The impact of repeated prescribed burning in semi-mature pine plantation forests of Mpumalanga on fuel loads, nutrient pools and stand productivity

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Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Forestry at the Faculty of AgriSciences, University of Stellenbosch.

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March 2016

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date……………………………

Abstract

Wild fires in South Africa destroy vast areas of plantations annually and a growing need exists to reduce the fire risk effectively, economically and sustainably. Periodic prescribed burning is viewed by many researchers and managers as the only cost effective method to reduce fire damage and risk, and as such is being implemented on a large scale in SA. This thesis documents the effects of *repeated prescribed burning* operations on fuel load reduction, tree damage and stand growth rate, as well as nutrient dynamics in the system. Five field trials in semi-mature *P. elliottii* and *P. patula* plantations were laid out in Northern Mpumalanga during January 2014 to determine the effect of under-canopy burning on fuel loads, nutrient pools and stand productivity. Each trial consisted initially out of three control, three first burn and three second burnt plots.

Fuel reduction. Under-canopy burning treatments were of low to moderate intensity with an average predicted FLI ranging between 44 and 602 kW m^{-1}. With burning, the forest floor (FF) was significantly reduced in all trials (6.3 t ha^{-1} and 12.9 t ha^{-1} in *P. elliottii* and *P. patula* trials per burning event, respectively). Small quantities of additional litterfall (that would counter the initial goal of FF reduction) were noted for a single month in 3 out of 5 trials, but the short duration of this effect meant that the cumulative effect was insignificant. Average litterfall rates per species were 5.52 and 8.82 t ha^{-1} yr^{-1} for *P. elliottii* and *P. patula*, respectively. In general, the highest litterfall rate occurred during the winter months and the lowest during the summer months. The goal of FF reduction to values around 10-15 t ha^{-1} can be achieved with two prescribed burns in many *P. elliottii* stands (with smaller FF's), but it may require at least 4 burning events in some *P. patula* stands with FF loads of more than 50 t ha^{-1}. A significant

reduction in understorey vegetation was still evident 8 months after treatment implementation except for one trial but species abundance returned to pre-burn levels 14 months after treatment implementation with no changes in species composition.

Effects on stand condition and growth. Crown damage was restricted to one trial whilst root combined with cambium damage occurred in two trials, a result attributed to the smouldering effect of the FF. Among burning treatments, only Non-significant dbh and BA increment differences were evident, 4 and 12 months after treatment implementation but a highly significant seasonal effect could be seen in all trials: dbh increment was 61% higher in summer than in winter.

Nutrient dynamics. FF nutrient loss was directly related to FF consumption by fires, with N loss varying from 33 – 119 kg ha^{-1}; P, K, Ca and Mg losses averaging 3.8, 12.6, 72.4 and 17.2 kg ha^{-1}. An increase in foliar macro nutrient concentration of freshly fallen needles was observed, but only during the first month after treatment implementation. Most soil nutrients showed modest changes that were not significantly different from other burning treatments. Modest increases in soil pH was observed with one in 5 trials recording a significant increase in pH (KCl) after the second burn. Total N mostly decreased with increasing number of burning treatments, but this effect was only of a significant magnitude in one out of 5 trials. Exchangeable Mg showed a small increase in all trials after burning, but the magnitude of this effect was only significant in one out of 5 trials.

In conclusion: The evidence collected across 5 replicated experiments showed that significant fuel reduction (in FF and understorey) is attainable with 2 to 4 low intensity, repeated prescribed burning events under pine tree canopies. There appears to be minimal damage to trees and no significant short term response in diameter increment after repeated prescribed burns. The effect on nutrient dynamics in the system is modest and non-significant in most cases.

Opsomming

Bosbrande vernietig jaarliks groot plantasie areas in Suid-Afrika en daarom bestaan daar ŉ groeiende behoefte om die brandrisiko op ŉ effektiewe, ekonomiese en volhoubare wyse te verminder. Periodieke beheerde brande word deur baie navorsers en bestuurders geag as die enigste koste-effektiewe metode in die vermindering van vuur skade en brandstof ladings en daarom word dit grootskaals geïmplementeer in SA. Die tesis dokumenteer die effek van herhaalde voorgeskrewe brand operasies op brandstof vermindering, boom skade en opstandsgroei, as ook nutriënte dinamika in die sisteem. Vyf veldproewe is uitgelê in semi-volwasse *P. elliottii* en *P. patula* plantasies in die Noordelike gebied van Mpumalanga gedurende Januarie 2014 om die effek van onderboom-brande op brandstofladings te bepaal so ver dit nutriënte poele en opstandsproduktiwiteit betref. Die navorsingspersele het elk aanvanklik bestaan uit drie kontrole, drie eenmalig gebrande en drie tweemalig gebrande persele.

<u>*Brandstoflading vermindering.*</u> Onder-boom brande het ŉ lae tot matige intensiteit gehad met ŉ voorspelde vuurfront intensiteit wat gewissel het tussen 44 en 602 kW m^{-1}. Deur middel van beheerde brand is die bosvloer-ladings beduidend verminder in al die navorsingspersele (6.3 t ha^{-1} en 12.9 t ha^{-1} per enkele brand in *P. elliottii* en *P. patula* persele onderskeidelik). Klein addisionele verskille in naaldeval (wat die oorspronklike doelwit van bosvloer lading-vermindering sou teenwerk) is aangeteken gedurende die eerste maand na behandeling in 3 van die 5 persele, maar die kort tydsduur van hierdie tendens het beteken die kumulatiewe effek nie beduidend was nie. Die gemiddelde naaldeval tempo per spesie was 5.52 en 8.82 t ha^{-1} yr^{-1} vir *P. elliottii* en *P. patula* onderskeidelik. Daar is bykomend gevind dat die hoogste natuurlike naalde-val tempo gedurende die wintermaande voorkom en die laagste

naalde-val in die somermaande. Die doelwit van brandstoflading vermindering na waardes tussen 10-15 t ha^{-1} kan behaal word in twee beheerde brande in meeste *P. elliottii* opstande (met kleinerige bosvloer ladings), maar minstens 4 brande mag benodig word in sekere *P. patula* opstande met aanvanklike bosvloer ladings groter as 50 t ha^{-1}. ʼn Beduidende afname in kreupelbosgroei was merkbaar 8 maande na implementering van behandelings (met uitsondering van een perseel), maar die aantal spesies per behandeling het vinning teruggekeer na voor-brand hoeveelhede: teen 14 maande na behandeling was daar geen verskil meer bemerkbaar in spesie samestelling nie.

Effek op boom kondisie en groei. Kroondakskade was beperk tot een navorsingsperseel en ʼn kombinasie van wortel en kambium skade het in twee persele voorgekom – ʼn resultaat toegeskryf aan die smeulende effek van die bosvloerbrand. Die verskille in dbh en basale oppervlak groei-tempo tussen behandelings was nie beduidend op tydstip 4 en 12 maande na implementering van behandelings nie, maar ʼn hoogs beduidende seisoenale effek is waargeneem in al die persele: die aanwas in dbh was 61% hoër in somer as winter.

Nutriënte dinamika. Bosvloer-nutriënte inhoud was sterk gekorreleer met die afname in bosvloer lading, en die verlies aan N was tussen 33 en 119 kg ha^{-1}; P, K, Ca en Mg verliese was gemiddeld 3.8, 12.6, 72.4 en 17.2 kg ha^{-1} oor al die persele. ʼn Toename in makro nutriënt-konsentrasies van vars – gevalde dennenaalde is gevind gedurende die eerste maand na behandeling. Die vlakke van nutriënte in die bogrond het meestal matige veranderings getoon wat nie beduidend verskil het van ander brand persele nie. Matige toenames is gevind in grond-pH, met ʼn beduidende toename in pH (KCl) merkbaar in slegs een van die 5 tweevoudig-gebrande persele. Totale N in die bogrond het meestal afgeneem met toenemende brand behandelings, maar die effek was sleg beduidend in een van die vyf persele. Uitruilbare Mg in die bogrond het 'n klein toename getoon oor al die persele na brande, maar die omvang van die effek was slegs beduidend in een van die vyf persele.

Ten slotte: Die bewyse versamel oor al 5 gerepliseerde eksperimente wys dat 'n beduidende afname in brandstoflading (bosvloer en kreupelbos) haalbaar is met 2 tot 4 lae intensiteit, voorgeskrewe brande onder denneboom kroondakke. Daar blyk minimale skade op bome te wees en geen beduidende kort termyn reaksie in deursnee groei na herhaalde beheerde brande is gevind nie. Die effek op nutriënte dinamika in die sisteem is beskeie en nie-beduidend in meeste gevalle nie.

Acknowledgements

I want to show my gratitude to everyone who has contributed to the success of this study especially:

- My supervisor Dr Ben du Toit for his guidance, patience and invaluable input throughout the whole study period.

- Dr Hannél Ham for her supporting role in funding, administration and initial encouragement of the study.

- Fire Risk Manager of KLF, Mr Ben Bothma who made this project possible and for the hospitality and friendship of his family.

- DAFF, for the student bursary, support from KLF and the funding of RTF and the THRIP programme of NRF.

- My father, for his patience, support and specifically, for the time and effort put into proofreading the chapters.

- My friends and family to whom I will forever be grateful for their support and belief, keeping me motivated throughout the whole project.

- To our almighty Father for the opportunity and ability He invested in me to successfully complete this project.

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Al	Aluminium
ANOVA	Analysis of variance
B	Boron
BA	Basal area
C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
ClLm	Clay loam
DBH	Diameter at breast height
ECEC	Effective cation exchange capacity
Fe	Iron
FF	Forest floor
FLI	Fire line intensity
FMC	Fuel moisture content
FSA	Forestry South Africa
HR	Harvest residue
ICP-OES	Inductively coupled emission spectroscopy

K	Potassium
KCl	Potassium chloride
LAI	Leaf area index
MC	Moisture content
Mg	Magnesium
Mn	Manganese
MPU	Mpumalanga
N	Nitrogen
N.A.	Not available
Na	Sodium
OM	Organic material
P	Phosphorous
Ppm	Parts per million
Rep	Replication
RSA	Republic of South Africa
SaClLm	Sandy clay loam
SaCl	Sandy clay
SaLm	Sandy loam
SiClLm	Silica clay loam

SPH	Stems per hectare
TPH	Trees per hectare
UCB	Under-canopy burn
Vol	Volume
W-Cape	Western Cape
Zn	Zinc

1. Introduction

South Africa is considered a fire prone country with three out of the five main vegetation types being dependent on fire for survival (Teie, 2009; Bridgett *et al,.* 2003). Fire will therefore always be part of South Africa's ecosystem and a growing need exists to effectively manage and control fires. Fire protection is one field of fire risk management that focusses on actively reducing the risk of fires occurring by being pro-active rather than reactive. A fire requires oxygen, heat and fuel in the right mixture to burn (Teie, 2009). Fuel is the only factor of the three mentioned that can effectively be managed pro-actively and therefore fuel management is one of the main focus points in fire risk management. Prescribed burning is one method implemented to reduce fuel loads to acceptable quantities in order to effectively control and extinguish fires.

1.1 Plantation fires in South Africa

Fires are on the increase in the plantation regions of South Africa (frequency and area damaged by fires) and this is becoming a growing concern for the forestry industry. There is an urgent need to implement effective methods for reducing the fire risk in plantations (Figure 1.1). According to Forsyth *et al.* (2010) the increase in fire frequency and area damaged is probably a combination of bad fire management practises and additional ignition sources.

During the period 2006 and 2007 the largest area damaged by fires (70 700 and 70 800 ha respectively) were recorded for the past 30 years. During 2007 alone almost six percent of the total planted plantation area in South Africa was damaged by wild fires. From the year 2000 onwards the *number* of fires drastically increased with 2010 recording the highest number of fires (Figure 1.1).

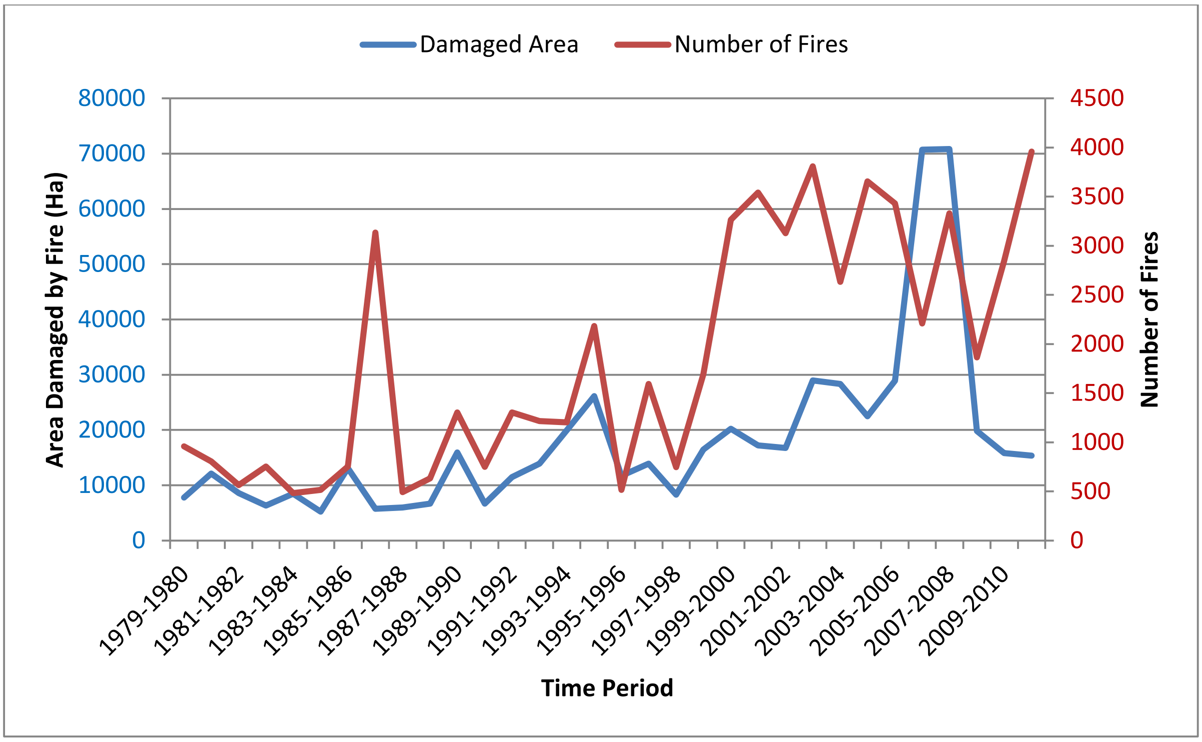

Figure 1.1: The relationship between the area burnt and number of fires in plantations of South Africa (FSA, 2013).

The total planted plantation area in South Africa has decreased over the same period that the area damaged by fires increased exponentially (Figure 1.2). From the year 1996 the total plantation area has declined steadily and only started to stabilize around 2008 whereas the area damaged by fires and the frequency of fires have steadily increased over the same period. In the year 1996 the total plantation area was the highest at 1 518 138 ha and the total area damaged by fire was only 13 901 ha whereas the largest area damaged by fire occurred during 2007 when the total plantation area was only 1 257 340 ha and the area damaged by fire 70 812 ha.

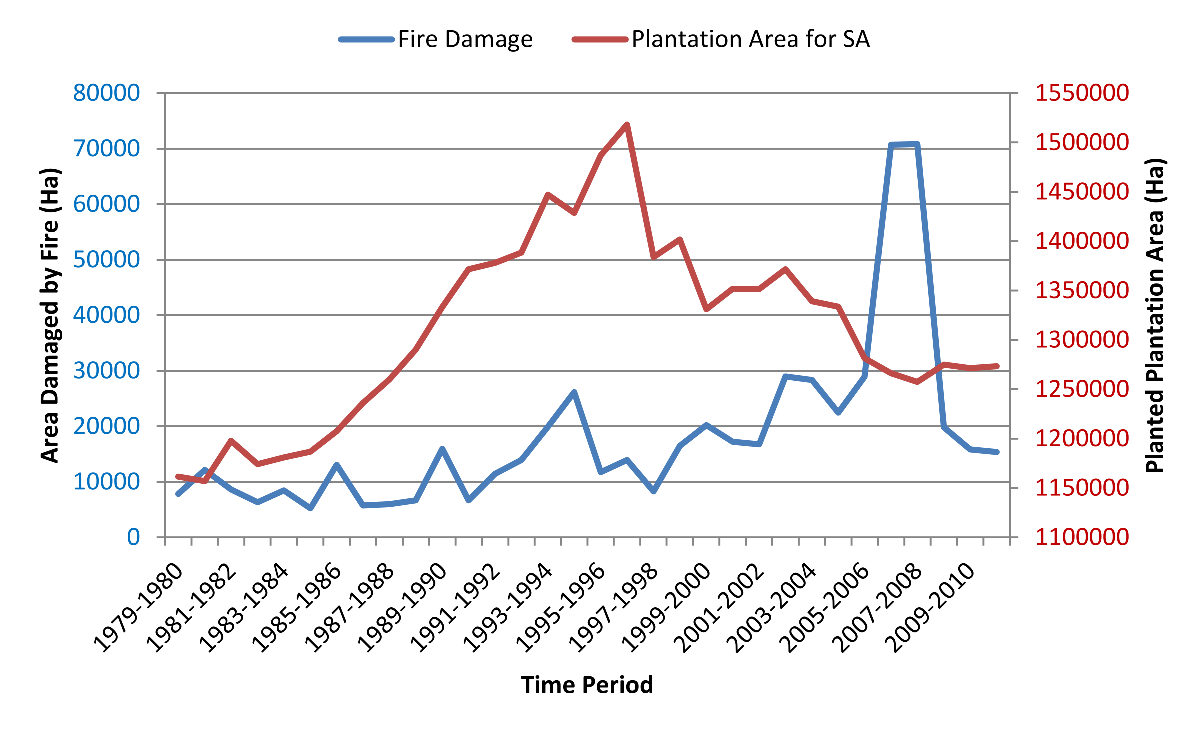

Figure 1.2: The relationship between fire damaged area and planted area from 1979 – 2010 (FSA, 2013).

During the period 2003 to 2010 natural causes of plantation fires only amounted to 6% of the total plantation fires recorded (Figure 1.3). When summed, the human-induced fires namely arson and accidental fires accounts for 44% of all fires. The unknown causes of plantation fires are the highest at 50% but according to Van der Sijde (2003) it can be assumed that most of the unknown causes of plantation fires are human-induced. It can therefore be accepted that humans are by far the main contributors to wild fires damaging plantations in South Africa.

With the human population of the country increasing each year by a few hundred thousand together with social unrest, longer drought periods, increased temperature and erratic rainfall weather patterns experienced in South Africa, it can only be assumed that the fire risk will continue to increase in the future if nothing pro-active is done to counter the increasing fire risk (Trading Economics, 2013; Davies, 2010).

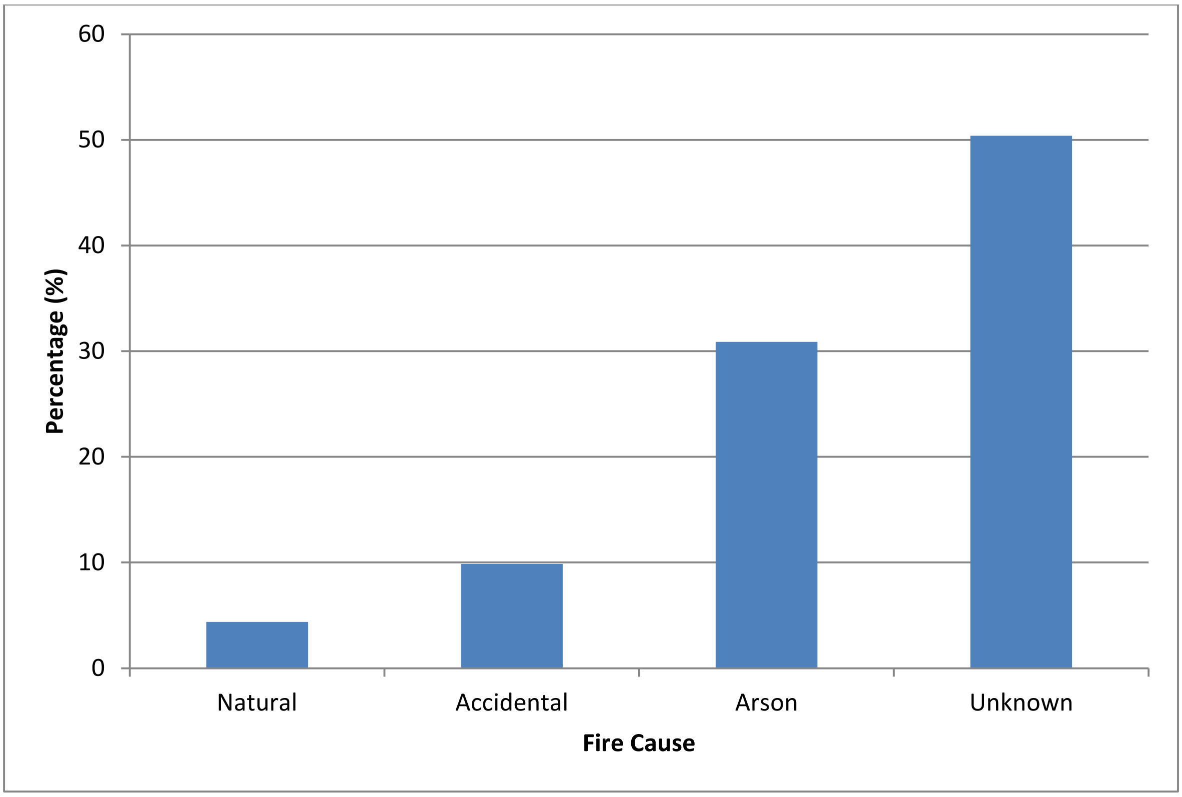

Figure 1.3: The causes of plantation fires for the time period 2003 – 2010 (FSA, 2013).

1.2 Fire in Mpumalanga

Mpumalanga Province is situated in the north-eastern parts of South Africa. The dominant natural vegetation is grassland in the Highveld and bushveld in the Lowveld resulting in the province being a high risk area for wild fires. During the year 2007 one of the worst wild fires ever was recorded for the region when more than 9% of the total area of planted plantation species (Softwood and Hardwood) was damaged by fires (Figure 1.4). The source of the information excludes the Belfast and Middelburg regions of Mpumalanga. The relationship between the number of fires and the area damaged by fires is rather interesting as it almost reflects inverse trends. As mentioned earlier, Mpumalanga had a devastating year in 2007 regarding fire damage when more than 54 068 ha were damaged. From 2008 the number of fires increased drastically while the area damaged by fire declined during the same period. This could partly be due to the pro-activeness of companies such as Komatieland Forests which uses under-canopy burning as a means of reducing the fire risk. The company makes use of aerial incineration techniques so as to be able to burn large areas simultaneously as ideal burning conditions do not occur frequently. With aerial ignition, areas of up to a 1000 ha per day can be burnt in perfect weather conditions with extensive planning beforehand. With the resulting reduction of fuel loads, wild fires can then be controlled more easily and fire damage will decrease. Improved fire risk management may thus explain why the area damaged by fire reduced for the same period during which the number of fires increased (Figure 1.4).

