24 presents the ANOVA results for root count per 10 cm depth for treatments and blocks. At the 5% confidence level, there was no significant difference in the abundance of fine root distribution patterns amongst the two treatments in any of the soil horizons. When comparing root count concentration in the top 10 cm between the treatments, an average of 30% for the B0 treatments and an average of 22% for the BD treatments was recorded (percentage of the total root count on a 1 x 1 m vertical profile wall). The B0 treatments still had a higher root count over the BD treatments at a depth of 0 - 50 cm: a cumulative root count averaged 76% for B0 treatments and 70% for BD treatments.

The negligible difference in fine root abundance among treatments reported in the current study is similar to observations reported by Madeira et al. (2012). At a depth of 0 - 10, he recorded root biomass of 0.101, 0.096, and 0.100 kg m^2 for control over 0.084, 0.099, and 0.108 kg m^2 for harrowing at 0, 14, and 26 months after treatment, indicating no evidence of significant changes in root mass among treatments. At a depth of 50 - 100 cm, B0 treatments exhibited a low cumulative root count concentration in contrast to the BD treatments in the present study. The B0 treatments had an average of 24% and the BD treatments had an average of 30%.

Though non-significant, the implementation of repeated disc harrowing throughout the stand rotation had an influence on the root distribution patterns for *Eucalyptus grandis x nitens.* The practice has resulted in a slight reduction in root count in the top 10 cm depth. However, this was compensated for by the fairly even root distribution throughout the profile wall in the BD treatments (see Figure 5.26 and Figure 5.27). Between the two blocks, evidence of significant difference in root count per horizon was only recorded at a depth of 20 - 30 cm. The rest of the soil horizons had no significant differences in root distribution patterns following the repeated disc harrowing treatments between Block 1 and Block 2. The significant difference observed between the two blocks can be associated with the stony layer occurring at different depths in these blocks (Figures 3.3 and 3.4).

The exponential root distribution curve diminishing as a function of depth observed in this study is comparable to findings reported by Laclau (2013). He measured root length density of a six years old *Eucalyptus grandis* tree per 25 cm^2 grid to a depth of 0 - 10 m using a profile wall method. Results were 10.34, 1.97, 0.28, and 0.11 cm cm^3 for 0.0 -

0.1, 0.5 - 1.0, 4.0 - 6.0, and 8.0 - 10.0 m depths respectively. In the present study, the B0 treatments had an average of 215.77 and the BD treatments had an average of 210 root counts in the top 10 cm as expressed by first values of the exponential equation in Table 5.28. The relatively low value exhibited by the BD treatment indicates a shift in the root distribution curve as a result of repeated disc harrowing treatment. In comparison to the non-disked treatment (Table 5.28), the fairly even root distribution patterns with depth are also expressed by the relatively lower k value, as observed for the repeatedly disked treatment in Figures 5.28 - 5.30. The B0 treatments had a slightly higher k value of 0.028 and the BD treatments had a relatively lower k value of 0.023 on average. The higher k value for the B0 treatment indicates a stronger curvature of the root distribution pattern curve for this treatment, showing a sharper decline in root count with increase in depth. In contrast, the lower k value for the BD treatments assumes a root distribution curve with a relatively gentle curvature, indicating a fairly even root distribution pattern.

Root distribution patterns indicated some differences among the treatments. For both treatments the highest root concentration was observed on the first 10 cm depth; only a low percentage was found at 100 cm depth. However, in BD treatments, there was a relatively lower concentration of roots in the first top 10 cm depth and the roots were fairly spread out throughout the profile wall. The repeatedly disked treatment had the highest total root count across all blocks for all tree classes. These findings correspond with observations reported by Gonçalves et al. (2004), which affirmed that disc harrowing increases root growth and eases root penetration into the soil. He reported 71% decline in root density with increasing penetrometer resistance, from 0.4 - 4.2 MPa. Similarly in the present study, where B0 treatment have a significantly higher soil bulk density there was a low total root count and conversely in the BD treatment.