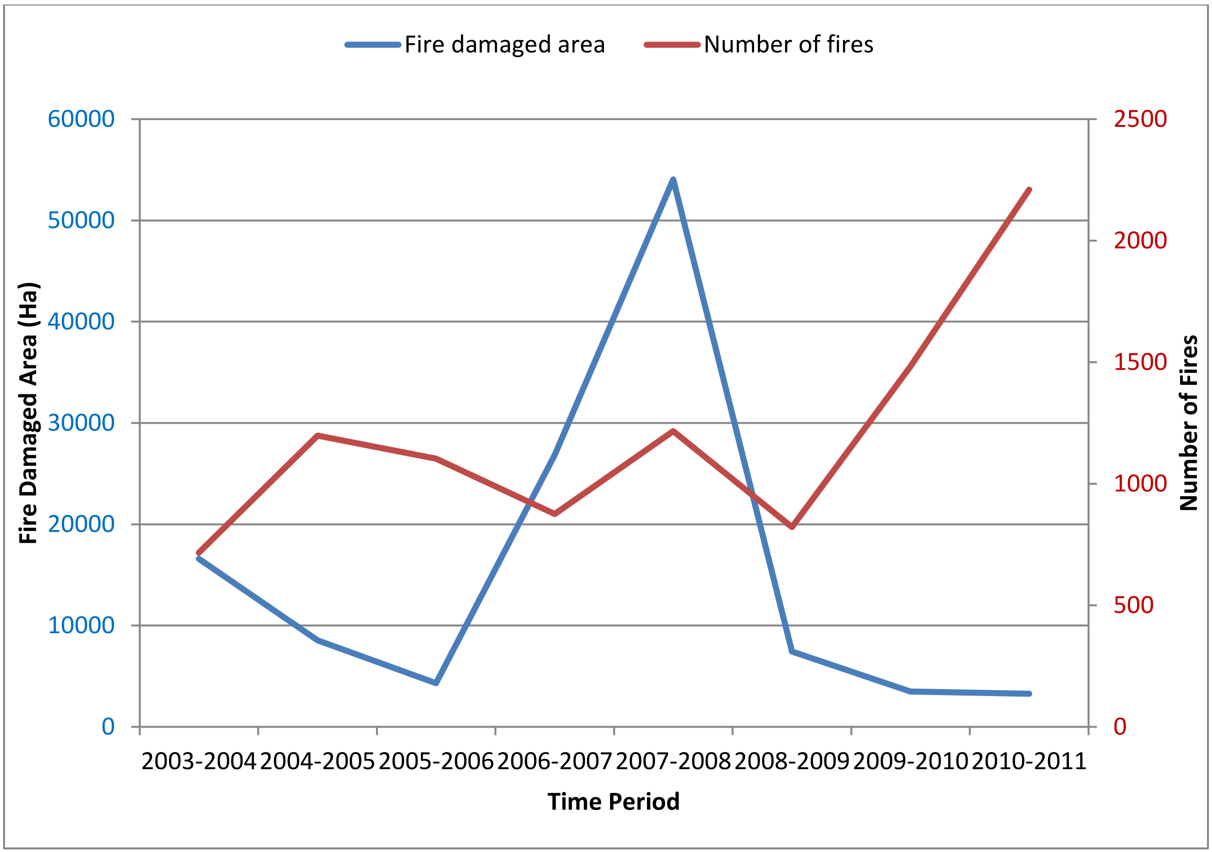

Figure 1.4: Relationship between the total area damaged by fires and number of fires for Mpumalanga North & South (FSA, 2013).

Prescribed fire is a low cost and practical method of reducing the fuel load to acceptable quantities. Prescribed burning can be divided in two categories namely prescribed under-canopy burning inside the stand and the burning of harvesting slash following clearfelling, both considered acceptable management tools for fuel load reduction (De Ronde *et al.,* 2004). Komatieland Forests uses both methods of prescribed burning on operational scale inside their plantations. The burning of slash after clearfelling, where slash is spread out and burnt to reduce fire intensity, takes place on 90% of all compartments. The remaining 10% are compartments that are not fit for burning and includes very steep compartments and compartments with sandy textures and organic-rich / peat topsoils.

1.3 Problem Statement and Objectives

Wild fires are destroying large areas of plantations in South Africa annually and are a major problem for the forestry industry, as described above. Reducing the available fuel loads and risk for fire through prescribed burning is one of the most effective management practises in protecting forest plantations (Van Wagtendonk, 1996). Komatieland Forestry Company (KLF) is a company implementing under-canopy burning on an operational scale. The company has been using this application with success but does not know what the longer term implications of this approach may be on their plantations. Furthermore, other forestry companies are hesitant in investing in under-canopy burning due to lack of information regarding the sustainability of the method. Before this application can be successfully deployed on a regional scale more forestry companies will have to buy in and implement under-canopy burning on an operational basis. This can only be achieved if the effects of *repeated* under-canopy burning in South African Pine plantations are well documented.

This study is the start of a much larger research project aimed at determining the sustainability of under-canopy burning and collecting enough evidence to be able to confidently approve or reject the use of this application in specific areas under specific conditions. The aim of this study is to obtain an indication of the effectiveness of under-canopy burning in reducing the forest floor (FF) and to determine its effect on soil nutrient content, tree damage, understorey growth and tree response in relation to soil, climatic and topographic conditions encountered in North-eastern Mpumalanga. The main species currently grown in this area is *Pinus patula* and *Pinus elliottii*.

1.4 Research Questions

The main objective of the study is to quantify the result of repeated under-canopy burning by focussing on the following points:

1. How does the FF mass change following different under-canopy burning treatments?
2. What is the medium-term effect of under-canopy burning on litterfall rate?
3. What is the effect of under-canopy burning on nutrient contents in the top soil, FF and litterfall foliage respectively?
4. To what extent does under-canopy burning damage the tree canopy, stem and root system?
5. Does under-canopy burning significantly change tree growth and, if so, is it by increasing growth rate due to a nutrient injection associated with the ash-bed effect or is it by decreased growth as a result of tree damage and stress?
6. What is the effect of under-canopy burning on the understorey growth, specifically the recovering time and species composition?

After researching literature regarding these topics the author came to the realisation that fuel loads in local pine plantations are quite different from international scenarios (Morris, 1986; Schutz, 1990; Ross & du Toit, 2004), but that only a small number of South African experiments had been conducted on under-canopy burning (De Ronde, 1982; De Ronde 1983; De Ronde, 2008; De Ronde *et al.,* 1990; Bird and Scholes, 2005; du Toit and Fischer, 2011). Most of these trials used single burn events in specific settings. Furthermore, the effects of prescribed under-canopy burning on root damage, leaf area index, and foliar nutrient status after the fire has not been documented to date in SA. There is thus clearly a need to continue with this line of experimentation (a) on a greater variety of sites (b) making use of repeated burning treatments, and (c) monitoring those effects that have not been adequately documented to date.

Notwithstanding the statements above, there is a fair amount of information on the effects of prescribed fires in pine plantations and the following scenarios could be constructed from the existing literature on the topic: The author expects that a significant FF reduction will occur and that this will be related to fire resistance time and fire line intensity. These factors will in turn be related to climatic conditions and fuel moisture content (Bird & Scholes, 2005; De Ronde, 1983). Increased litterfall may appear in certain trials where crown scorch and/or stand stress occur and may last for some time depending on the severity of damage, and this may lead to a reduction in growth. With a low-intensity prescribed under-canopy burn, however, no serious damage and stress is expected as trees are already mature and consequently no short term reduction in growth is expected (De Ronde, 1983). Soil pH is expected to increase due to the ash bed effect which is rich in base cations such as K, Ca and Mg (Geldenhuys *et al.,* 2004). With increased soil pH, phosphorous may also increase as

P availability is directly related to pH levels (Certini, 2005). Inorganic nitrogen could also increase due to enhanced microbial activity and the thermochemical process called pyrolysis (Covington & Sackett, 1992). Understorey plants most probably will regrow to pre-burn densities at some point in time, but this will be species- and fire severity-dependent as high intensity fires may stimulate the seed bed if total FF consumption occurs (De Ronde *et al.,* 2004).

1.5 Limitations of this study

The opportunities for finding representative trial sites were always limited because of the fact that so many factors have to be constant across sites in order to make valid comparisons. Finding suitable control plots was also difficult as, at age 20, most compartments suitable for under-canopy burning had been burnt or damaged by wild fire at some stage during the specific rotation. Finding burning and silviculture history for specific compartments dating back 20 years presented a challenge of its own. Furthermore, the remote location of the research area in relation to the University of Stellenbosch from which this research was conducted, by necessity impacted negatively on the number of visits possible and ultimately the level of control over the trials. Time always remained a constraint as the study had to be completed in two years.

Because of the fact that it was only possible to burn certain trials during the second year of the study, monitoring the effects of under-canopy burning became rather restricted. Sampling of these trials could only occur once-off in July-August 2015 as time ran out. The weather played a pivotal / critical role in this study as under-canopy burning could only be applied during perfect weather conditions after sufficient rainfall. The under-canopy burns could also not be performed alone and the availability and organisation of fire teams became quite challenging due to the number of failed burn attempts.

Despite all the limitations we did manage to retrieve meaningful data which includes litterfall, FF reduction, FF, foliar and soil nutrients, tree damage and growth as well as understorey response between treatments from which meaning full conclusions could be made regarding the sustainability of the application.

1.6 Thesis Structure

The thesis consists of seven chapters. Following the introduction is an in-depth review off literature relevant to this subject. All materials and methods used during the study are explained in Chapter 3, including statistical and chemical analysis procedures. Chapter 4 contains all relevant results obtained after thorough analysis of the data acquired and this is followed by an in-depth discussion in Chapter 5 explaining the outcome of this study within the context of and by comparison with other similar studies. Chapter 6 contains a conclusion and this is followed by the main recommendations that can be made as a result of this study, in Chapter 7.

2. Literature Review

2.1 Forest Floor

The forest floor (FF) is essential in any forest environment and helps with water infiltration, protects the soil from erosion and serves as insulating layer protecting the soil from extreme weather conditions such as frost and temperature changes. The FF also provides energy for micro-organisms that break down the organic matter to release nutrients to the soil. Forest floor accumulation is a result of an imbalance between the input and output of organic material in the soil ecosystem in the absence of disturbances such as wild fires (Dames *et al.,* 1998; Ross & du Toit, 2004; Fisher and Binkley, 2000).

2.1.1 Forest Floor Structure and Function

Forest Fuel load can be classified as shrubs, timber slash, grasses and the FF (Ross *et al.,* 2004; Anderson, 1982). The FF is defined as the litter layer and all decomposing organic layers on the soil surface (Binkley & Fisher, 2000; De Ronde, 1993). The FF can be divided into three main layers namely litter, fermentation and humus layer (Figure 2.1). The L (Litter) layer is the surface layer and consists of unchanged plant and animal remains. The F (Fermented) layer is directly beneath the L layer and consists out of partially decomposed organic material from which the origin can still be derived. Beneath the F layer lies the H (Humus) layer that consists of well decomposed, amorphous organic material (Schutz, 1990; Ross, 2004; Fisher and Binkley, 2000).

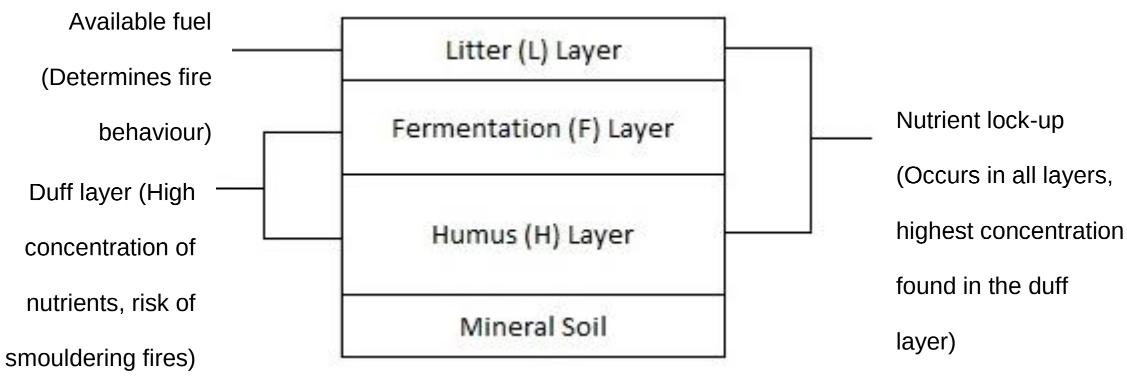

Figure 2.1: The structure of the forest floor (Ross & du Toit, 2004).

When FF accumulation occurs it is known as a "mor" layer. This condition is regarded as a threat for various reasons - it results in nutrient lockup, harmful organic acids are released, it reduces moisture infiltration, causes access difficulty and increases fire risk (Schutz, 1990). There are two types of mor layers in South Africa namely humimor and fibrimor. Humimor layers are usually found in the Southern Cape region on clay soils and are characterized by a dominant humus layer with normal litter and fermentation layers. Fibrimor FF layers usually develop under *P. patula* plantations in the summer rainfall areas at altitudes exceeding 1400 meters. Fibrimor consists of a very thin H layer and a thick F layer due to a lack of microbial activity which slows down decomposition of the fermentation layer (Ross, 2004; De Ronde 2008). Two other FF types have been identified in South Africa namely moder and mull. Moder FF formations have a normal litter and fermentation layer with no prominent humus layer and is usually found in sandy soils with low fuel loads. Mull FF formations only consist of a thin L and F layer (Fisher & Binkley, 2000). Mull FF formation is usually found in the Southern Cape fynbos region under *P. radiata* (De Ronde, 2008).

2.1.2 Forest Floor Accumulation

Pinus patula is one of the most planted pine species in Mpumalanga and is considered to generate one of the heaviest FF formations of pine species globally. Studies conducted in *Pinus patula* plantations in Mpumalanga on FF accumulation have shown FF depths ranging from 39 – 121 mm with an average of 100 mm (Dames *et al.,* 1998). Average FF depth for *Pinus elliottii* in Mpumalanga was found to be 49 mm, compared to 104 mm for *P. patula* (Schutz, 1990). Schutz (1990) have found FF layers in the Mpumalanga region for *Pinus patula* exceeding 300 t ha^{-1} – this is the highest recorded value in the world for any pine species. Forest floor formations in *Pinus patula* stands in Swaziland have been found to increase up to 37% from the first to the second rotation under the same conditions even when slash was burned before re-establishment of the second rotation (Morris, 1984, 1995). Morris (1993) found *P. patula* to reach FF mass equilibrium at age 10 (40 t ha^{-1}) at low altitudes, compared to high altitudes where FF mass accumulated up to 34 years. Forest floor accumulation is higher in high altitudes - lower temperature and higher moisture are two of the main drivers, resulting in a decrease in microbial activity (Ross, 2004).

Decomposition rates are dependent on various factors, such as the quality and structure of the organic material, humidity, temperature, moisture, pH, microbial activity and the composition of soil micro flora and fauna (Ross, 2004). Pine species acidify the soil, which reduces fungal activity that contributes largely to FF accumulation. Various authors, however, reported that prescribed burning increases soil pH, surface temperature and soil moisture thus creating a more favourable micro climate for fungi, which in turn increases litter breakdown of the FF (De Ronde *et al.,* 2004; Fisher & Binkley, 2000; Covington & Sackett, 1984; Schoch & Binkley, 1986). Some studies found that FF decomposition rates decrease or remain unchanged following a fire (Grigal & McColl, 1977 in Fisher & Binkley, 2000; Monleon *et al.,* 1996).

2.1.3 Litter Production

Litter production in *Pinus patula* stands is a continuous process changing throughout the year with March to September reported as the months with the highest litter production rates in Mpumalanga. Litter production is not strongly influenced by altitude and increases with age according to Dames *et al.* (1998). Litter production increases to canopy closure where after it decreases slowly, mainly due to silvicultural activities such as thinning and pruning (Ross, 2004). According to Gholz *et al.* (1985) needle fall peaks at age 10 when the tree leaf biomass also peaks and changes from age 14 onwards when bark and woody parts form a bigger part in litterfall. According to Dames *et al.,* (1998) the increasing litter production with stand age has been recorded in previous studies and the average litter production observed also corresponds to other *Pinus patula studies* in India and Tanzania. Average litter production rates for *Pinus elliottii* ranges from 2.90-4.99 t ha^{-1} yr^{-1} in different countries (Dames *et al.,* 1998).

2.1.4 Fuel Management

Following forestry operations such as thinning, pruning and harvesting, tree debris is left behind. These slash piles are well aerated and dry out much quicker than the surrounding fuels resulting in a serious fire risk hazard. Slash build up, additionally provides ideal conditions for insect pests and negatively effects seedling growth (Ross, 2004). FF build up occurring in conditions unfavourable for microbial activity (Ross, 2004) and additional ladder fuels further increase the fire risk (De Ronde *et al,* 1990). Aerial fuels such as flammable canopies of understorey growth, dead needles, and flammable debris suspended on understorey vegetation and tree crops are referred to as ladder fuels (De Ronde *et al,* 1990). These fuels act as a medium for ground fires to reach the crown canopy of the living trees known as crown fires. Fuel management can be divided into non-burn and prescribed burning methods to effectively reduce fuels loads.

Table 2.1: Non-burn and prescribed burning methods used to manage fuel loads (Teie, 2009).

Non-burning methods	**Prescribed burning methods**
Natural decomposition	Hand piling and burning
Hand piling	Machine piling and burning
Broadcasting	Spot burning
Chopper roll	Broadcast burning
Mulching and Chipping	Under-canopy burning
Herbicide application	Progressive burning
Slashing	

2.2 Prescribed Under-canopy Burning

Prescribed burning can be defined as the intentional application of a fire in a skilful manner to a specific site under selected weather conditions to accomplish specific pre-planned land management objectives (De Ronde *et al.,* 2004; Teie, 2009). Prescribed burning in South Africa can be divided into slash burning and under-canopy burning. Slash burning in South Africa is mainly used following clearfelling, i.e. to improve access for re-establishing purposes whereas under-canopy burning is mainly used to reduce fuel loads underneath tree canopies. Other objectives of prescribed burning include improving accessibility, improving growth (reducing competition), changing plant species composition, pest management, managing competition in silvo-pastoral systems and other ecological conditions (De Ronde *et al.,* 1990; De Ronde *et al.,* 2004; Carter & Foster, 2004; Teie, 2009). A fuel load below 11 t ha^{-1} is considered low enough to have a chance of being effectively controlled in case of a fire threatening a plantation. A simulation to determine the effectiveness of under-canopy burning in reducing the fire risk shows the main drivers of fire behaviour were crown height, surface and ladder fuels (van Wagtendonk, 1996). The simulation showed that prescribed under-canopy burning reduced 50% of the surface and understorey fuels up to two meter in height. When a wild fire was simulated inside the prescribed area no crown fires occurred. The rate of spread dropped from 1.88 m min^{-1} in the control area to 1.74 m min^{-1} in the under-canopy burned area. Fireline intensity decreased from 491 to 117 kW m^{-1}, flame length decreased from 1.27 to 0.68 m and the heat calculated per unit of area decreased from 14.63 to 4.02 kJ m^{-2} from the simulated control plots to the under-canopy burned plots respectively. From all the methods for reducing the fire risk in the specific study, prescribed under-canopy burning was by far the most effective method (van Wagtendonk, 1996).

2.2.1 Burning Conditions

Prescribed under-canopy burning is carried out during the wet season in pine plantations when the top section of dead fuel is dried out and the understory vegetation, such as grasses, is alive. Under-canopy burning can be applied when enough rain has fallen, wetting the whole FF up to the mineral soil and allowing enough time for only the L layer to dry out, which is usually between two to seven days following good rain (De Ronde *et al.,* 2004). An under-canopy burn study conducted in a five year old *P. patula* stand in the Eastern Cape showed average tree mortality of 20% during the wet season in comparison with 50% during the dry season in a grassland vegetation cover (De Ronde, 2008).

2.2.1.1 Temperature

Air temperature is strongly correlated with fuel moisture content and plays a vital role in the drying out of fuels. The hottest time of the day is usually between 12:00 – 15:00 and will therefore be the period when the relative humidity is lowest and fuels the driest causing undesirable higher intensity fires (Trollope *et al.,* 2004). During under-canopy burning the ideal temperature to burn ranges from 5 – 15 °C inside the stand minimizing fire intensity (Chandler *et al.,* 1983; Teie, 2009).

2.2.1.2 Relative Humidity

Relative humidity partly determines the moisture content of the fuels. With increasing temperature the moisture in the air will decrease. With every 20 °C increase in temperature the relative humidity is reduced by half and *vice versa*. When the relative humidity decreases below 30% it becomes difficult and dangerous to control a fire (Trollope *et al.,* 2004). According to Teie (2009) a relative humidity above 25% should result in moderate to slow burning conditions with anything below 25% becoming very dangerous.

2.2.1.3 Wind

Wind is one of the most dynamic variables influencing fire behaviour (Chandler *et al.,* 1983; Teie, 2009). Wind speeds at eye level inside the stand of 2 - 5 km^{-1} are considered ideal for under-canopy burning but this may vary under specific site conditions (De Ronde *et al.,* 1990). Wind provides oxygen to the fire and has a large effect on the rate of spread. Wind forces the flames on an angle thus reducing flame length and increasing the drying rate of the fuels ahead of the fire front which results in increased rate of spread and ultimately the occurrence of higher intensity fires. This will also reduce crown scorch percentage. This is however not valid for back-burning as the fire front is burning into the wind. Back burning advances at a slow rate which is more controllable and increases resistance time, usually resulting in more complete burns (Teie, 2009). Wind direction will determine the direction in which the fire will spread. Unstable air will also have an effect on fire behaviour through wind speed and direction differences resulting in unpredictable burning conditions (Trollope *et al.,* 2004; Teie, 2009; De Ronde *et al.,* 1990).

2.2.1.4 Fuel Moisture

Higher moisture content in fuels will slow down the combustion rate as more energy is used to evaporate water rather than increasing temperature and thus fire intensity further. The higher moisture content in fuels suffocates the fire due to the water vapour being released from the burning fuel - called the smothering effect (Trollope *et al.,* 2004). Fine fuel moisture percentage above 7 and below 35% is considered dry enough to successfully achieve under-canopy burning if the duff layer is sufficiently moist (De Ronde *et al.,* 1990). Fuel moisture is dependent on the atmosphere, precipitation and the ground. High relative humidity will result in high fuel moisture and *vice versa*. Fast changes in relative humidity will not have a big effect on moisture content especially in thicker fuels with slower drying out rates. Other atmospheric conditions such as wind speed and temperature will play a large role in the relative humidity and consequently the moisture content of fuels (Trollope *et al.,* 2004).

2.2.2 Ignition Techniques

Different ignition patterns have been developed for prescribed burning. Depending on the objectives and specific conditions of the burn, the best suited ignition pattern is chosen. In some conditions it may even be necessary to integrate several ignition patterns to achieve the desired outcome. Head fires are the highest intensity fires with backing fires the least intense. Head fires will result in the most crown scorch due to high flame height and a fast rate of spread. The backing fire on the other hand has a very slow rate of spread and short flame height. The backing fire usually consumes more FF than head fires. Edge burning is usually used on the edges of compartments as edge fuels dry out faster than inside the compartment due to more exposure to wind and sun. The fuel load is usually more at the edge of the compartment and therefore edge burning is applied as a backing fire to burn the edges under ideal conditions before the rest of the compartment follows. Other burning techniques used are the point source ignition, strip-head fire, flank-fire, centre firing and chevron burning pattern (De Ronde, 2008; Brown & Davis, 1973; Teie, 2009; Marshall *et al.,* 2008; De Ronde *et al.,* 1990).

2.2.2.1 Manual vs Aerial Ignition

Aerial ignition has been implemented in some countries to increase productivity. With large areas being prescribed for burning every year, and lack of time due to specific weather conditions being required, the need to increase the area burnt when the right conditions occur, has led to the more general implementation of aircraft. In Australia aerial ignition can burn more than 4 000 ha a day underneath tree canopies in ideal conditions. Aerial ignitions make use of the point source (grid) ignition pattern. The intensity of the fire is controlled by spacing the fires. This technique is not as controllable as strip-head fire and may cause some degree of crown scorch and stand damage. Stand damage in Australia from aerial ignition ranges from 5 – 35% with 20% or less being considered acceptable (Chandler *et al.,* 1983; Brown & Davis, 1973).

2.3 Nutrients

When an imbalance in the input and output of nutrients to a system occurs, the nutrient balance of the system will change. Wild fires and management practises such as prescribed burning, fuel wood harvesting and tree harvesting remove nutrients from the site resulting in an overall decrease in the nutrient budget (Mackenson, 1999; Du Toit & Scholes, 2002; Ross, 2004). Mismanagement of nutrients should be avoided as this will lead to reduced site productivity and consequently reduce growth (Mackenson, 1999).

2.3.1 Plant Nutrients

Plant nutrients are elements that are essential for plant growth. Three of these elements (carbon, hydrogen and oxygen) are not considered limiting factors to plant growth. Nutrients can be divided into those that plants require large quantities of (500-14000 ppm), called macro nutrients, and micro nutrients that consist of nutrients that plants require small quantities (<100 ppm) of. There are six macro nutrients namely: nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg). Micro nutrients are zinc (Zn), boron (B), iron (Fe), chloride (Cl), copper (Cu), nickel (Ni), molybdenum (Mo) and manganese (Mn) (Garrison-Johnson, 2002). Most plant nutrients come from the soil being released from the parent material over time (Garrison-Johnson, 2002). Nitrogen is considered the most limiting growth factor world-wide and together with its low volatilization temperature has been the most studied nutrient, especially regarding fires (Fisher & Binkley, 2000; Hatten *et al.,* 2012; Carter & Foster, 2004).

2.3.2 Nutrient Cycling

Plant nutrients cycle through the ecosystem through various paths, called nutrient fluxes. The nutrient flux system in plantations is operative in the plantation stand from the tree top to the end of the root system and includes all plant and animal life, as well as the atmosphere, lithosphere and hydrosphere of the specific system. The ecosystem can be divided into four main nutrient pools namely tree overstorey, ground cover vegetation, FF and mineral soil (De Ronde, 1992). The nutrient fluxes can be divided in inter- and intra-specific systematic nutrient fluxes. Intra-specific systematic nutrients fluxes are nutrients that transfer through the system, for example litterfall, which does not change the total nutrient budget of the system. Inter-specific systematic nutrient fluxes on the other hand are nutrients that increase or decrease the total nutrient budget through adding or removing nutrients from the system. Inter-specific systematic nutrient fluxes can further be subdivided into management-dependent or independent fluxes. Nutrients can be added (inputs) into a system through atmospheric deposition, biological N-fixation and weathering of soil parent material. Nutrients are removed (outputs) from a system, resulting in a decrease in the nutrient budget of a system, through leaching, denitrification, erosion and gaseous losses. Management-dependent nutrient losses in plantations include site management practises such as harvesting, volatilisation and areal ash transport due to burning and extra leaching and erosion (Mackenson, 1999; Du Toit and Scholes, 2002). Nitrogen is very volatile with significant losses usually recorded at temperatures above 400 °C. Nutrient concentrations lost during a fire is very dependent on the volatility and mobility of nutrients and is the reason why high concentrations of Ca and Mg are commonly found in post-fire soils (Geldenhuys *et al.,* 2004; Fisher & Binkley, 2000; Hatten *et al.,* 2012).

2.3.3 Foliar Nutrients

Macro nutrients (N, P, and K) are found in large quantities in the phloem sap where it rapidly cycles through the plant, called remobilization (Reuter & Robinson, 1997). This ability of plants ensures that N, P and K, which are required in large quantities, are not lost though shedding of old dying tissue and is recycled to new juvenile growth areas. Sulphur, Cu and Zn only remobilize to some extent and Ca, Mg, B, Mn and Fe are considered phloem-immobile as they do not have the ability to remobilize (Reuter & Robinson, 1997). Plant foliage nutrient status is used to determine nutrient deficiency in plants. If soil nutrients are inadequate it will reflect in the foliage of plants. Various methods of determining the nutrient status of plants have been developed, each with specific pro's and con's. The different methods are:

- Critical Levels
- DRIS (Diagnosis Recommendation & Integrated System)
- Nutrient Ratios
- Vector Analysis

(Gregoire & Fisher, 2004; Linder, 1995)

Pinus radiata are considered deficient when nutrient concentrations drop below the critical levels of : <1.0, <0.1, <0.35, <0.05 and < 0.04 for N, P, K, Ca and Mg respectively (Reuter & Robinson, 1997). A study by Schutz (1990) in Mpumalanga recorded average macro nutrient concentrations of 2.15, 0.18, 0.87, 0.26, 0.17, 0.03 and 0.16 for N, P, K, Ca, Mg, Na and S respectively, in fresh foliage of *P. patula*.

2.3.4 Forest Floor Nutrients

Nutrients in biomass are returned to the soil through two main pathways namely canopy leaching and dead organic material. Canopy leaching consists of stem flow and throughfall, and dead organic matter through litterfall and root death (Morris, 1986). A study by Ross *et al.* (2005) on *Pinus patula* stands showed concentrations of N and P in the FF are the only two macro elements that increase from the L to the F layer. Nitrogen and P concentrations decrease from the F to the H layer but in the case of N are still higher than in the L layer. The remaining macro nutrients show a decreasing trend from the L to the H layer (Ross *et al.,* 2005; Ross, 2004). The continuous increase in N concentration through the FF layers can be partly explained by the longer exposure to microbial activity releasing N. The largest nutrient pools are contained in the duff (F & H) layers of the FF due to the greater mass in the duff layers (Ross *et al.,* 2005). According to Ross (2004) the FF contributes the largest amount of nutrients between FF and slash. Gholz *et al.* (1985) focussed on *Pinus elliottii* and found that nutrient concentrations decreased over time, accept for N which increased. The nutrient budget for all nutrients increased over time as FF mass increased with age.

Studies showed N concentrations of 0.64 and 1.11% in *P. patula* stands, 1.15 and 1.11% in *P. radiata* stands for the L and duff layers respectively and 0.33, 0.44 and 0.59% for *P. elliottii* in the L, F and H layers respectively (Ross, 2004; De Ronde, 1992). A Study by Baker and Attiwill in 1985 showed N and P concentrations increase in the litter over time due to mass loss occurring through decomposition and according to De Ronde (1992); Feller (1988) recorded increased N and P concentrations in *P. elliottii* FF formations after burning. Ross *et al.* (2005) recorded mean N concentrations in *P. patula* stands of 0.76, 1.03 and 0.85% in the L, F and H layers respectively.

2.3.5 Soil Nutrients

Most fire-related nutrient studies focus on short term impacts rather than the longer term impacts. The repeating effect of prescribed burning has also not received much attention with most researchers focusing on a single event. This is mainly because of the time required to monitor the longer term impacts seeing that a typical pine rotation age for growing sawtimber in South Africa is 25 - 30 years. It is well known that prescribed under-canopy burning improves certain nutrient levels in the soil such as the uptake of N by plants following a fire (Covington & Sackett, 1992; Schoch & Binkley, 1986; Fisher & Binkley, 2000). Fire commonly increases mineralisation rates by increasing soil microbial activity in two ways. Soil temperature increases and the C/N ratio decreases leading to more favourable conditions for soil microbes (Geldenhuys *et al.,* 2004). Nitrogen is usually the most limiting factor in plant growth and with a low volatilization temperature of 200 °C is the main reason for nutrient loss during fires (Fisher & Binkley, 2000; Hatten *et al.,* 2012). Nitrogen can only be used by plants in the inorganic form nitrate (NO_3^-) and ammonium (NH_4^+). These inorganic N forms occur after a fire and may last up to several years depending on various factors such as soil texture and fire intensity (Erickson *et al.,* 2008; Covington & Sackett, 1992).

A long term study on the effect of repeated prescribed under-canopy burning on *Pinus* species showed little differences in N for control and burned treatments. The study area was burned for thirty years from establishment over 1, 2, 3 and 4 year intervals and N was measured in the FF and topsoil. The study found that N content in the soil increased with increasing fire frequency and N content decreased substantially in the FF with increasing fire frequency (Wells, 1971 in Fisher & Binkley, 2000). This can mainly be explained by the loss of biomass from the FF. With partial consumption of the FF after each treatment N levels per hectare would be proportional to the FF remaining after each treatment. The loss of total N content from the 1 year burning interval, compared to the control, was 300 kg ha^{-1} over 30 years out of a combined N content of 2500 kg ha^{-1} in the FF plus 0 – 30 cm of topsoil. Only 12% N was lost over 30 years in a stand burned every year (Fisher & Binkley, 2000; Binkley *et al.,* 1992). Another study by Wells in 1971, focusing on loblolly pine, with a similar 30 year rotation and with a burning interval of 1 and 4 years, recorded reduced N content in the FF and similar increases of N content in the topsoil, resulting in no net loss of N, in a stand burned every year for thirty years (Fisher & Binkley, 2000). Nitrogen has the ability to re-enter the system through nitrogen fixation and, together with wet and dry atmospheric deposition may explain why big nitrogen losses are not often found in long term studies (Geldenhuys *et al.,* 2004).

Phosphorus, also a great limiting factor for plants, has not been studied as much as nitrogen. This is partly due to its relative higher volatilisation temperature of almost 800 °C and the fact that P does not leach as much as N (Hatten *et al.,* 2012; Certini, 2005). Phosphorus becomes more available for plant uptake following a fire due to increasing pH levels in the soil which can last a few years depending on various factors (De Ronde, 1992; Geldenhuys *et al.,* 2004). Phosphorus is changed into orthophosphate during a fire, the main P plant uptake form for plants (Certini, 2005; Hatten *et al.,* 2012). Soil pH of 6.5 ensures optimal availability of P for plant uptake, indicating that any change in soil pH as a result of fire has an effect on P availability. A study by De Ronde (1992) on P availability in soil found that P concentrations increased from 0.98 to 1.57 mg kg^{-1} after burning. A longer term study conducted by De Ronde (1992) showed a non-significant P increase from 1.73 to 2.43 in the control and under-canopy burn with slash burning after clearfelling.

2.3.6 Ash Bed Effect

Large quantities of ash are left behind after fires typically ranging from 2-15 tonnes per hectare. Nutrients found in ash are highly concentrated, varying from 20 – 100 kg ha^{-1} for nitrogen, 3 – 50 kg ha^{-1} for P and 40 – 1600 kg ha^{-1} for calcium. White ash has higher nutrient concentrations than black ash, usually a result of high intensity fires, resulting in more effective oxidation of carbon, thus leaving a more concentrated ash behind. It must be noted that heat generated from fires may release nutrients from soil organic matter even if the organic matter is not consumed in the fire (Fisher & Binkley, 2000). Ash from plants tends to increase the pH of soils as it is rich in oxides and carbonates of macro nutrient ions such as calcium, magnesium and potassium. This increase is more significant in sandy soils with a poor buffer capacity (Geldenhuys *et al.,* 2004).

Following prescribed burning, soil inorganic N availability increases dramatically during the first few months (Monleon *et al.,* 1996; Covington & Sackett, 1992; Schoch & Binkley, 1986; Carter & Foster, 2004; Hatten *et al.,* 2012). Organic nitrogen is transformed into inorganic nitrogen forms (NH_4^+ and NO_3^-) following a fire. These high concentration inorganic nitrogen forms are readily available for plant uptake. Ammonium nitrogen release usually occurs immediately after a fire whilst NO_3^+ increases only at a later stage. This higher nutrient concentration following a fire is called the ash-bed effect and is most common in the top 10 cm of the topsoil. The duration of this effect is short term with numerous studies around the world showing that nutrient spikes peak within the first few months following prescribed-burning, and then decrease. The duration of this nutrient spike is dependent on various factors such as fire intensity and soil type. The high concentration of NH_4^+ is a result of a thermochemical process in the absence of oxygen called pyrolysis. The increase in

NO_3^- and decrease in NH_4^+ is due to the nitrification of NH_4^+ into NO_3^-. Ammonium-nitrate can, however, also be lost through leaching, immobilisation by plant uptake or microbial activity and denitrification (Covington & Sackett, 1992).

Covington & Sackett (1992) found that ammonium-nitrate increased dramatically in the first few months following a relatively high prescribed burn and decreased substantially after one year, but still remained higher than pre-burn levels. The NO_3^- concentrations only started increasing 6 months after the burn treatment with the biggest increase recorded one year after the burn. Monleon *et al.* (1996) also found an initial spike of inorganic nitrogen in the topsoil that decreased to pre-burn levels one year following the burn. He monitored the inorganic nitrogen levels during the first year, at 5 years, and at 12 years following the burning treatment. The burn was of low intensity and therefore more representative than that of Covington & Sackett (1992). It is interesting of this study to note that lower inorganic nitrogen levels occurred in the burned treatment compared to the control treatment 5 years after burning but this changed at 12 years when the inorganic nitrogen levels were higher in the burned treatment than in the control. This indicates that inorganic nitrogen levels fluctuate initially but over time return to pre-burn levels.

Binkley *et al.* (1992) found that, compared to the control treatment, nitrogen increased with 0.2 g kg^{-1} one year after burning, in the topsoil of the burnt treatment, and decreased with 0.2 g kg^{-1} two years following the burn treatment. These results refer to two different treatments - the first was only prescribed burned once whilst the second result was for a plot that had already been burned twice before it was sampled two years following the burn. One plot that had already been burned 4 times were measured one year following the fourth burn and showed a 0.3 g kg^{-1} increase in N in the soil. A similar result was obtained for a plot that was burned three times and measured three years following the third burn. They concluded that no real negative or positive impacts in the soil chemistry of the topsoil could be found after a 30 years of burning treatment. Another study showed no significant differences between inorganic nitrogen concentrations from 1-7 years following the burn (Hatten *et al.,* 2012). Following prescribed burning, Weston and Attiwill (1990) found inorganic nitrogen to return to pre-burn levels 16 months following the application (Certini, 2005). Binkley *et al.* (1992) found moderate decreases in P activity in soils sampled 1-3 years after the last prescribed burn whilst Hatten *et al.* (2012) found higher P availability that lasted for 2 years after the burning application - the result of increased soil pH according to them.

2.4 Tree Damage

Trees are damaged by fire through needle scorch, cambium damage, root damage and secondary damage such as insects and diseases as *Rhizina undulata* (De Ronde *et al.,* 1986; De Ronde *et al.,* 2004; Scott, 2001) Studies regarding tree damage focus mainly on plant meristems as it is responsible for regrowth of damaged plants. There are two types of meristems usually found in plants, apical meristems and lateral meristems. Apical meristems are found in the buds of plants and controls branches, buds, foliage, cones and flower production. Lateral meristems on the other hand are found in the cambium and are responsible for xylem and phloem production. The lethal temperature for cell death (heat-induced necrosis) is assumed to be 60 °C but length of time of heat exposure also plays a big role in cell death of plants (Michaletz & Johnson, 2007).

Tree damage is influenced by a number of different factors such as species, age, site, tree height and fire intensity (De Ronde, 1982). Brown and Davis (1973) listed nine factors influencing stand damage. All of them can be grouped into the factors mentioned by De Ronde in 1982. The nine factors are:

1. The initial temperature of the vegetation, as low temperatures of the vegetation will require higher temperatures to achieve the lethal plant cell temperatures. This can be controlled by selecting certain days and time of the day for burning.

2. The size and morphology of the critical tree portion exposed, as young trees, leaves, small branches and buds are highly susceptible to fire damage.

3. The thickness and character of the bark is one of the most important factors protecting trees from fire. The insulating capacity of the bark is determined by the structure, composition, density, moisture content and thickness of the specific tree bark.

4. Branching and growth habit also play a role as some trees such, as certain *eucalyptus* species, self-prune, thereby naturally developing open crowns free of fuels thus decreasing fire intensity at the stem.

5. The rooting of trees determines how easily it is damaged by fires. Roots are very susceptible to fire and therefore species with shallow root systems will easily be damaged especially in smouldering fires.

6. The FF plays a significant role in root damage as thick FF's will protect shallow roots if only partly consumed.

7. The flammability of foliage determines tree damage - conifers are considered relative highly flammable due to turpentine containing resin.

The last two factors listed by Brown and Davis (1973) are stand habitat and season and growth cycle.

8. Stands with very dense undergrowth have a higher risk of fire damage compared to open clear stands.

9. The season and growth cycle determines the moisture content of crowns and consequently flammability.

The recovery of trees is determined by the resources available. This fluctuates between seasons, as succulent growth is more susceptible to fire damage.

2.4.1 Stem Damage

Bark thickness plays a vital role in protecting the cambium from fire damage. Cambium is highly susceptible to heat damage with 60 °C being considered as the lethal temperature for living plant tissue (Odhiambo *et al.,* 2014; Michaletz & Johnson, 2007). Bark thickness is usually directly related to age with the thickest bark occurring at the bottom of the tree (De Ronde, 1988; Michaletz & Johnson, 2007; Marshall *et al.,* 2008). Bark thickness is also important in bud protection. Thicker bark usually protects the buds better than thin bark and consequently also the resprouting ability (Chandler *et al.,* 1983). Trees react differently to cambium damage. When cambium damage occurs around the whole tree stem, phloem damage will also occur, as phloem is external to cambium. This will result in death of trees as the canopy will continue to fix carbon and grow without the ability to move the photosynthate down to the roots. The root system will be able to survive for some time until the carbohydrate reserve is depleted which will result in tree death due to water stress. When fire damage does not occur around the whole tree stem, trees will recover, leaving a fire scar. Fire scars usually occur in windy conditions on the leeward side of trees. It is assumed that vortices develop on the leeward side, pulling the fire in, and thus causing stagnant hot areas. This increases the heating duration as well as the flame temperature and results in stem damage. Larger stems will experience more damage as the vortice effect increases with tree diameter. Small trees do not alter the flow of wind enough to cause vortice formation and any significant stem damage (Michaletz & Johnson, 2007). When *P. elliottii* has a bark thickness of 15 mm or more it can be assumed that negligible cambium damage will occur during controlled burning operations. Different pine species have different fire resistance capabilities. A study by De Ronde (1982) showed that *P. elliottii* can withstand a heat source of 600 °C for two minutes in comparison with *P. pinaster* and *P. radiata* which could only withstand 400 °C for one minute before cambium damage occurred in a 12 mm thick bark.

2.4.2 Crown Damage

Crown damage is usually determined by the amount of needles scorched, as measured 2 – 3 weeks after a fire event and is considered the main indicator of tree death. If scorched needles are still present on tree branches some period after the burning event it can be considered an indication of branch death (De Ronde *et al.,* 1990; Marshall *et al.,* 2008). Crown scorch results in higher needle fall rates and may partially counter the initial aim of fuel load reduction. A study by De Ronde (1983) recorded needle fall rates of 3.7 t ha^{-1} in pine plantations after severe crown scorching, during the first month following the application. This value is the same as the average needle fall mass per hectare per year (Dames *et al.,* 1998; Morris, 1986). De Ronde (1983) found no significant change in the growth rate two years following under-canopy burning of commercial pine stands where crown scorch was absent or confined to the lowest branches of the trees. In controlled burning operations cambium damage is rarely observed and crown scorch is the main factor for causing tree death following a fire. The height of scorch can be roughly determined by multiplying the flame length by six (De Ronde *et al.,* 2004). The tree crown also has an effect on the height of scorch as the crown character serves as a shield, reducing convection rates to the crown canopy (Michaletz & Johnson, 2007). If more than 20% of the crown canopy is consumed during a fire, survival amongst these trees is usually very low (De Ronde *et al.,* 1990). In stands where no live needle consumption occurred, a small increase in growth may occur during the first growth season after the fire. This is only valid if no root damage occurred, in which case a small decrease in growth is most likely in a stand subjected to 0-33% crown scorch. If 34 – 66% crown scorch occurs, a volume growth loss of less than 40% can be expected during the first year after the fire. In stands subjected to 67 – 100% crown scorch, tree mortality and growth reductions where one year's growth is spread out over three years may occur (Wade & Lunsford, 1989 cited in De Ronde *et al.,* 1990).

2.4.3 Root Damage

Root damage caused by fire occurs through the conduction of heat into the root tip which can lead to tree stress, reduced growth, secondary damage and ultimately tree death (Michaletz & Johnson, 2007; Scott, 2001; Sacket & Haase, 1998; Marshall *et al.,* 2008). Heat is transferred from the flame to the soil, through the soil and from the soil to the root. Studies have tried to determine root damage by using models to determine the soil depth to which the lethal temperature of 60 °C penetrates. The lethal temperature for roots differ greatly due to the smouldering effect, which can expose roots to higher temperatures for longer periods and in this way ultimately damaging roots at a lower temperature. Thick roots are better protected from heat damage than small roots as heat conduction through the small roots is slower and more difficult (Michaletz & Johnson, 2007).