Karuma et al. (2014), states that proper tillage operations potentially eases plant root penetration; improves soil water retention and infiltration, and improve soil fertility, thus ideal root growing conditions. Similar conditions (improved nutrient availability and reduced soil bulk density) were observed in the BD treatment. The slightly high total root in this treatment can thus be linked to this phenomenon.

7. CONCLUSION

The implementation of repeated disc harrowing to reduce the risk of wildfire is effective in reducing fuel loading and breaking fuel horizontal continuity in 1 hour and 10 hour fuel classes. These two fuel characteristics significantly contribute to fire behaviour, particularly to the fire rate of spread and fire intensity. The act of disking three rows between every seventh row of trees in commercial stands breaks the fuel horizontal continuity, potentially reducing the rate of surface fire spread. To some degree, this practice also separates the compartment into blocks that may possibly contain the fire burning in one area. Secondly, repeated disc harrowing reduces fuel loading in the disked swathes, thus fire is more easily controlled and more safely suppressed. By reducing fuel loading, fire will cause minimal damage on soil chemical and physical properties. Implementation of this practice effectively reduced fuel loading for 1 hour and 10 hour fuels, the most active fuel classes. Considering the findings from this study, slash burning at site preparation incorporated with repeated disc harrowing throughout the stand rotation is an effective tool that can be safely implemented with guaranteed effectiveness on fuel load reduction in these two classes. Unlike prescribed burning practices, repeated disc harrowing is a safe method to reduce fuel loading that can be executed under almost any weather condition successfully, although limited to flat or moderately sloping terrain conditions and tree spacing.

Repeatedly disc harrowed sites demonstrated significant changes in the forest floor structure in comparison to non-disked sites across both blocks studied. Disc harrowing reduced the forest floor structure to only the litter and mineral soil layer in the disked swathes. The non-disked site had a forest floor consisting of the three generic forest floor strata as well the mineral soil layer.

The practice of disking was associated with an improvement in soil chemical and physical properties that were measured in this study. The soil total C, total N and Bray II P underwent no significant changes following repeated disc harrowing practices throughout the rotation, even though these analyses indicated a slight increase in the disked sites. However, disc harrowing significantly increased the quantity of exchangeable base cations (K, Ca, and Mg) in the topsoil, with the exception of Na where the increase was not significant. Furthermore, the practice significantly reduced soil bulk density at a depth of 0 - 20 cm throughout the blocks. Disc harrowing in this study has no negative implications for soil nutritional sustainability as nutrients are essentially moved from the litter pool to the soil pool, rather than lost from the system. The increase in levels of exchangeable bases also means that these nutrients in the soil are more readily available for plant uptake.

Repeated disc harrowing had no significant effects in all growth and stand productivity related variables measured in this study. The practice was associated with increased stand density, but this was not significant. In contrast, the above ground tree growth at the stand level (basal area, volume, and plant biomass) was non-significantly greater in non-disking sites compared to repeatedly disked sites across both blocks. However, the marginal difference in growth response measured in this experiment indicated that the implementation of repeated disc harrowing throughout the rotation has no significant implications on *Eucalyptus grandis x nitens* tree growth and stand productivity.

There were no significant changes in root distribution patterns following repeated disc harrowing practice throughout the rotation. Disc harrowing slightly reduced root count in the topsoil. The reduction was more pronounced in the top 0 - 10 cm depth. The practice also resulted in a slightly higher total root count in the entire profile wall. Repeated disc harrowing slightly (but not significantly) altered the curvature of *Eucalyptus grandis x nitens* root distribution pattern curves, thus showing evidence of subtle changes in the abundance of fine root distribution patterns throughout the profile wall.

These findings suggest that fuel loading reduction can effectively be accomplished through the implementation of repeated disc harrowing throughout the rotation in *Eucalyptus grandis x nitens* stand, with a positive benefit of improved soil nutrient status and bulk density. However, a slight decline in tree growth and stand productivity may be expected most probably as a result of the severing of superficial roots. The negligible reduction in stand productivity following repeated disc harrowing is overshadowed by the significant fuel load reduction and the reduced wildfire risk. The results showed similar findings across all blocks indicating applicability beyond the level of a single case study.

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