Root damage caused by fires is commonly determined by the carbohydrate status of roots (Varner *et al.,* 2009). A study by Varner *et al.* (2009) indicated a reduction in coarse root carbohydrate concentration after a smouldering fire. They also observed that the heating duration of the duff and mineral soil layer caused no change in carbohydrate concentration in fine roots. Trees use carbohydrate reserves to replenish fine roots damaged and killed by fire thus depleting carbohydrates to the expense of the tree, which causes stress that can lead to secondary damage and death (Varner *et al.,* 2009). Tree injury as a result of under-canopy burning usually increases from spring to autumn in summer rainfall areas due to lower fuel moisture content and increasing FF mass which increase the smouldering duration and forms an ash insolating layer which keeps the heat trapped against the soil (Varner *et al.,* 2009; Sackett & Haase, 1998).

2.5 Stand Response

There is some controversy regarding tree response following under-canopy burning (De Ronde *et al.,* 1990). Some studies found no significant difference in growth after under-canopy burning of low intensity (Reinhardt & Ryan, 1988; De Ronde, 1988; Bird & Scholes, 2005). In a specific study by Reinhardt & Ryan (1988), they found radial growth of Western Larch in the burn treatments surpassed that of unburn treatments from the second to the end of the seven year study period. A study conducted in thinned *P. ponderosa* forests in Central Oregon showed significant but small volume and basal area decrease in low-intensity under-canopy burned areas in comparison to unburned areas during a 6 year monitoring period (Busse *et al.,* 2000). They found that loss in growth was due to crown scorching, O-horizon reduction and site productivity. In sites with higher productivity the decrease in growth was more prominent. They concluded that low intensity under-canopy burning has a minor effect on tree growth for *P. ponderosa* in thinned stands.

A study on *P. patula* in Mpumalanga, South Africa, regarding the effect of different fire intensities on tree growth, showed low intensity under-canopy burning has minor negative effects on height and diameter growth. The study concluded that low-intensity under-canopy burning achieved sufficient fuel reduction and recommended that this practice should be expanded to operational scale (Bird & Scholes, 2005). Pine species differ in needle morphology and this plays a big role in their resistance to fire. Resprouting only occurs when foliage dies, stimulating the buds to produce new sprouts. *Pinus elliottii* is considered one of the most fire resistant pine species and has been found to resprout after 100% crown scorch (De Ronde, 1988). *Pinus elliottii* has a high resistance to cambium damage, survives complete crown scorch easily and has a very good resprouting ability. *Pinus patula* on the other hand has a lower resistance to cambium damage but fortunately cambium damage is usually restricted to wild fires. The ability of species to survive after complete crown scorching is variable depending on fire intensity and resistance time. The resprouting ability of *Pinus patula* is dependent on stress levels and season, and ranges from no resprouting to excellent resprouting following a fire (De Ronde, 2007).

2.5.1 Leaf Area Index

Leaf Area Index (LAI) is the area of projected foliage measured in square meters of foliage per square meter of ground area. Leaf densities play a fundamental role in the regulation of light interception, carbon uptake and transpiration (McDowell *et al.,* 2007). Under-canopy burning may result in some degree of crown scorch which reduces light interception of tree stands, as has been found by De Ronde (1983). This may cause higher stress levels in trees and decrease the photosynthesis surface area, reducing growth and stimulating understorey growth as a result of increased light penetration (De Ronde, 1988; 2007; Fecko *et al.,* 2008). There are few studies available regarding LAI changes following under-canopy prescribed burning. One study in America investigated the understorey response in mixed forests after a burning application, by measuring LAI nine years following a wild fire (Turner *et al.,* 2004). Other studies used LAI measures to determine the effect of various growth and silviculture activities on light penetration (Gonzalez-Benecke *et al.,* 2012; McDowell *et al.,* 2007).

2.6 Understorey Weed Growth

Weed growth is usually suppressed by plantation trees when canopy closure occurs. Certain weed species, however, sometimes survive and continue to grow underneath plantation trees. The understorey has a direct impact on fire behaviour by providing additional fuel, such as ladder fuels, which acts as a medium for the fire to spread into the tree canopy. Weeds can be comprised of either previous rotational commercial species, exotic species, such as lantana, acacia species or indigenous species such as ferns etc. Certain species may have a seed bed in the soil and depending on the fire intensity, the fire may or may not stimulate germination. Low intensity fires will only consume part of the FF, which will leave the weed seedbed unaffected and regeneration following the fire application will therefore be less and usually patchy (De Ronde *et al.,* 2004). Prescribed burning could be used to stimulate regeneration and improve re-sprouting of shade-tolerant indigenous species or for suppressing certain species such as lantana which is a big problem under pine plantations in Mpumalanga (De Ronde *et al.,* 2004, personal observation, 2013).

2.6.1 Different Burning Strategies

Unfavourable plant species can be controlled through prescribed burning by depletion of their reproductive structures. Plant species have different survival strategies adapted to survive in their natural environment. These differences in plant communities usually require more than a single burn, together with other control methods such as mechanical, cultural, biological and chemical methods, in a long-term management strategy to effectively control undesired weed growth. Certain weeds, such as woody species, are not controlled effectively by fire as some of them can re-sprout from the stem. Annual species should be burned before seeds are matured or dispersed. Certain weed species may have seed beds which will require consecutive burns to deplete the seed bed (Ditomaso *et al.,* 2006). Other species, such as rhizomes, have underground organs that re-sprout after fires, whilst herbaceous species with protected meristems, require a higher intensity fire to kill the plant (Ditomaso *et al.,* 2006; Chandler *et al.,* 1983).

Other management practises, such as thinning can have an impact on understorey response as more light is available for the species. Thinning combined with prescribed burning has been studied together to determine the combined effect of this application on understorey vegetation (Phillips & Waldrop, 2008; Huffman *et al.,* 2013). In these two studies, thinning combined with prescribed burning, increased understorey vegetation. The study by Phillips & Waldrop (2008) found that thinning and burning favoured shrub and graminoid growth, while only burning favoured forb growth. Herbicide combined with fire is also a management strategy used to combat weed infestation (Iglay *et al.,* 2010).

2.6.2 Effect on Plant Structure and Densities

The effect of under-canopy burning on unfavourable plant communities is inconsistent in the literature with some studies recording a decrease and others finding an increase or no significant effect. The specific species and conditions under which the burning is conducted will play a major role in the outcome as will be briefly discussed. A study by De Ronde (1988) in Tsitsikamma on the effect under-canopy burning on weed response has shown a variation between different weed types. He concluded that indigenous trees and shrubs decreased drastically, restioids generally decreased and herbs exhibited an irregular response following a burning application. Grass species increased following a fire due to crown scorching allowing higher light penetration which resulted in increased grass production. It was also noted that more than one burning application did not have a significant effect on understorey vegetation. *Acacia* weeds usually increase following a fire, whilst ferns, such as *Gleichenia,* are effectively decreased after a fire (De Ronde, 2007). The structure of the understorey species is also important to consider as this will influence tree damage. A blanket of understorey growth would be of low risk if the species is short stemmed but even a few long stemmed species will act as ladder fuels increasing tree, specifically crown damage. Removing ladder fuels before under-canopy burning commences is very important to ensure consistent burning in a controlled environment.

Studies in Northern Portugal showed forb and grass cover increased during the first years following prescribed fire, after which re-sprouting shrubs began to dominate the area (Rego *et al.,* 1990; Iglay *et al.,* 2014). Shrubs increase linearly from time burnt whilst herbaceous species reached a maximum development at three years following the burn (Moreira *et al.,* 2003). It was found that prescribed fire had no significant effect on species diversity with most species recovering to pre-burn densities within 6 months following the burning application (Rego *et al.,* 1991).

A study in Central Oregon, following a low intensity under-canopy burn, showed shrub cover was reduced and remained less than pre-burn levels for 6 years following the application. Herbaceous cover remained the same before and after burning with a slight increase in species diversity (Busse *et al.,* 2000).

Another study in the USA on the effect of prescribed burning on invasive plant communities showed that weeds increased following a prescribed burn. These increases were highly dependent on species abundance before the burning application and led to the proposal of two strategies to control these weeds:

1. By reducing the initial weed population before the burning application the weed response following the burning application, should be less, as a strong correlation was found in weed populations before and after a burning application.

2. Fire severity also played a role in weed growth following a prescribed burning application leading to their second strategy of controlling fire severity (Symstad *et al.,* 2014).

3. Research Methodology

3.1 Study Area

The study area is situated in the north-eastern parts of Mpumalanga, South Africa. The province is divided by the Drakensberg escarpment. On the western side of the Drakensberg escarpment the area is known as the Highveld and on the eastern side the Lowveld. The Highveld is predominantly grassland with altitudes above 1700 m. This high altitude results in cooler temperatures than the Lowveld with frost occurring on a regular basis. The Lowveld has lower altitude, higher temperatures and consists predominantly of bushveld. Frost is not a regular occurrence and the area is subtropical due to the latitude and the warm Indian Ocean adjoining Mpumalanga on the eastern side. The Drakensberg escarpment, with its steep, broken and rocky topography, receives a high annual rainfall, is less suitable for agricultural activities but conditions are ideal for forestry. The area around the town of Sabie is known for its forest industry and is one of the largest afforested areas in South Africa. The research trials of this specific study are all situated on the eastern side of the Drakensberg escarpment at different altitudes.

All research was conducted inside the forests of Komatieland Forests (Pty) Ltd. The research trials are spread out over four different plantations namely Blyde, Witklip, Berlin and Nelshoogte (Figure 3.1).

Figure 3.1: Map indicating the position of the general study area and the location of all 5 trials in the province of Mpumalanga, South Africa.

3.2 Experimental layout and Trial site information

Our aim was to create a chronosequence of treatments at each location that was (a) unburnt, (b) burnt once and (c) burnt twice, the latter two treatments both making use of under-canopy fires. To achieve this goal, we selected compartments that had been unburnt for the last rotation, preferably adjacent to compartments that had received a prescribed burn in the form of an under-canopy fire. We could then implement a second prescribed burn in demarcated sub-sections of the once burnt compartment to create the twice burnt treatment. The sequence of unburnt, once burnt and twice burnt plots were replicated three times on each site. Typically, we aimed to place each replicated sequence on a slightly different topographical position in the compartment, e.g. crest, upper midslope, lower midslope. This was done to avoid pseudoreplication. The actual implementation of this design was met with some practical difficulties, due to the widespread under-canopy burning that had already been done in this region. It meant that some adjustments had to be made to the design, as described in the section that follows.

A nested experimental design was used according to which study results for different species from different altitudes receiving exactly the same treatment are compared. The research experiment was designed to compare under-canopy burned sites, burnt once and twice respectively, with unburned sites which are otherwise similar in all aspects. The following factors were compared with trials and treatments:

- Forest floor mass & nutrients
- Litterfall rate
- Foliar litter nutrients
- Soil nutrients
- Understorey growth
- Tree growth
- Tree Damage

All trial names refer to the specific plantation in which it is situated with Witklip additionally having the species added to its name due to multiple trials occurring in the same plantation.

Control plots refer to plots receiving no form of fire within the specific rotation whilst burnt plots received a representative under-canopy burn once or twice previously. All trial sites were planted between 1987 and 1995 with site indices (SI_{20}; measured in metres) around the mid-twenties (Table 3.1). The number of trees per hectare ranged from 220 – 290 and was calculated for each plot and averaged per treatment. Berlin and Nelshoogte are the only trials for which an unburnt control treatment could be demarcated in a compartment situated immediately adjacent to the burnt compartment. This meant that, after treatment implementation we could compare unburnt plots with once and twice burnt plots (see treatment details in Section 3.5 below). For the remaining trials (Blyde, Witklip *P. patula* and Witklip *P. elliottii*), control plots on similar terrain positions with similar stand characteristics could not be found on adjacent compartments, simply because all adjacent sites had been subjected to some form of burning in the last 10 years. For these trials, we positioned unburnt control plots on non-adjacent sites, but as we started with detailed sampling, it became apparent that the plot differences were partly location-related and not just treatment related. This meant that we had to abandon these unburnt controls and limit ourselves to a comparison between once burnt and twice burnt compartments on these three sites. All trials were subjected to a first thinning comprised of selective thinning combined with a 7th row thinning, followed by a second and in some cases a third thinning. Pruning heights varied between 7 and 9.5 m and all trials had an initial spacing of 2.7 x 2.7 m except for Blyde which had a spacing of 3.5 x 3.5 meters.

Table 3.1: Relevant compartment data for all five trials in the study.

Trial	Plot	Compt	Planting Date	SI_{20}	TPH	Soil	Dom Slope	Altitude (m)
Berlin	Control	M31	1995	23.1	225	Inanda	0-30	1659
	Burnt	M29	1995	23.2	221	Kranskop		1656

Blyde	Burnt	A87	1995	27.4	288	Hutton	0-30	1414
Nels	Control	E38	1989	24.9	256	Inanda	0-30	1408
	Burnt	E28a	1990	25.7	276	Inanda		1407
Witklip P. ell	Burnt	B67	1987	22.2	251	Hutton	0-30	1072
Witklip P. pat	Burnt	M33a	1992	24.1	264	Hutton	0-30	1059

**P. ell & P. pat: Pinus elliottii and Pinus patula respectively.*

The experimental sites were selected from compartments that are situated at low, medium and high altitude sites along the Mpumalanga escarpment (Table 3.2).

Table 3.2: Research trials with the corresponding altitude and species.

Altitude (m)	Species	
	Pinus elliottii	*Pinus patula*
1000	Witklip	Witklip
1400	Blyde	Nelshoogte
1600	X	Berlin

X: No trial could be found for the required site conditions.

3.2.1 Plot Layout

The trials were divided into two compartments each, representing burnt and unburnt sites. Three plots representing control treatments were laid out in the unburnt compartment and six plots were laid out in the burned compartment. Three of these once-burnt plots were burned a second time under ideal conditions (Table 3.3). Each treatment was replicated three times meaning that each trial consists of nine research plots. The control plots are as close as possible to the burned compartment to ensure that the compartments are fully comparable. Poles with painted heads were used on the four plot boundaries and each tree inside the plots was numbered for identification and additionally marked at 1.3 m for DBH measurements.

3.2.2 Plot size

The plot size for each research plot was determined on site after considering all contributing factors. The plots were all in the region of a 1000 m^2 varying between 900 – 1200 m^2 which insured that the plots were big enough to acquire accurate data from it, but also small enough to implement treatment with relative ease and to fit into the compartment on the same terrain position as the other treatment plots in that sequence. In areas with no restrictions on area availability the plots were laid out in a rectangular form of 30 x 40 meters thus containing an area of 1200 m^2. In Berlin plantation one of the replications measured 50 x 20 m due to limited area.

3.2.3 Trials

The Witklip and Blyde plantations comprise of *Pinus elliottii* trials with the Witklip plantation also having an additional *Pinus patula* trial (Table 3.2). Witklip plantation has the lowest altitude and Berlin the highest altitude. Berlin and Nelshoogte comprise of *P. patula* trials but unfortunately no suitable, high altitude *P. elliottii* trial could be found for this study.

3.2.3.1 Berlin

Trial Berlin was planted in 1995 and has a current age of 20 years (Figure 3.2; Table 3.1). The trial is situated at a 1650 m above sea level. The compartment received its final selective thinning during 2007 which was the same year in which under-canopy burning occurred. The control compartment received four pruning lifts to 8.5 m and the burnt compartment received five lifts to 9.5 m, with pruning operations ending in 2006 and 2005 respectively. The soil has a dolomite parent material and a dominant slope class varying from 20 – 35%.

Figure 3.2: Trial Berlin with corresponding coordinates located near the town of Kaapsche Hoop (above right).

3.2.3.2 Blyde

Trial Blyde was planted with *Pinus elliottii* in 1996 and has a current age of 19 years (Table 3.1). The trial is situated at 1400 m above sea level with a SI_{20} of 27.4 (Figure 3.3). The compartment received two thinning’s with the final selective thinning occurring during 2013. The compartment was under-canopy burnt during 2007 and the burning was of relatively high intensity according the plantation manager. The compartment received seven pruning lifts to 9.5m, ending in 2007. The soil is derived from dolomite and has a dominant slope class varying from 0-12%. The compartment has been subjected to some degree of baboon damage.

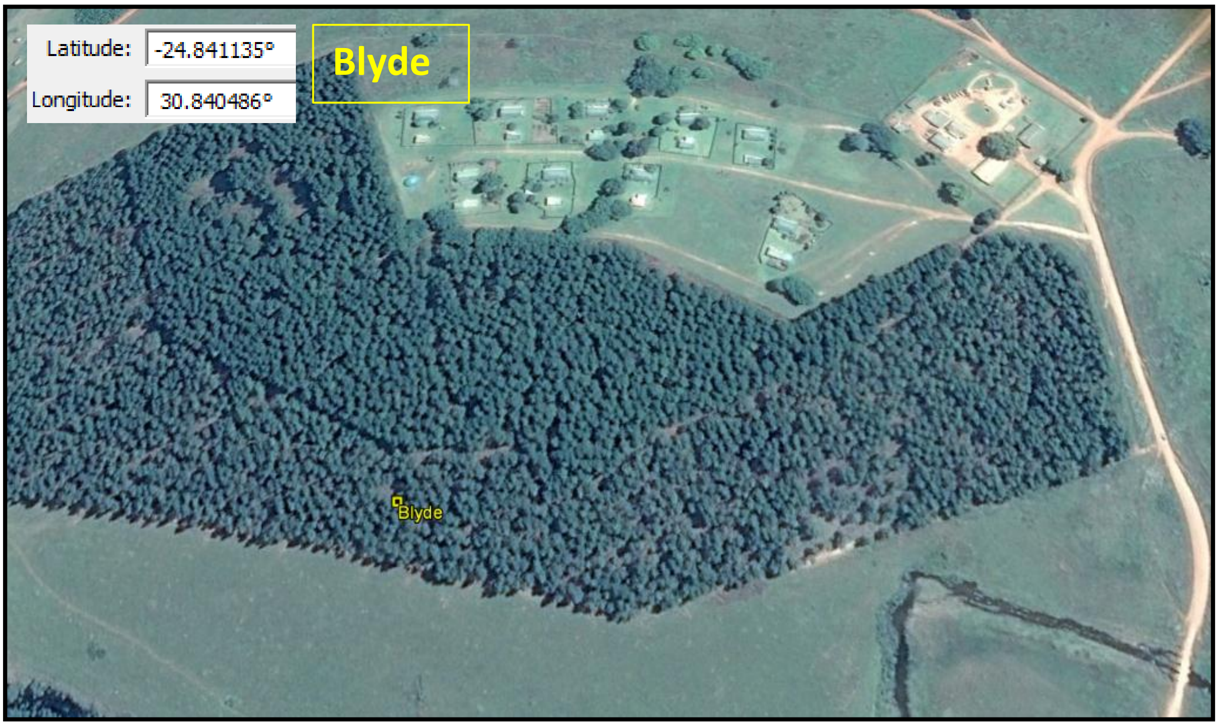

Figure 3.3: Trial Blyde with corresponding coordinates located near Graskop.

3.2.3.3 Nelshoogte

The control and burnt trials in Nelshoogte were planted with *Pinus patula* in 1989 and 1990 respectively (Table 3.1). The control and burnt trials have a current age of 26 and 25 years, respectively and are situated at 1400 m above sea level (Figure 3.4). The control and burnt compartments have a SI_{20} of 25.6 and 26.2, respectively. The compartments received three thinning's with the final selective thinning occurring during 2006 and 2007 in the control and burnt compartments respectively. The latter compartment received under-canopy burning in the same year. Both compartments received four pruning lifts to seven meters, ending in 2001. The soil is derived from granite and the dominant slope class varies from 12-20%.

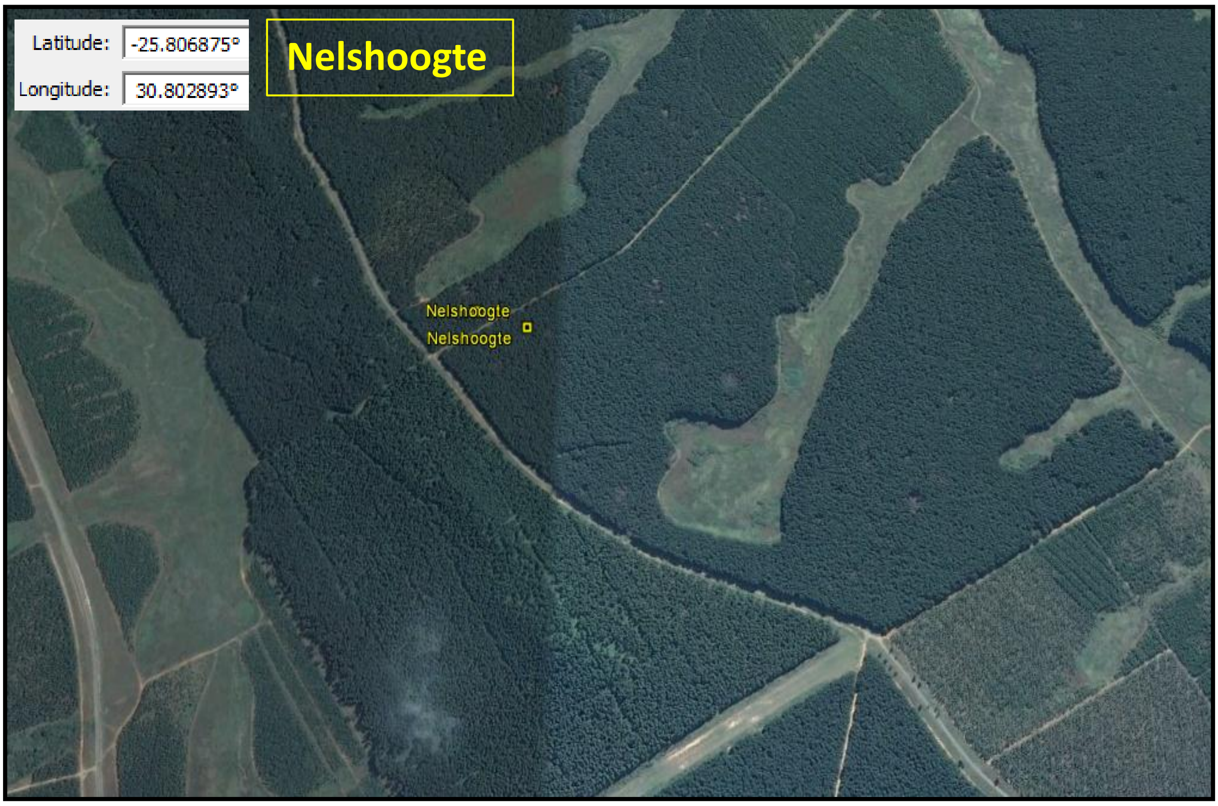

Figure 3.4: Trial Nelshoogte with corresponding coordinates located between Barberton and Carolina.

3.2.3.4 Witklip P. elliottii

Trial Witklip *P. elliottii* was planted with *Pinus elliottii* in 1987 and has a current age of 28 years (Table 3.1). The trial is situated at 1070 m above sea level with a SI_{20} of 22.2 (Figure 3.5). The compartment was subjected to three thinning's and received its final selective thinning during 2005 – it was under-canopy burnt during 2006. The compartment received three pruning lifts to a maximum of seven meters, ending in 1999. The soil is derived from granite and has a dominant slope class varying from 0-12%. The compartment has been subjected to some degree of baboon damage.

Figure 3.5: Trial Witklip *P. elliottii* with corresponding coordinates located near Witrivier.

3.2.3.5 Witklip P. patula

Trial Witklip *P. patula* was planted with *Pinus patula* in 1992 and has a current age of 23 years (Table 3.1). The trial is situated at 1060 m above sea level with a SI_{20} of 24.1 (Figure 3.6). The compartment was subjected to two thinning's, receiving the final selective thinning during 2006 - the compartment was under-canopy burnt during the same year. The compartment received 5 pruning lifts to a maximum height of 8.5 m in 2004. The compartment is situated on a granite geological formation and has a dominant slope class varying from 0-12%.

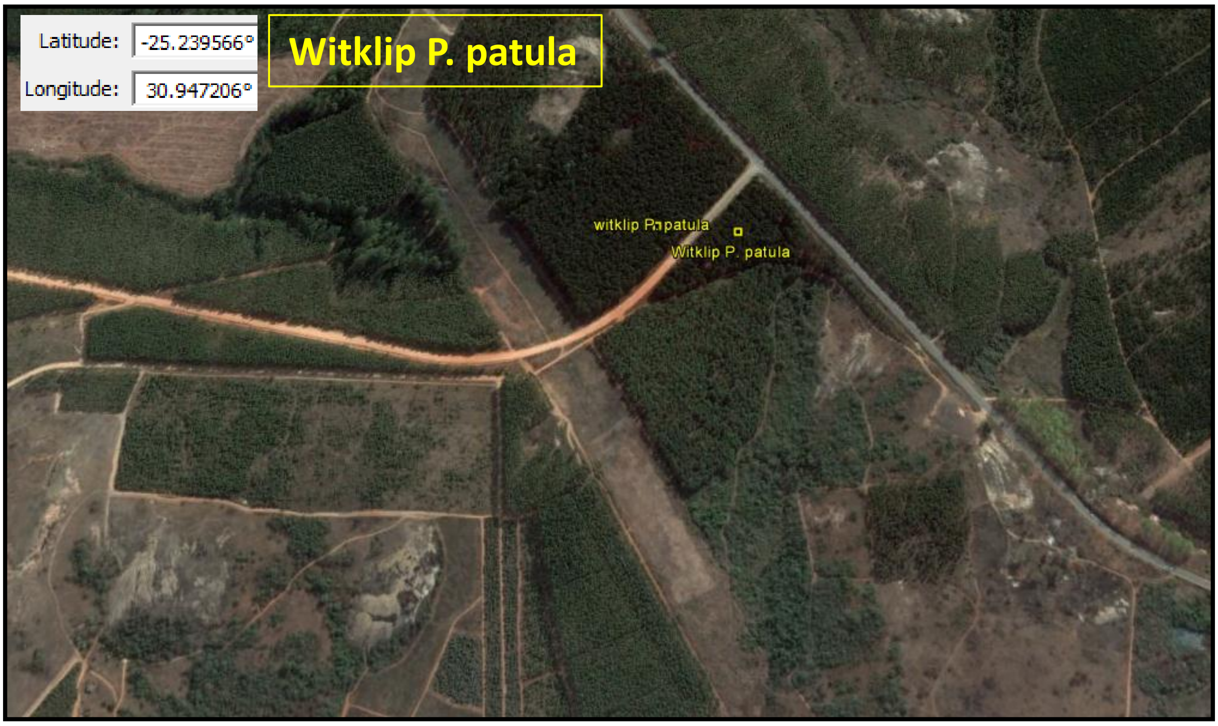

Figure 3.6: Trial Witklip *P. patula* with corresponding coordinates located near Witrivier.

3.3 Climate

Monthly mean daily temperature, humidity and rainfall figures were used to describe the climatic conditions for each trial. Gridded weather data of Schulze *et al. (*2007) was used to obtain accurate predicted weather data for each specific trial site. Mean monthly weather data was generated for each trial location except for the Witklip trials for which data was combined.

3.3.1 Temperature

The highest monthly mean temperatures for all trials occur during January and February and the coldest during June and July (Figure 3.7). Trial Witklip (with lowest altitude) has the highest mean annual mean temperature of 17.3 °C (highest monthly mean of 21 °C – Figure 3.7) and Berlin the lowest (14.8 °C) being 0.7 °C cooler than

Nelshoogte (15.4 °C). Blyde has an average annual temperature of 15.9 °C. Mean annual temperatures are highest in the low altitudes and lowest in the high altitudes.

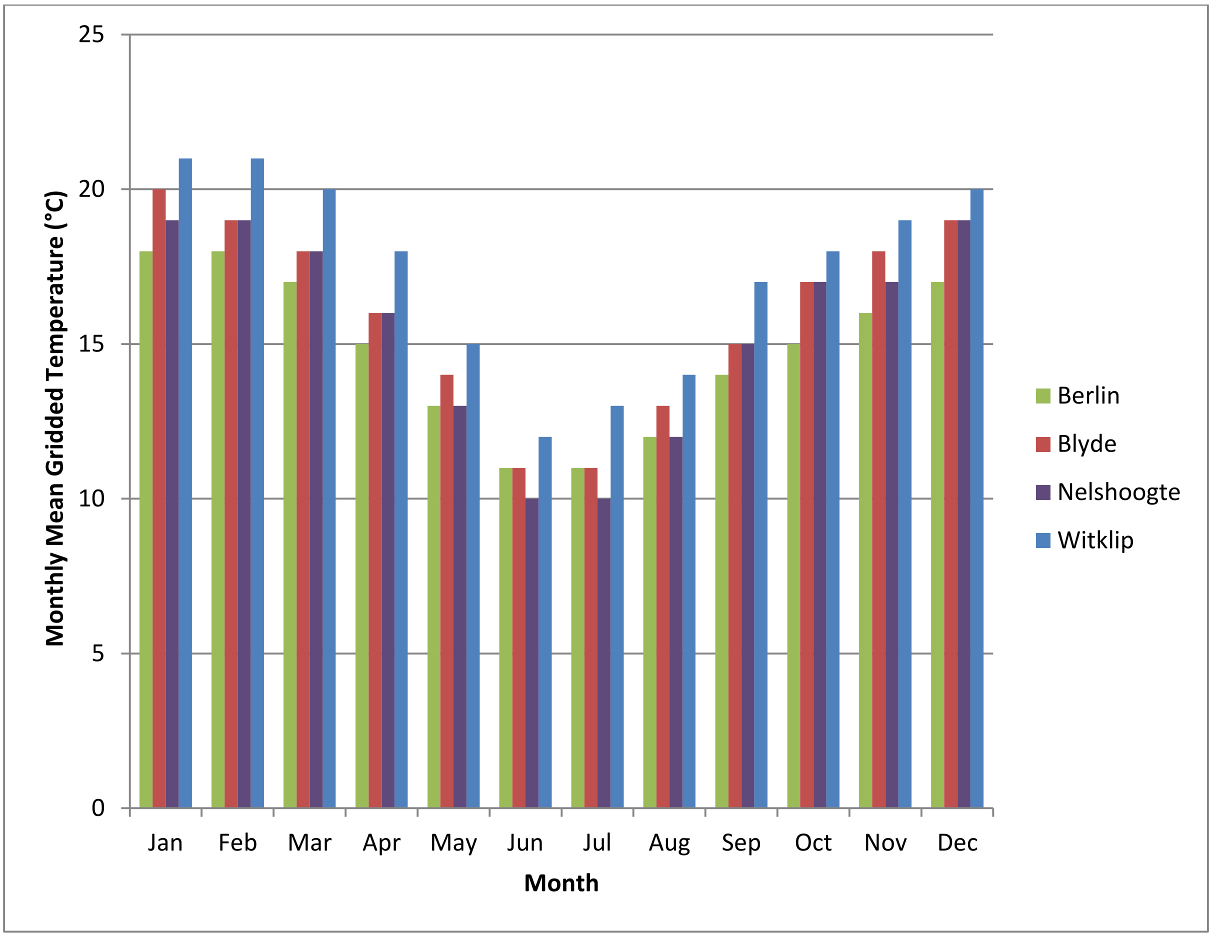

Figure 3.7: The monthly mean gridded temperature data for all trial locations.

3.3.2 Humidity

The estimated humidity for each month is shown in Figure 3.8. The highest monthly mean humidity occurs during January and February and the lowest in July and August (Figure 3.8). The models used by Schulze (1997) predict a much higher humidity percentage for trial Berlin during the winter months in comparison to the rest of the trials. The reason for this is not entirely clear but may be due to the cooler MAT and/or the orographic effect of cooling air currents and subsequent increases in relative humidity at the site. Berlin has the highest mean annual humidity of 69% (highest monthly mean of 72%) with both trials Blyde and Nelshoogte having a mean annual humidity of 66%. Trial Witklip has an annual mean humidity of 67%.

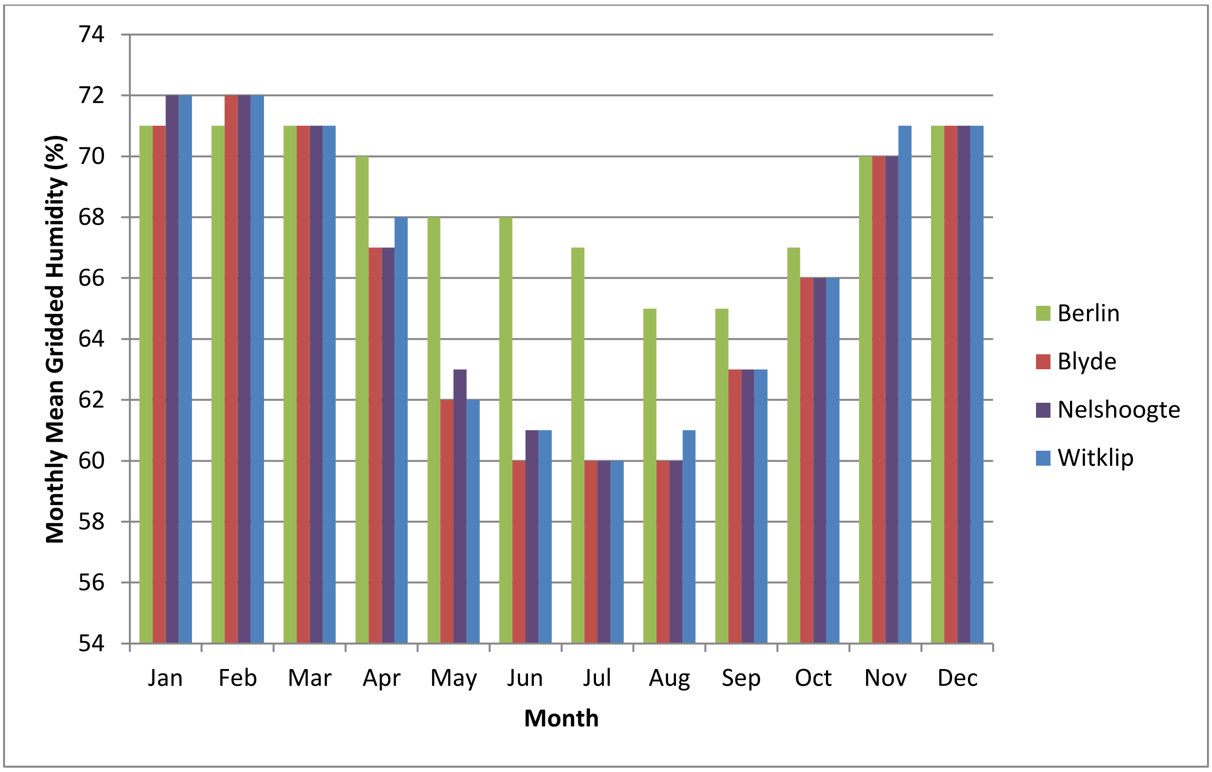

Figure 3.8: The monthly mean gridded humidity data for all trial locations.

3.3.3 Rainfall

The highest mean monthly rainfall for Blyde and Berlin occurs during January and February and during December and January for Nelshoogte and Witklip. The lowest rainfall occurs during the winter months of June to August (Figure 3.9). Rainfall varies considerably between summer and winter with summer months receiving a combined average monthly rainfall of 180 mm in comparison with 14 mm during the winter. Trial Blyde receives the highest annual rainfall of 1200 mm (highest mean monthly rainfall of 235 mm) and Witklip the lowest at 920 mm. Trial Berlin and Nelshoogte receives 1140 and 940 mm of annual precipitation, respectively.

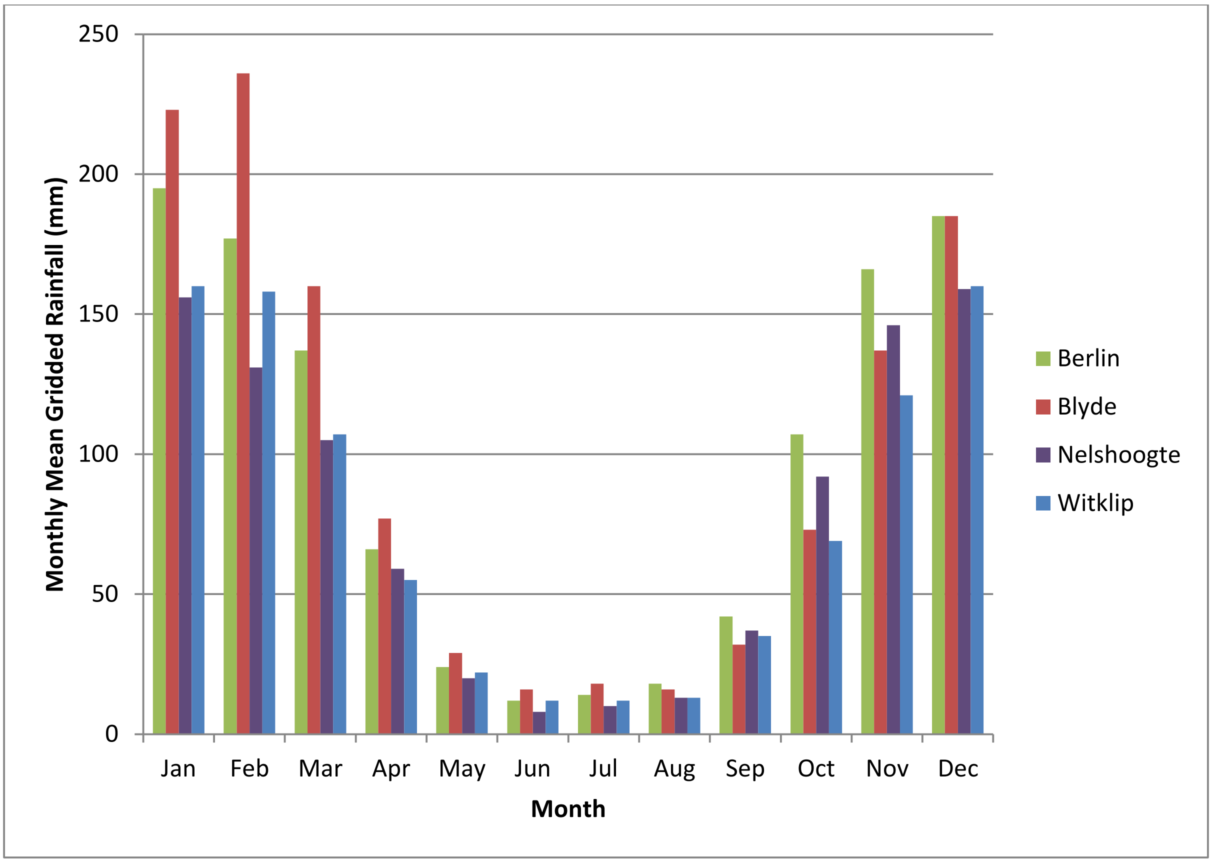

Figure 3.9: The monthly mean gridded rainfall data for all trial locations.

3.4 Selection Process

3.4.1 Altitude

FF accumulation increases with altitude due to decreasing microbial activity (Ross, 2004). Dependent on the availability of suitable areas, three areas from different altitudes were chosen representing low, medium and high altitude environments for each species.

3.4.2 Soil

The dominant soil formations occurring in the escarpment region is Hutton (57%), Oakleaf (13%) and Glenrosa (10%), (Schutz, 1990). Hutton form has an orthic A-horizon followed by a red apedal B-horizon. Oakleaf form is characterized by an orthic A-horizon followed by a neocutanic B-horizon. These two soil forms have many similarities between the A and B-horizons with the main difference being the slightly more structured B-horizon of the Oakleaf form. The Glenrosa form, on the other hand, differs a lot more from both the Hutton and Oakleaf form and consists of an orthic A-horizon followed by a lithocutanic B-horizon. The B-horizon gradually transforms to weathered rock (Soil Classification Working Group, 1991). The Hutton soil form is regarded as being the most representative of the study area.

3.4.3 Species

The two major species planted in the study area is *Pinus patula* and *Pinus elliottii* and were therefore chosen for the study. The two species *P. patula* and *P. elliottii* show marked differences in their specific leaf morphology - *Pinus patula* has very long thin needles whilst *P. elliottii* has shorter, thick needles. This difference affects the FF formations of the two species.

3.4.4 Age

A semi-mature age of 20 - 25 years was chosen across trial sites to ensure uniformity and to avoid complications from silvicultural regimes such as thinning, pruning, slash management at younger ages, and harvesting at year 28.

3.5 Sampling Techniques

The following sampling techniques were used during data collection for this study.

3.5.1 Fire Breaks

Fire breaks were constructed around each plot being burnt. The fire breaks consisted of a strip between one and two meters in width in which all vegetation and flammable material was removed up to the mineral soil surface using rake hoes and slashers (Figure 3.10).

Figure 3.10: The construction of the fire breaks using rake hoes to remove all flammable material.

3.5.2 Under-canopy Burning

All first burns were carried out in 2006/2007 by KLF management. The second burning treatment at Blyde and Witklip trials was applied during February/March 2014 and the rest of the trials were burnt in May 2015 (Table 3.3). This was due to difficulties encountered in burning the higher altitude *P. patula* sites. The 2014 burning season was a very wet year and FF on some sites would not sustain a fire, despite repeated attempts to burn it. The average moisture content over all five trials was 25 and 54% in the L and duff layers respectively (Table 3.3). Temperatures were in the high twenties and wind speeds below 10 km/h during the individual burns. The relative humidity was above 50%, except for Berlin and Nelshoogte, which were very low at

35 and 26%, respectively (Table 3.3). Trial Berlin had a lot of ladder fuels reaching heights exceeding 4 meters and was therefore slashed a few months before under-canopy burning was successfully implemented.

Table 3.3: Under-canopy burn data presenting burn date, fuel moisture content and weather conditions on the day of burning.

Trial	Burn Date		FMC for second burns (%)		Mean Weather Conditions for second burns		
	Fist	Second	L	Duff*	Temp (°C)	Humidity (%)	Wind (Km/h)
Berlin	2007	May 2015	12	41	27	35	< 6
Blyde	2007	Feb 2014	32	63	27	52	< 6
Nels	2007	May 2015	11	35	26	26	< 7
Witklip P. ell	2006	Feb 2014	25	67	25	60	< 6
Witklip P. pat	2006	Feb 2014	45	62	26	58	< 6

** The Duff layer is a synonym for the combined F + H layers of the forest floor (Figure 2.1).*

3.5.2.1 Fuel Moisture Content

Forest floor samples were collected for each replication receiving a burn treatment on the day of burning. During sampling the litter layer was separated from the fermentation and humus layer, together representing the duff layer. These two samples per plot were weighed and oven-dried until constant mass was achieved using Equation 3.1 (Reeb & Milota, 1999).

Equation 3.1

$$\mathrm{MC} = \frac{Initial\ weight\ -\ Oven - dry\ weight}{Oven - dry\ weight} \times 100\%$$

3.5.2.2 Burning Technique

All under-canopy burns were initiated using drip torches. The point source ignition pattern (spot firing) was used to mimic aerial ignition. Every burn started with a back burn from the fire break followed with the spot or strip burn pattern (Figure 3.11 & 3.12). The point source ignition pattern makes use of many different ignition points that burn towards each other. Fire intensity is controlled by spreading the fires. In certain instances spot burning did not work and alternative methods such as strip-head fire was used – in this method a continuous line of fire is drawn from which the fire then spreads. This burning method is of higher intensity but was used where necessary in order to obtain a representative under-canopy burn as required for this study (Teie, 2009).

Figure 3.11: Point source ignition pattern used to implement the under-canopy burn in trial Blyde.

Figure 3.12: Strip-burn ignition pattern used to implement the under-canopy burn in trial Nelshoogte.

3.5.2.3 Safety Equipment

Only one research trial was burned per day as trial sites are spread out far apart (Figure 3.1). Before each burn a burning permit from the relevant fire protection association had to be acquired. Every under-canopy burn was accompanied by one fire truck, at least one *bakkie sakkie* (mobile fire tender) and three or four workers with knapsacks patrolling the fire breaks. After the completion of the burns the workers stayed on site for some time for mopping up purposes. This consisted of spraying any smouldering coals and spreading any fuels left after burning to avoid flare ups.

3.5.3 Soil

Soil nutrients were sampled using a Beater auger (Figure 3.13). Ten random samples per research plot were sampled, sampling only the top 10 cm of the soil. The FF was cleared away to the mineral soil surface for the use of the Beater auger. The 10 samples were then mixed together in order to get one representative bulked sample for the whole plot. The soil samples were sent to a commercial laboratory for soil nutrient analyses. Soil sampling was carried out during July 2014 except for the second burnt plots at Berlin and Nelshoogte which were sampled after the burn during July 2015.

Figure 3.13: Beater auger used for sampling of the top soil.

3.5.4 Forest Floor Sampling

Two FF samples per research plot were bulked together to obtain one representative sample for each plot. Sampling consisted of first clearing the FF around the sample point and then accurately sampling all the material inside the sample area down to the mineral soil surface. This approach was very important as collecting a larger area on top would influence the nutrient concentration of the sample. The two samples were placed in a brown paper bag and marked appropriately. The sample was thereafter oven dried at 70 °C until constant mass was achieved and placed in a sealed zip lock bag to avoid moisture uptake. Forest floor sampling was carried out during November 2014 except for the second burnt treatments in Berlin and Nelshoogte which was carried out in September 2015 after the burn treatment.

Dried FF samples from each of the three replications were mixed together on a clean table and milled using a lab scale Retch ZM 200 Mill. One combined FF sample for each trial was then sent to a commercial laboratory for nutrient analysis.

The nutrient concentrations were multiplied with the FF mass (see Section 3.6.5) of each trial treatment to acquire the amount of FF nutrients per hectare and then used to determine nutrient loss through biomass loss as a result of the under-canopy burning treatments.

3.5.5 FF Mass Determination

Depth measurements were used to calculate FF mass per hectare using species-specific depth mass regressions. A total of 20 depth readings were measured after the burning treatment (Figure 3.14). The 20 measurements were randomly sampled using a shovel to open the FF to the mineral soil. For consistency a small note book was placed on top of the FF to flatten down the needles on top. A ruler was then placed inside the cavity opened up with the spade and a measurement was taken from the top of the FF directly beneath the note book to the point where the mineral soil met the FF. The 20 depth measurements were averaged per research plot and then used in the corresponding species-specific regression to calculate average FF mass in tons per hectare. Forest floor depth measurements were carried out during July 2014 except for trials Berlin and Nelshoogte which were measured during July 2015.

Figure 3.14: Determining FF depth with a ruler after exposing the whole FF profile using a shovel.

Some trials burnt with an erratic pattern: flames consumed only a portion of FF between trees (as planned), but burnt right down to the mineral soil in a small area adjacent to tree stems. The area around each tree where complete FF consumption occurred as a result of smouldering in trials Berlin and Nelshoogte were calculated and averaged. The average area was multiplied by the number of trees in order to obtain the total area clear of FF. This area was then incorporated with the FF mass that had been predicted from depth measurements to determine the real FF mass. Additional needle fall that occurred after the burn was measured two months following burning and these results were added to the total FF mass.

The regression used in predicting FF mass for *P. patula* was developed by Ross & Du Toit (2004) in KwaZulu-Natal and Mpumalanga (Equation 3.1). The regression used for FF mass prediction in *P. elliottii* plantations was acquired from Komatieland Forests (Pty) Ltd (KLF); (Equation 3.2). An FF depth mass table used by KLF was used to calculate a regression used in this study to determine FF mass under *P. elliottii* (Appendix 1A).

P. patula

$$LM = 0.70(LD) - 8.71 \quad \text{Equation 3.1}$$

LM = Forest Floor mass (t ha^{-1}), LD = Forest floor depth (mm)

P. elliottii

$$LM = 0.3656(LD) + 1.545 \quad \text{Equation 3.2}$$

LM = Forest Floor Mass (t ha^{-1}), LD = Forest Floor Depth (mm)

(KLF, pers. comm., 2014).

3.5.6 Litterfall Rate

Litterfall was calculated by measuring litterfall per month using self-made littertraps (Figure 3.15). These littertraps were constructed using 50 x 60 cm rectangular wooden boxes fitted with 80% shade cloth (area of 0.3 m^2) to catch the pine needles and ensure drainage. The littertraps were fitted with wooden feet 50 cm long to provide a stable platform well above the ground.

Figure 3.15: Illustration of the littertraps built and used for this study to calculate monthly litterfall rates.

Littertraps were placed inside the second burnt and first burnt plots. For each of the two treatments three littertraps were placed inside one representative plot directly following the burning application. Littertraps were cleaned once a month and the litterfall collected in brown paper bags. The paper bags were oven dried at 70 °C until constant mass was achieved. All twigs, pine cones, branches and other non-needle debris were separated from the sample after which only the needles were weighed and placed in sealed zip lock bags to avoid moisture uptake. Litterfall rate was calculated upscaling the litterfall of each littertrap to one hectare and averaging the three littertraps for each treatment. Due to the delayed implementation of some trials, Blyde and Witklip *P. patula* has litterfall data for 17 months, Witklip *P. elliottii* 10 months and Berlin and Nelshoogte only 4 months.

3.5.7 Tree Damage

To determine the effect that prescribed burning has on stand health and stand condition, all trees within the plots were inspected for damage by determining crown scorch, cambium damage, root damage and tree mortality.

3.5.7.1 Tree Mortality

Tree mortality was measured by observation, i.e. counting dead trees in the burned area 3-4 months following the burning treatment. Certain pine species such as *P. elliottii* can resprout after receiving 100% needle scorch and therefore tree mortality was only determined at a later stage when enough time had gone by for resprouting to occur (De Ronde, 1986). Dead trees were defined as trees with 0% green needles after 3 months following the burning treatment.

3.5.7.2 Cambium Damage

Cambium damage was determined within a few days after burning by lifting the bark of trees suspected of suffering cambium damage on the lee side at the soil surface where the highest temperatures would have occurred (Michaletz & Johnson, 2007). Cambium damage was identified by determining the areas showing discoloration and resin on the stem (De Ronde *et al.,* 1986, De Ronde, 1982; Figure 3.16). Where cambium damage was suspected a small cambium sample was placed in a 1% tetrazolium/water solution (Figure 3.17). The cambium was considered alive if the solution became light pink (De Ronde, 1982; De Ronde *et al.,* 2004).

Figure 3.16: Resin visible on the tree stem one day after the burn treatment in Berlin.

Figure 3.17: Discoloration of the tetrazolium solution on the right hand side indicate that the cambium sample is still alive.

3.5.7.3 Crown Damage

Crown scorch was determined by observing the height, to which scorched needles occurred in the crown canopy and determining the number of trees with scorch inside each replication. The total percentage of crown scorch per plot was calculated by multiplying the midpoint of the average crown height percentage with the percentage of trees scorched per replication.

The crown scorching percentage was classified into the following categories:

- Low Damage (≤25% crown scorch)
- Medium Damage (>25% ≤ 50% crown scorch)
- High Damage (>50% ≤ 75% crown scorch)
- Very High (>75% crown scorch)

3.5.7.4 Root Damage

Root damage following the burning application was determined by identifying spots in the FF where the fire burnt down to the mineral soil (Figure 3.18). Roots which were burnt through were classified according to the following specific thickness classes:

- 2 – 10 mm = medium roots
- 10 – 25 mm = coarse roots
- > 25 mm = very coarse roots

Each tree was inspected for root damage by counting the number of medium to very coarse roots burnt through and then grouping the tree according to the appropriate damage class (Table 3.4). Debris was removed around the tree and every root larger than 2 mm was examined. Only roots burnt through were counted as damaged roots record variable severity of damage not useful for this kind of study (Figure 3.19).

Table 3.4: Root damage severity class description used for damage evaluation.

Damage Class	Description
0	Did not burn to mineral soil, no root damage
1	less than 4 medium roots burned off
2	4 or more medium burned off
3	2 or more coarse roots burned off*
4	1 or more very coarse root(s) burned off*

**Note that in classes 3 and 4, it is common for several medium roots to have burnt through in addition to the coarse roots.*

Figure 3.18: Smouldering effect consuming FF to the mineral soil around trees in trial Berlin.

Figure 3.19: Very coarse root burnt through during the burn treatment at Berlin.

3.5.8 Understorey Growth

Understorey vegetation was grouped according to species and area they inhabit (Figure 3.20). Understorey growth was recorded in October 2014 and April 2015 when enough time had lapsed for resprouting and growth to occur.

Figure 3.20: Understorey growth at trial Berlin before the compartment was slashed for under-canopy burning.

3.5.8.1 Cover Abundance

Each plot was divided into 4 quadrants and individually rated using the Braun-Blanquet cover scale and averaged to get one representative value for each plot (Table 3.5).

Table 3.5: Braun-Blanquet cover abundance scale.

Braun-Blanquet Cover Scale	
Value	Cover %
+	Less than 1 %
1	1 – 5 %
2	6 – 25 %
3	26 – 50 %
4	51 – 75 %
5	76 – 100 %

(Kent & Coker, 1992)

3.5.8.2 Species

All the species growing inside each research plot were identified. The most common species were found to be the broad leafed grass species *setaria megaphylla*, *Lantana camara*, *Solanum mauritianum,* also known as bugweed, and the bracken fern species *Pteridium aquilinum*. Other non-dominant species, such as *Bidens pilosa* (blackjack) and *Acacia mearnsii* (black wattle) also grow beneath the tree canopy and were recorded in certain research trials (Table 3.6).

Table 3.6: Main understorey species recorded in the present study.

Species	Trial				
	Berlin	Blyde	Nelshoogte	Witklip *P. elliottii*	Witklip *P. patula*
Setaria megaphylla	✓	✓	✓	✓	✓
Solanum mauritianum	✓	✓		✓	
Lantana camara				✓	
Bidens pilosa		✓			✓
Acacia mearnsii		✓			

3.5.9 Growth

Stand response to under-canopy burning was determined through foliar nutrients, LAI measurements and diameter increment.

3.5.9.1 Foliar nutrients

Foliar nutrient status was assessed using needles collected from the littertraps. Needles collected during the first and second month after burning were sampled for both treatments (burnt & control) and sent to a commercial laboratory for nutrient analyses. Three samples from each of the three littertraps in each treatment were bulked together to acquire a single representative sample per treatment per month.

3.5.9.2 Dendrometer Tapes

Tree diameter growth is strongly influenced by stand density and by the tree's relative size in a stand (Pretzsch, 2009). While it is possible to determine stand diameter growth response over several years by measuring all the diameters on an annual basis, using ordinary diameter tapes, this would not inform us about the short-term response of the trees. Only a limited number of permanent dendrometers could be sourced for this project and it was thus important to fit these on trees in various treatments that experience similar competition from neighbours. Three trees inside each of the 45 research plots were chosen and a DBH distribution was calculated using the statistical package R Commander to determine small, medium and large DBH classes (Q_1, Mean and Q_3) for each species. Within each dbh class among research plots at each site, trees with comparable DBH's and a comparable value for the Hegyi competition index (see below) were chosen to be fitted with dendrometer tapes (Table 3.3).

Table 3.7: DBH class distribution for *P. elliottii* and *P. patula.*

			DBH			
Species	Min	Q_1	Mean	Q_3	Max	Average
P. elliottii	16.7	30.5	33.7	36.6	47.7	33.5
P. patula	13.4	33.9	37.8	41.8	65.0	37.9

The Hegyi competition equation was used to determine the growth competition index. The equation uses a fixed radius and all neighbouring trees to the focal tree inside the fixed radius are measured (Pretzsch, 2009). The DBH of a nearby competing tree (d_i in equation 3.3) is divided by the dbh of the focal tree (d_j) and multiplied by the inverse of the distance from the focal tree. This value is summed for all competing trees in the fixed radius around the focal tree.

Equation 3.3

$$DCI_j = \sum_{i=1}^{n} \left(\frac{d_i}{d_j} \times \frac{1}{dist_{ij}} \right)$$

The larger the tree diameter and the further the chosen tree grows from any other tree, the lower the growth competition for the chosen tree and *vice versa*. A desirable radius, dependent on the initial planting density, was calculated to ensure that all trees in the near vicinity of the chosen tree were included in the study. Two planting densities of 3.5 x 3.5 m and 2.7 x 2.7 m respectively were identified in the research trials for both species. The radius calculated for the 3.5 x 3.5 m spacing was 10.6 m and 8.4 m for the 2.7 x 2.7 m spacing. In a square planting grid, the use of aforementioned radii would include two rows of trees on all four sides of the focal tree into the competition index. The sum of all the competition factors within the specific radius from the measured tree provides the total growth competition factor. These competition factors were then compared to competition factors of the same diameter class and species. In cases where the measured tree varied too much from the relevant average DBH competition factor, it was replaced by another tree with a more acceptable competition factor. Growth rates were then compared to growth rates in other plots with the same growth competition factor. With all other variables considered as virtually constant, any significant difference in growth rate between treatments was considered to be the result of the specific treatment.

The dendrometer tapes for most trials were fitted to the chosen trees during November 2014. The research trials in Nelshoogte and Berlin were fitted with the tapes in May 2015 as these trials were only burnt then.

Dendrometer data was used to predict seasonal growth differences and treatment differences.

3.5.9.3 DBH Measurements using conventional diameter tapes

Trunk diameter at 1.3 m height was measured for all trees inside the research trials using DBH tapes during July 2014 and again in July 2015 thus representing 12 months of growth. DBH measurements were used to predict treatment differences because of the longer available period of growth, the larger sample size and the fact that, when analysed, dendrometer data showed consistent trends.

3.5.9.4 LAI Measurements

For this study an AccuPAR model LP-80 PAR/LAI Ceptometer was used to measure LAI prior to and following the burning application to determine any changes in tree canopy development between treatments. The measurements were acquired during the day on sunny days with no overhead clouds. During summer most of these measurements were taken during the morning as thunder clouds usually appeared in the afternoon. Ten readings were taken in the open field away from any obstacles or shadows that could affect the Ceptometer. Then, walking back into the research plot, 60 measurements were taken randomly, holding the Ceptometer horizontal. The Ceptometer takes 80 radiation readings per measurement point. The mean of all measurement points outside the canopy is than contrasted with the mean of the measurement under the canopy is then used to calculate the LAI using the Beer-Lambert law (Equation 3.4). An extinction coefficient of 0.5 was used in the specific study. The LAI was calculated according to the equation from Binkley et al. (2013).

Equation 3.4

$$LAI = Q_0 e^{-kF}$$

LAI = Leaf area index

Q_0= Photon flux density above the canopy

k = Extinction coefficient (dimensionless)

F = Cumulative leaf area

Theory predicts that with increasing nutrient uptake resulting from the ash-bed effect, trees will respond positively and expand their leaf area, t resulting in more needle fall. This can potentially result in increased FF accumulation. LAI measurements were successfully recorded twice throughout the duration of this project and the results compared between treatments.

3.6 Soil & Foliar Nutrients Analyses

Nutrient analysis was conducted by an independent analytical laboratory which made use of the following methods.

3.6.1 Soil pH, P & C

The soil samples were air dried and sieved through a 2 mm sieve to determine the stone fraction. The soil pH was determined using 1 M KCl using a 1:2.5 soil solution ratio. Plant-available P was gauged using the Bray II extraction. The organic matter content was determined using the Walkley-Black method (The non-affiliated Soil Analyses Work Committee, 1990). Cations were extracted in 1M ammonium bicarbonate and the Varian ICP-OES optical emission spectrometer was used for analysing the chemical composition in the extracted solutions.

3.6.2 Total C and N in Soil

For determining the total C and N content of the soil samples a Leco Truspec® CN N analyser was used to determine the C and N content through total combustion of the samples.

3.6.3 Effective Cation Exchange Capacity of Soil

The Non-affiliated Soil Analyses Work Committee (1990) method was used for determining the ECEC of soil samples. The ECEC was determined using 0.2 M ammonium acetate and leached with 0.2 M K_2SO_4. 1N KCl was used to extract the total NH_4^+ and determined colorimetrically as an indication of ECEC on a SEAL AutoAnalyzer 3 with a 15 mm flow cell and 520 nm filters.

3.6.4 Foliar Nutrient Analyses

Dried needles were milled and combusted at 480 °C and then shaken up in a 50:50 HCl (32%) solution for extraction through filter paper (Campbell & Plank, 1998). A Varian ICP-OES optical emission spectrometer was used to measure the cation and micro nutrient (B, Fe, Zn, Cu, and Mn) content of the extract.

3.7 Statistical Analyses

All statistical analyses were conducted using the statistical package R Commander. Analysis of variance (ANOVA) combined with the Tukey Contrast test was used to determine any significant changes between treatments. Treatments with $p<0.05$ were reported as significant and $p<0.1$ as weakly significant. All data was initially tested for normality using the Shapiro-Wilk test. Error bars shown in all graphs represents the standard error with a 95% confidence interval level.

4. Results

This section will provide all results obtained and analysed during the two year experimental period. Certain treatments were implemented at different times as will be indicated in each section. Trials in Witklip and Blyde do not have control treatments after compartment differences came to light during data analysis. The first burn treatments will serve as the control treatment as the under-canopy burns for these treatments occurred 7 years back. The remaining two trials (Berlin and Nelshoogte) have control treatments as the control and burnt compartments are adjacent to each other making them comparable. All figures to follow except Berlin and Nelshoogte contain the letters P. pat and P. ell referring to *Pinus patula* and *Pinus elliottii* trials respectively.

4.1 Forest Floor

To determine the effect that under-canopy burning has on FF formation, litterfall and mass of the FF were calculated following treatment implementation.

4.1.1 Litterfall

4.1.1.1 Litterfall Rate

Average litterfall rates were similar, although relatively higher in this specific study compared to other studies around the world (Table 4.1). Litterfall rate for *P. elliottii* was very similar to findings by Gholz *et al.,* (1985) and De Ronde *et al.,* (1990). *P. patula* fell close to the average of ranges reported for the species (Table 4.1). Litterfall were approximately 3 t ha^{-1} higher for *P. patula* than *P. elliottii*. Litterfall rates for *P. patula* were 3 t ha^{-1} more than were found in a previous study conducted in the same area (Dames *et al.* 1998).

Table 4.1: Litterfall rates recorded around the world for matured pine species.

Location	*P. elliottii* (t ha^{-1} yr^{-1})	*P. patula* (t ha^{-1} yr^{-1})	Reference
Present study	5.52	8.82	
W-Cape, RSA	6.50		De Ronde *et al.* (1990)
MPU, RSA		5.89	Dames *et al.* (1998)
Tanzania		6.22	Lundgren (1978)
India		11.42	Singh (1982)
USA	4.99		Gholz *et al.* (1985)

No significant differences in litterfall rate were found between treatments when analysed over the full experimental period (Figure 4.1 to 4.3).

Figures 4.1, 4.2 and 4.3 show the litterfall rate of the different trials from treatment implementation, up to seventeen months after treatment implementation. A significant difference (p=0.002) is evident between treatments following the first month after treatment implementation in trial Blyde. This difference is evident in Figure 4.1, which shows a clear difference in the pattern of litterfall during the month following the second burn application. The litterfall rate increased from March to April in the control and decreased for the same period in the burnt area. This effect only lasted for the first month following treatment implementation where-after it followed the same trend line as the control. The fact that the pattern changed between the two treatments is an indication of a treatment effect. An interesting trend is noticeable inside the Witklip *P. patula* and Blyde *P. elliottii* trials. Except for the first month after burning (which is driven by needle scorch), the burnt treatment had lower litterfall than the control treatment which changed towards the end of the second growing season (February – May) when the burnt treatment had higher litterfall.

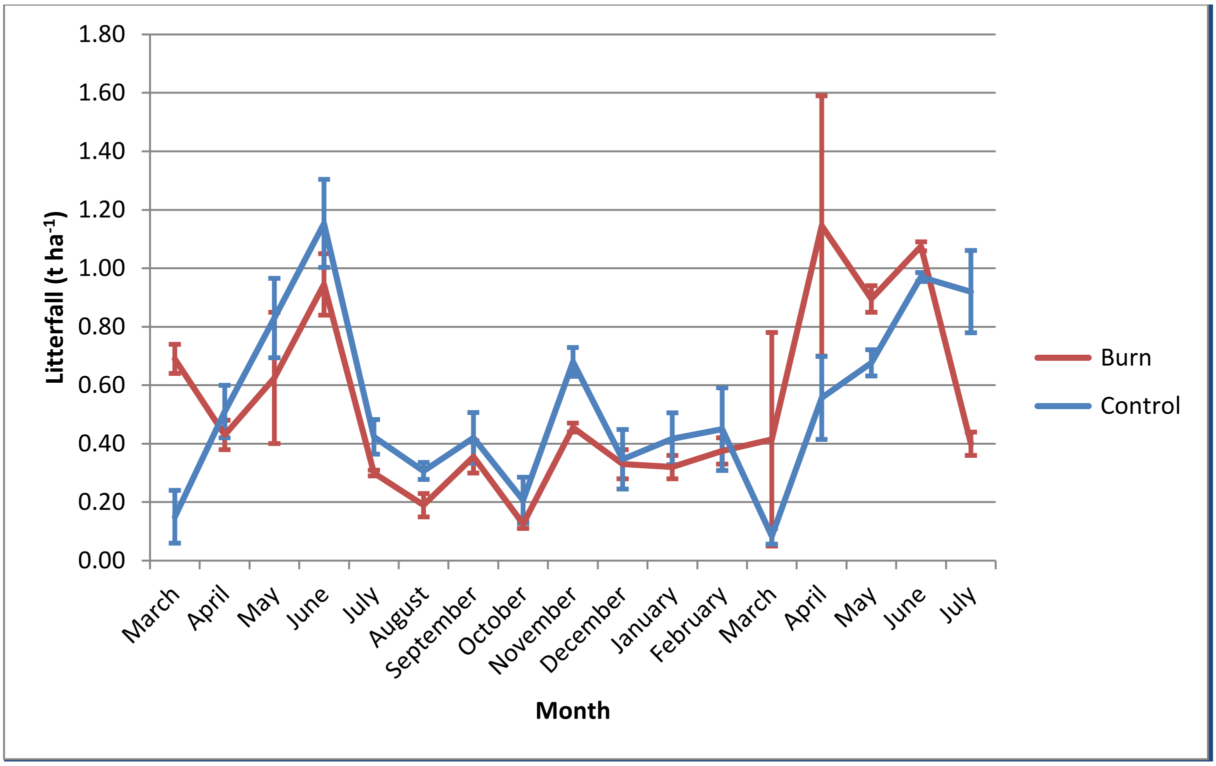

Figure 4.1: Blyde litterfall rate for *Pinus elliottii* collected from March 2014 – July 2015.

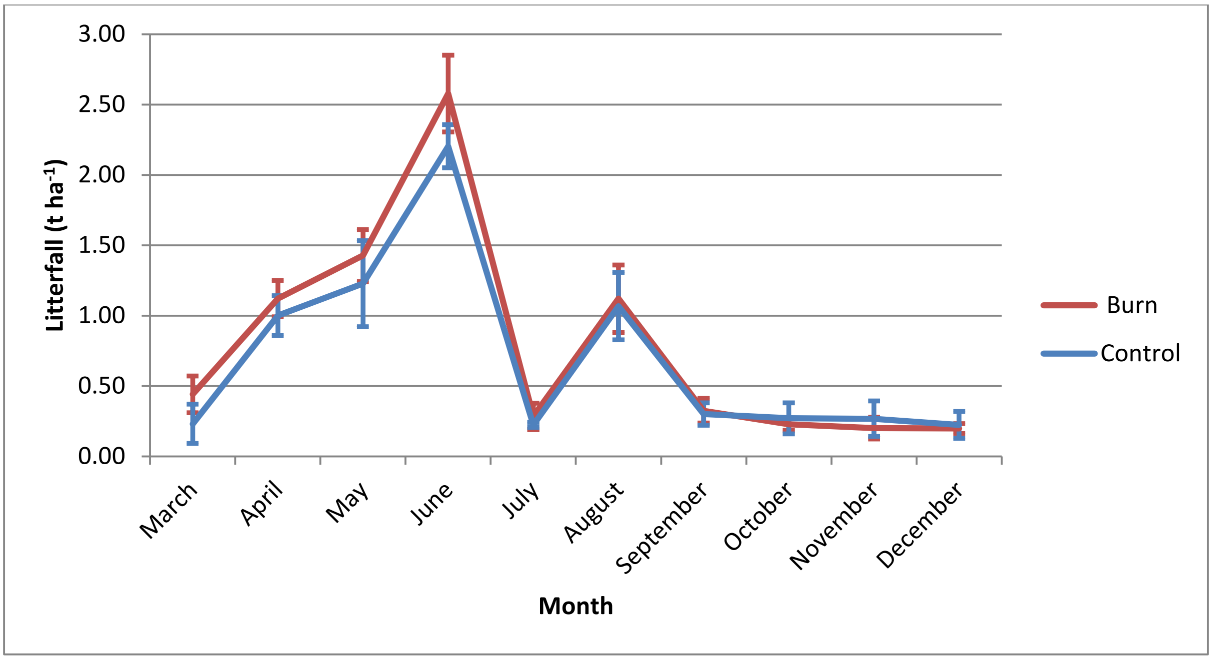

Figure 4.2: Witklip litterfall rate for *Pinus elliottii* collected from March – December 2014.

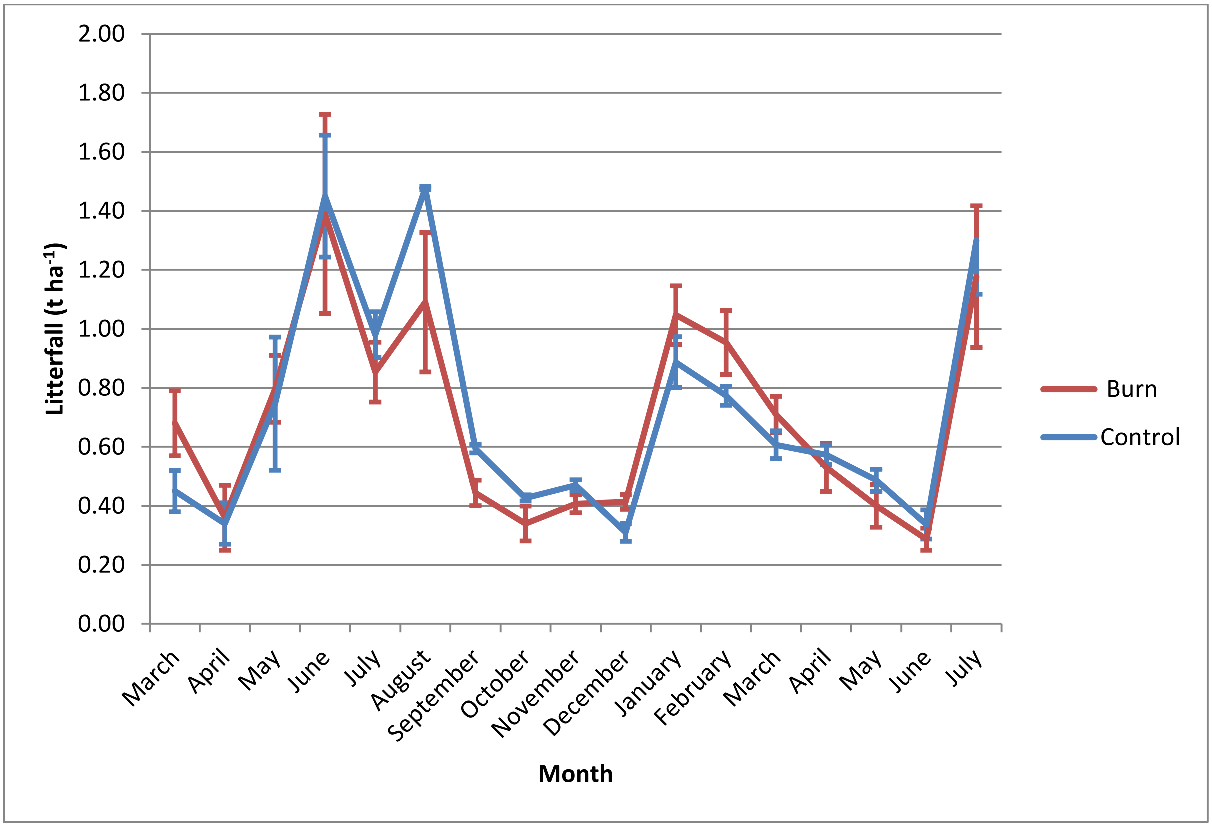

Figure 4.3: Witklip litterfall rate for *Pinus patula* collected from March 2014 – July 2015.

Litterfall rate decreased from July to August in trial Berlin and Nelshoogte (Figure 4.4 - 4.5). Nelshoogte showed a non-significant difference (*p*=0.176) between the control and burnt plots in the first month following treatment implementation. The two trials showed similar trend lines over time between treatments, thus indicating no treatment differences.

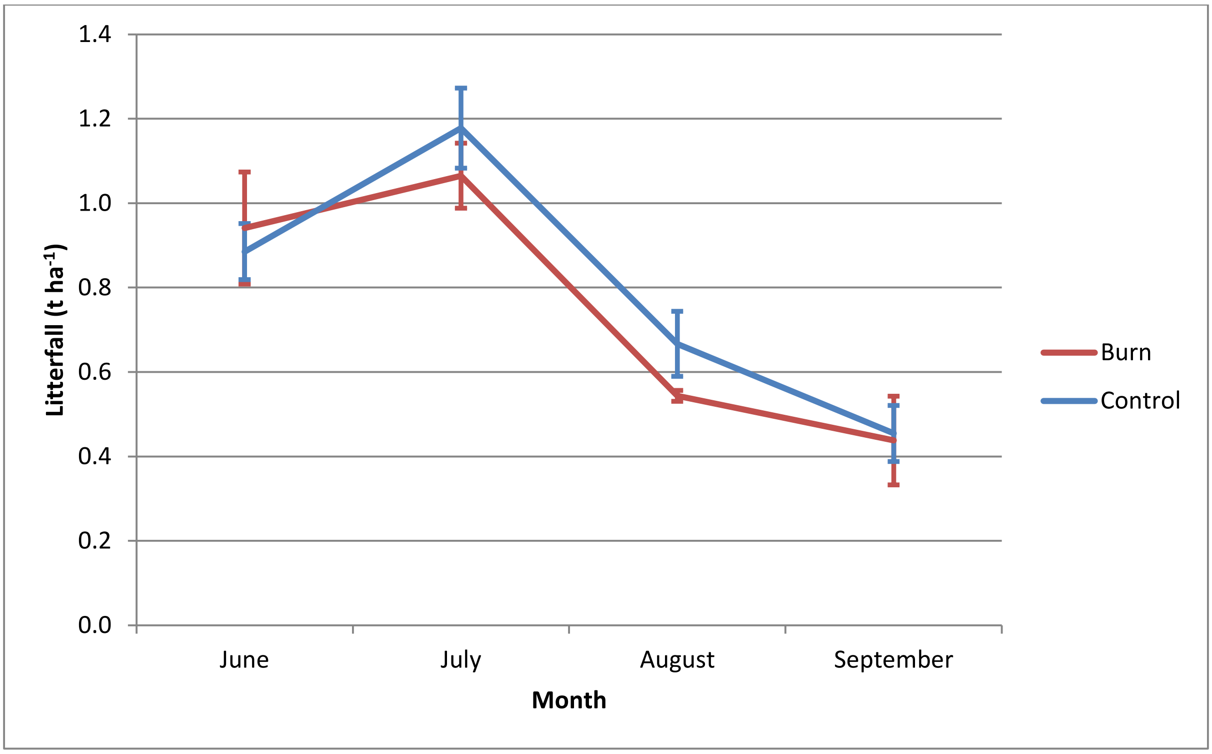

Figure 4.4: Litterfall rate for trial Berlin for the first 4 months following treatment implementation.

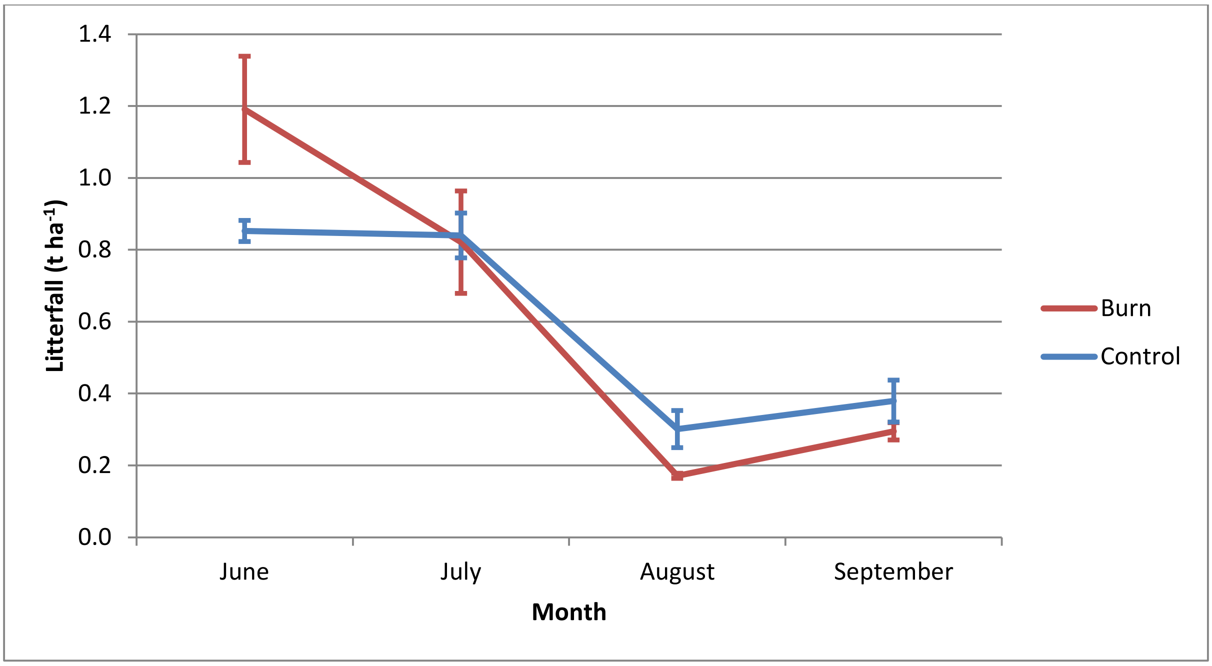

Figure 4.5: Litterfall rate in trial Nelshoogte for the first 4 months following treatment implementation.

4.1.2 Seasonal Trend

All three trials analysed show a significant seasonality difference (Table 4.2). Seasonality was divided into spring, summer, autumn and winter. Significant differences occurred between winter and spring and between winter and summer over all trials except trial Witklip *P. elliottii* for which no summer data is available (Table 4.3). Trial Witklip *P. patula* shows the most significant differences between seasons.

Table 4.2: ANOVA Table presenting *p-value*s for seasonality differences in litterfall rate.

ANOVA (Type I test)					
Trial	Df	Sum Sq	Mean Sq	F value	*p - value*
Blyde					
Season	3	1.283	0.428	4.452	0.006
Residuals	81	7.783	0.096		
Witklip *P. elliottii*					
Season	2	8.941	4.471	11.48	<0.001
Residuals	51	19.863	0.389		
Witklip *P. patula*					
Season	3	5.103	1.701	16.46	<0.001
Residuals	96	9.918	0.103		

Table 4.3: Tukey Contrast Table presenting *p-value*s for seasonality differences in litterfall rate.

Trial	Spring / Autumn	Summer / Autumn	Winter / Autumn	Summer / Spring	Winter / Spring	Winter / Summer
Blyde	0.287	0.256	0.447	0.999	0.020	0.017
Witklip *P. elliottii*	0.009	N.A	0.244	N.A	<0.001	N.A
Witklip *P. patula*	0.606	0.278	<0.001	0.045	<0.001	0.012

**Grey Shading: Indicating significant litterfall differences between seasons.*

**N.A: Data not available*

The highest litterfall rate over all three trials occurred during winter (Figure 4.6). The second highest litterfall rate occurred in the autumn, except for trial Witklip *P. patula* which had a higher summer litterfall rate. This was due to increased litterfall rates during January and February 2015 (Figure 4.3). The lowest litterfall rates generally occurred during spring and summer.

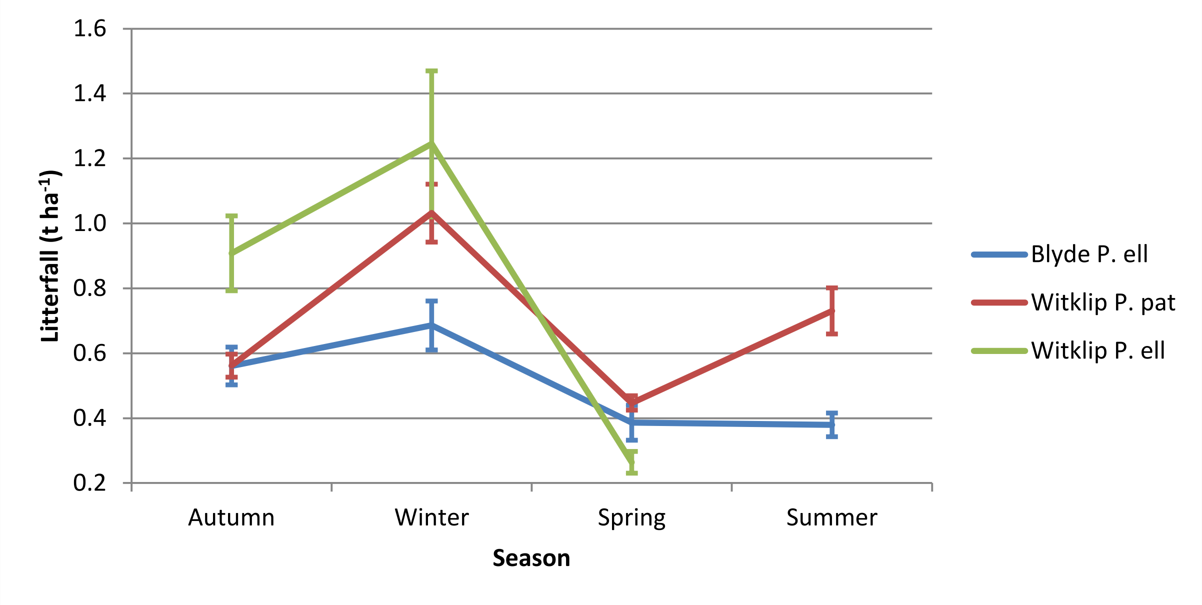

Figure 4.6: The seasonality trend of litterfall for different trials and species.

4.1.3 Forest Floor Mass

The FF data was collected at different time periods between experimental sites. Trials Blyde and Witklip were burned during February 2014 and depth measurements were made during June/July 2014. Nelshoogte and Berlin trials only received burn treatments during May 2015 and depth measurements were made during the end of July 2015. Forest floor depth was used in the statistical analysis (Table 4.5 - 4.6).

Forest floor mass in this specific study was well within the range found in local and international studies (Table 4.4). Schutz (1990) recorded litter depths under matured *Pinus* stands in Mpumalanga and using the depth mass regressions per species found very similar weights. This table clearly shows the difference in FF mass between *P. elliottii* and *P. patula*.

Table 4.4: Forest floor mass (t ha^{-1}) recorded for *P. elliottii* and *P. patula* around the world.

Location	Age	*P. elliottii* (t ha^{-1})	*P. patula* (t ha^{-1})	Reference
Present Study	19 - 25	19 - 25	29 - 70	
MPU, RSA	Mature	20	64	Schutz (1990)
KZN & MPU, RSA	11 - 37		22 - 168	Ross & du Toit (2004)
Tanzania	10 - 30		25 - 35	Lundgren (1978)
Australia	14 - 19	13 - 20		Maggs (1988)
USA	34	41		Gholz & Fisher (1982)

A significant difference between FF depths occurred over all five trials (Table 4.5). Significant differences in FF depth were detected for both trials Berlin and Nelshoogte between second burnt and control plots and between the second burn and the first burnt plots (Table 4.6). No significant differences existed between the first burn and control plots for both trials.

Table 4.5: ANOVA Table representing *p-value*s for FF depth in all trials following treatment implementation.

ANOVA (Type I test)					
Trial	Df	Sum Sq	Mean Sq	F value	*p- value*
Berlin					
Treatment	2	254.4	127.20	18.7	<0.001
Residuals	177	1204.2	6.80		
Nelshoogte					
Treatment	2	261.6	130.82	25.75	<0.001
Residuals	175	888.9	5.08		
Witklip *P. patula*					
Treatment	1	18.04	18.04	21.22	<0.001
Residuals	58	49.31	0.85		
Witklip *P. elliottii*					
Treatment	1	178.5	178.54	40.2	<0.001
Residuals	58	257.6	4.44		
Blyde					
Treatment	1	16.64	16.643	20.34	<0.001
Residuals	58	47.45	0.818		

Table 4.6: Tukey Contrast Test Table presenting FF mass differences between treatments.

Trial	First Burn – Control	Second Burn - Control	Second Burn - First Burn
Berlin	0.106	<0.001	<0.001
Nelshoogte	0.344	<0.001	<0.001

**Grey Shading: Significant differences*

Berlin, being the highest altitude site (1600m), was expected to yield the highest FF mass. However, Nelshoogte (1400m) as compared to Berlin in Figure 4.7, shows a higher average FF mass over the whole range of treatments. This could be explained by the age difference between the two trials with Berlin being five years younger than Nelshoogte and by the fact that FF mass generally increases with age (Morris, 1993). The FF mass was reduced from 65 to 48 t ha^{-1} during the second burn treatment in trial Nelshoogte. In trial Berlin the FF mass was reduced from 50 to 36 t ha^{-1}.

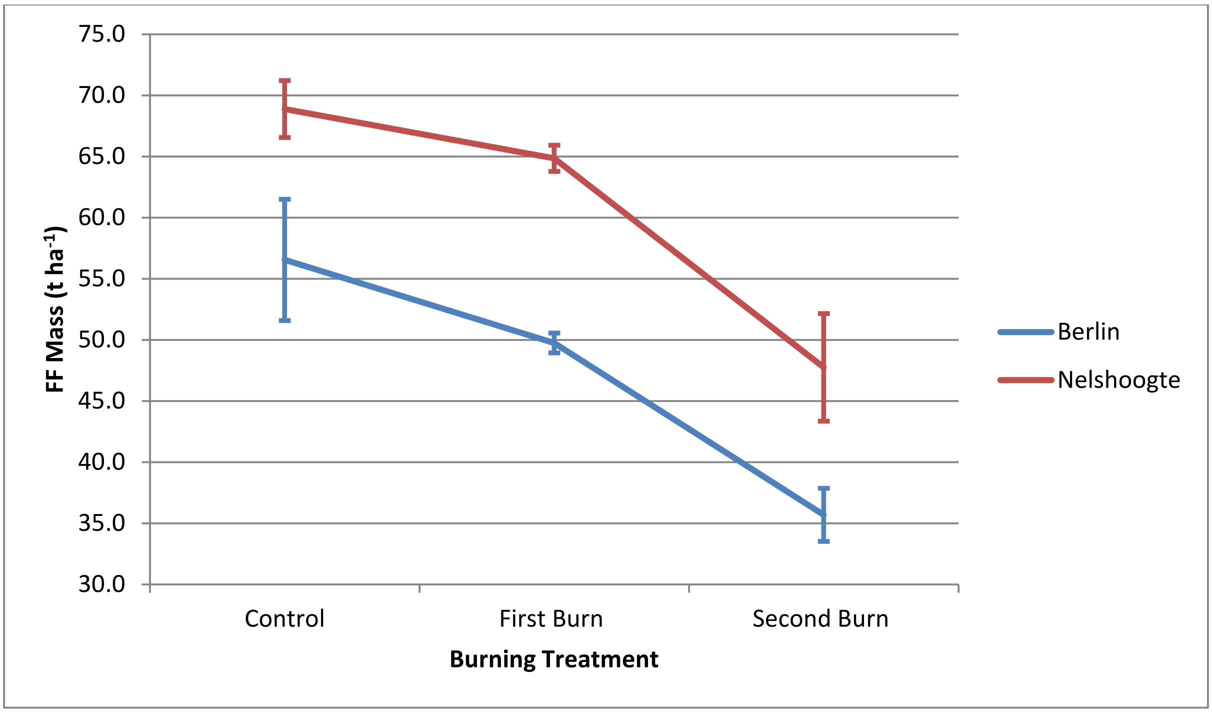

Figure 4.7: Forest floor mass 2 months following treatment implementation.

Trial Blyde had the lowest FF mass of all trials, even though the trial is considered a medium altitude site (Figure 4.8). Trial Blyde is seven years younger than trial Witklip, adjacent to grassland and received a relatively hot under-canopy burn during 2007. The *Pinus patula* species in trial Witklip show a higher FF mass than *Pinus elliottii,* as was expected. For both trials in the Witklip plantation the FF mass was reduced by 8 to 10 t ha^{-1}. A target FF mass of 10 t ha^{-1} for these two Witklip trials should be achieved with one further under-canopy burn treatment.

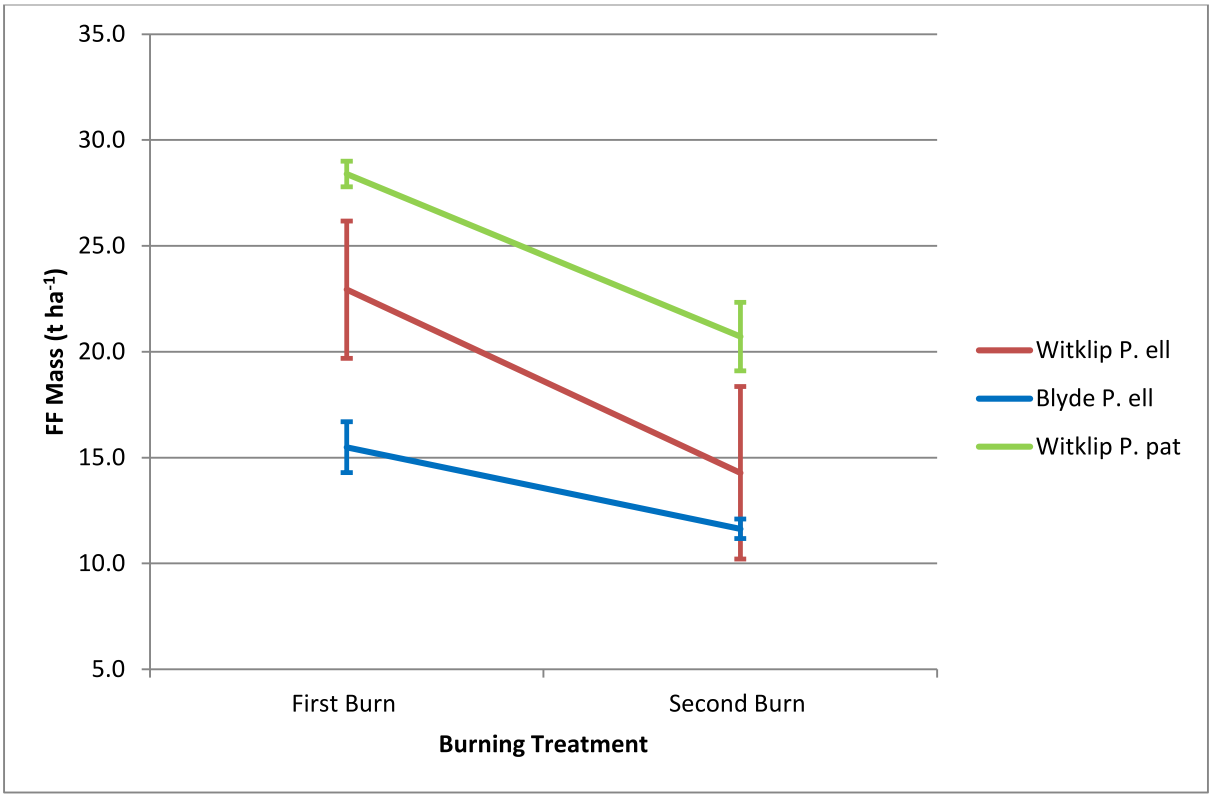

Figure 4.8: Forest floor mass 4 months following treatment implementation.

4.2 Growth

4.2.1 Growth increment over size classes

The Hegyi growth competition factor decreases with increasing tree diameter (Table 4.7). This is expected as larger trees should have less competition thus explaining the superior growth. The table shows the average competition factor for each trial and also the average over all trials. The total growth competition factor decreases with 0.19 units from the small to medium size trees and 0.13 units from the large to the medium size trees. In the trial at Blyde the medium size trees shows a higher Hegyi index than the small trees. The tree sizes were very similar and thus exhibit very small variance in growth competition over the three DBH classes.

Table 4.7: Hegyi growth competition factors for three different DBH size classes.

Trial	Small DBH	Medium DBH	Large DBH
Berlin	1.10	0.83	0.74
Blyde	1.50	1.52	1.45
Nelshoogte	1.44	1.15	0.96
Witklip *P. elliottii*	1.37	1.17	1.02
Witklip *P. patula*	1.26	1.02	0.91
Average	1.33	1.14	1.01

Due to time of treatment implementation differences occurring, growth data varies in the time frame measured. Blyde and Witklip *P. patula* has 3 months of dendrometer data for winter and summer (Figure 4.10 and 4.11). Berlin and Nelshoogte only has 4 months of dendrometer growth data during winter (Figure 4.13). Mean growth between different size classes and treatments were measured after 12 months of growth without using competition indices, measuring all trees using normal DBH tapes (Figure 4.9 and 4.12).

A significant growth difference (p=0.007) exists between small and large trees in trial Witklip *P. patula* (Table 4.8 - 4.9). Blyde shows a weakly significant difference (p=0.068) between the small and medium diameter size class (Table 4.9).

Table 4.8: ANOVA Table representing growth differences between tree size classes in trials Blyde and Witklip.

ANOVA (Type I test)				
	Df	Sum Sq	F value	*p - value*
Blyde DBH Class Increment				
Treatment	2	0.712	2.656	0.075
Residuals	116	15.544		
Witklip *P. patula* DBH Class Increment				
Treatment	2	1.099	5.338	0.007
Residuals	59	6.071		

**Grey Shading: Significant & Weakly Significant Differences*

Table 4.9: Tukey Contrast Table presenting differences between tree size classes.

Trial	Medium - Large	Small - Large	Small - Medium
Blyde	0.203	0.068	0.839
Witklip *P. patula*	0.259	0.005	0.237

**Grey Shading: Significant & Weakly Significant Differences*

Figure 4.9 shows an increase in diameter increment with increasing DBH class. Witklip exhibits a linear increase with increasing DBH class while Blyde shows a steeper increase in increment between medium and large size trees in comparison to small and medium size trees. The diameter growth increment ranges from a minimum of 0.05 cm for small diameter trees to a maximum of 0.5 cm in the big tree size class. The difference in growth increment between DBH classes can be attributed to the decreasing Hegyi competition factor with increasing tree diameter.

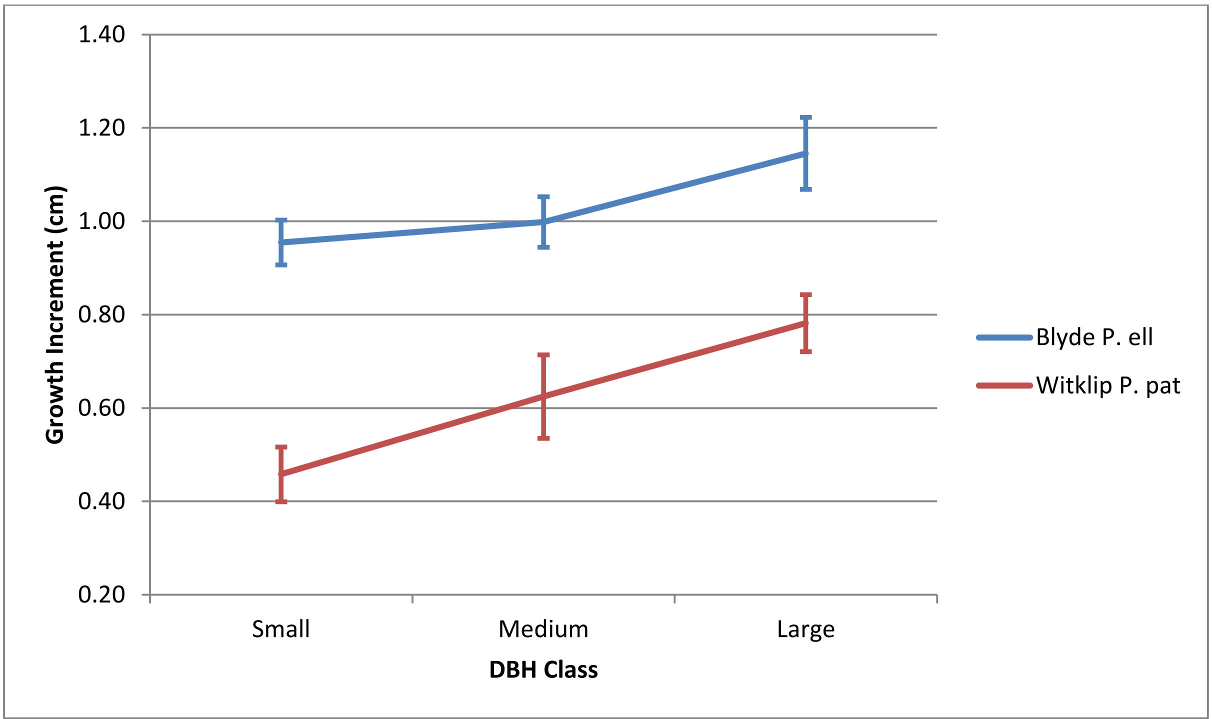

Figure 4.9: Mean growth increment over twelve months for different size class groups in Blyde *Pinus elliottii* and Witklip *Pinus patula* trials.

4.2.2 Mean seasonal growth increment

The mean seasonal growth increment was determined using the dendrometer tapes. A significant difference (p=0.007) exists between season's summer and winter for trial Blyde and a weak significant difference (p=0.088) for trial Witklip (Table 4.10). No significant differences were detected between treatments and no significant interaction was observed between treatment and season.

Table 4.10: ANOVA Table presenting differences in diameter increment between treatments seasonal growth for trials Blyde and Witklip.

		Blyde Seasonal Growth Increment		
Season	1	0.155	8.554	0.007
Treatment	1	0.008	0.448	0.510
Season: Treatment	1	0.033	1.838	0.187
Residuals	25	0.453		
		Witklip *P. patula* Seasonal Growth Increment		
Season	1	0.034	3.213	0.088
Treatment	1	<0.001	0.027	0.870
Season: Treatment	1	<0.001	<0.001	0.989
Residuals	21	0.220		

**Grey Shading: Significant and weakly significant difference*

The general trend in both trials is a significant decrease in growth from summer to winter (Figures 4.10 – 4.11). This is expected as the area is subjected to summer rainfall which is therefore obviously also the growth season. Blyde shows a higher average diameter growth increment (0.24; 0.10 cm) compared to Witklip (0.10; 0.03 cm) in both summer and winter.

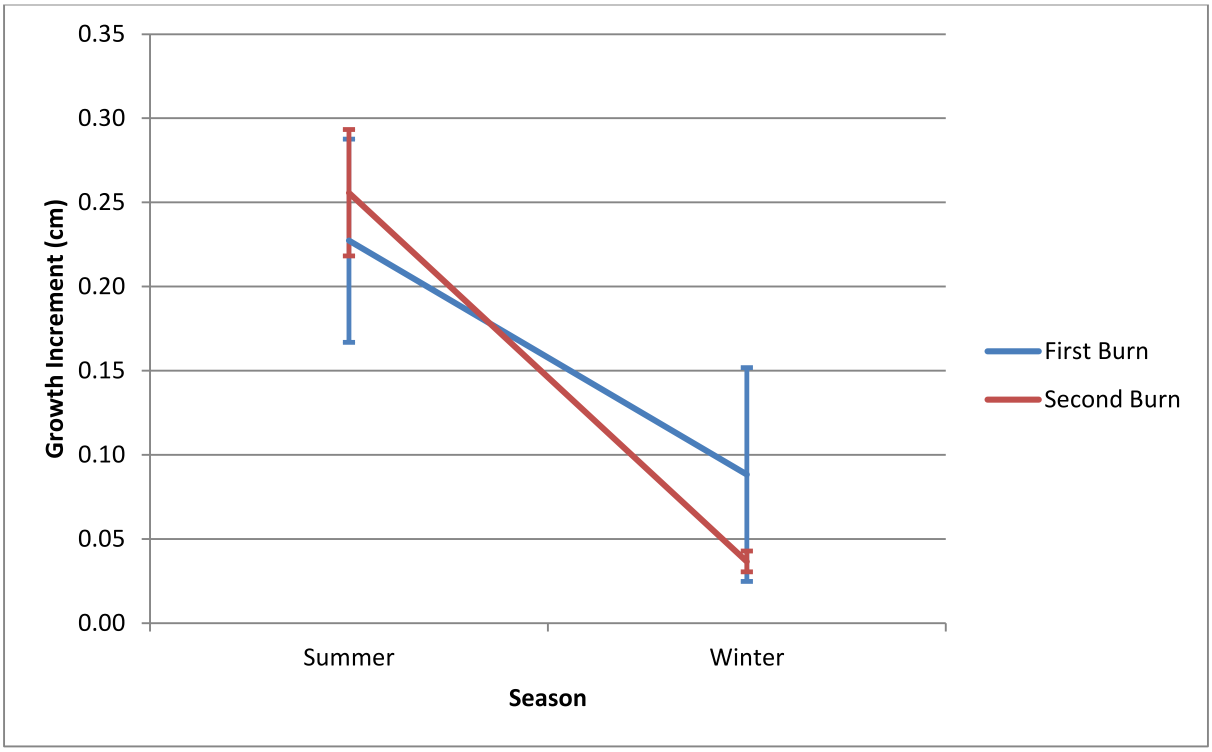

Figure 4.10: Mean seasonal growth increment over 3 months during summer and winter for First burn and Second burn treatments in trial Blyde.

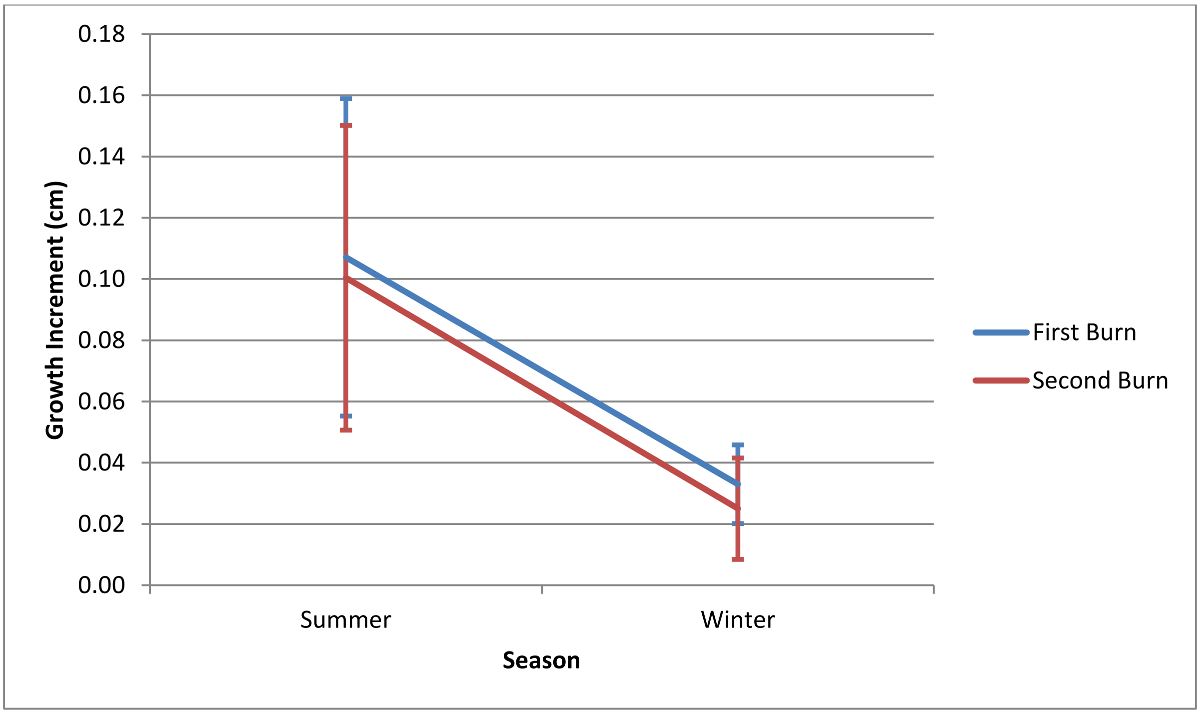

Figure 4.11: Mean seasonal growth increment over 3 months during summer and winter for First burn and Second burn treatments in trial Witklip *P. patula*.

4.2.3 Growth increment between treatments

Growth increment between treatments was determined using normal diameter tapes. No significant growth increment differences are evident between treatments following 12 months of growth after treatment implementation for both trials. Using DBH measurements of all trees in trial Blyde and Witklip *P. patula*, growth increment is displayed as BA per hectare which is a more accurate growth predictor than diameter increment due to tree size differences which is not accommodated for by diameter increment (Figure 4.12).

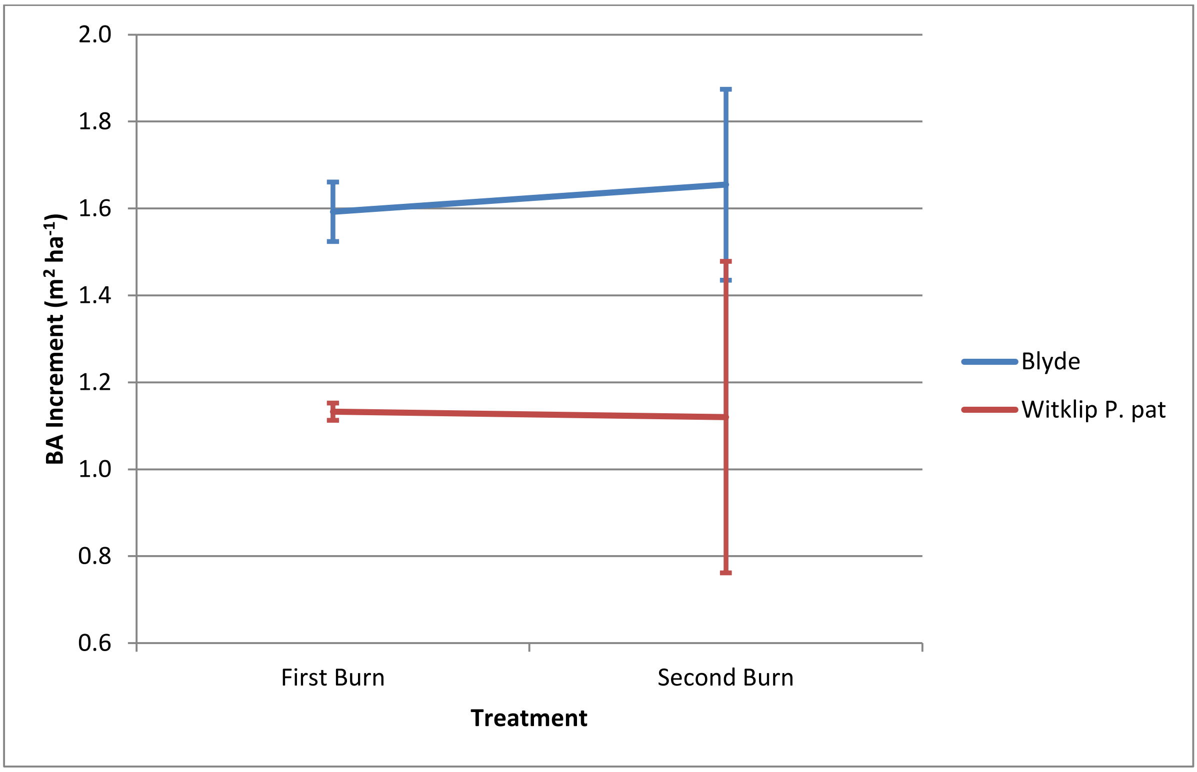

Figure 4.12: Mean BA growth increment over 12 months for two treatments in Blyde *Pinus elliottii* and Witklip *Pinus patula* trials.

No significant growth increment differences occur between treatments for Berlin and Nelshoogte (Figure 4.13). The low diameter increment observed over the 4 month period can be explained by the time of year measured. The growth was measured from the end of May 2015 to the end of September 2015 falling into the dry and cold season.

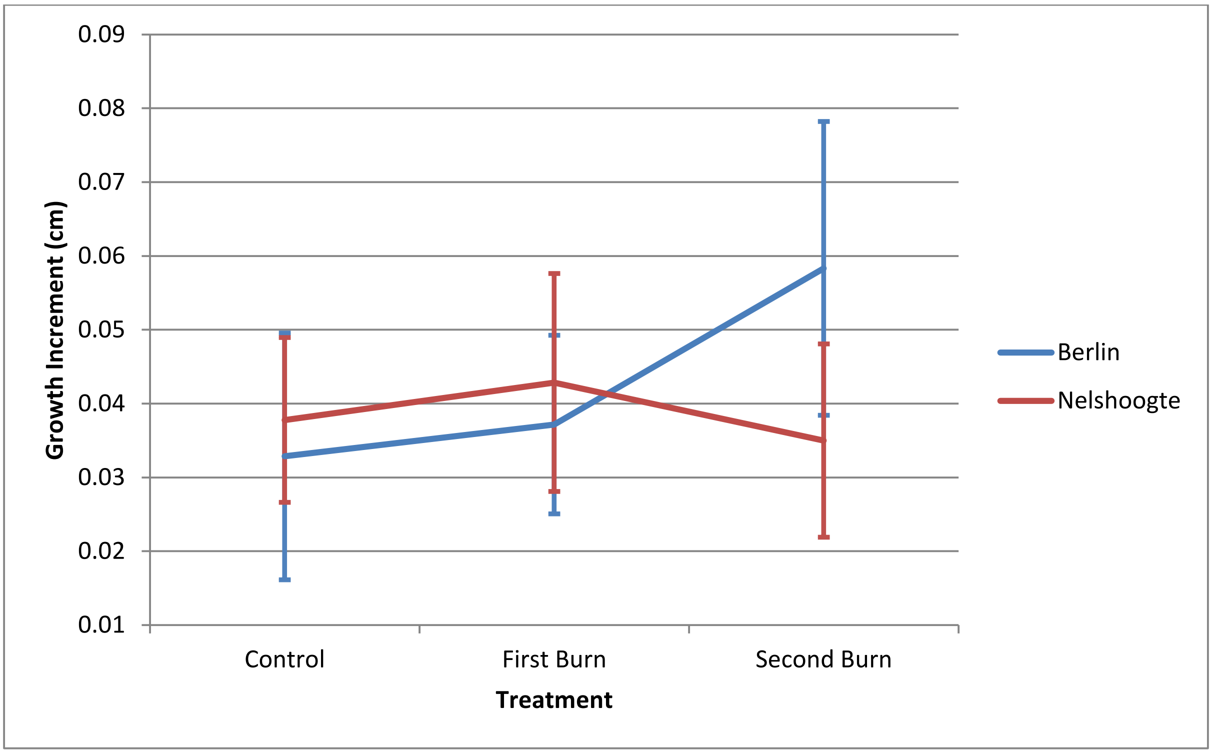

Figure 4.13: Growth increment 4 months during winter following treatment implementation.

4.2.4 Leaf Area Index

Only trials Blyde and Witklip *P. patula* were suitable for detecting change within the leaf area index of stands due to the late treatment implementation of trials Berlin and Nelshoogte.

In both trials Blyde and Witklip *P. patula* a significant difference was observed in the leaf area measured during December 2014 and May 2015 (Table 4.11). No significant differences were detected between treatments in trial Blyde, Nelshoogte and Witklip *P. patula* and therefore the data is not presented graphically.

Table 4.11: ANOVA Table presenting the seasonal difference in LAI between December 2014 and May 2015.

ANOVA (Type I test)				
Trial	Df	Sum Sq	F value	*p - value*
Blyde Seasonal Difference				
Treatment	1	1.756	21.061	<0.001
Residuals	10	0.834		
Witklip *P. patula* Seasonal Difference				
Treatment	1	1.643	22.303	<0.001
Residuals	10	0.737		

Pinus patula exhibits a higher LAI than *Pinus elliottii* (Figure 4.14). Both species show the same LAI trend over time with the highest being recorded in May. December is the beginning of the growth season when trees only start to grow new needles whilst May is at the end of the growth season when maximum needle growth has been achieved, thus explaining the LAI differences observed in Figure 4.14.

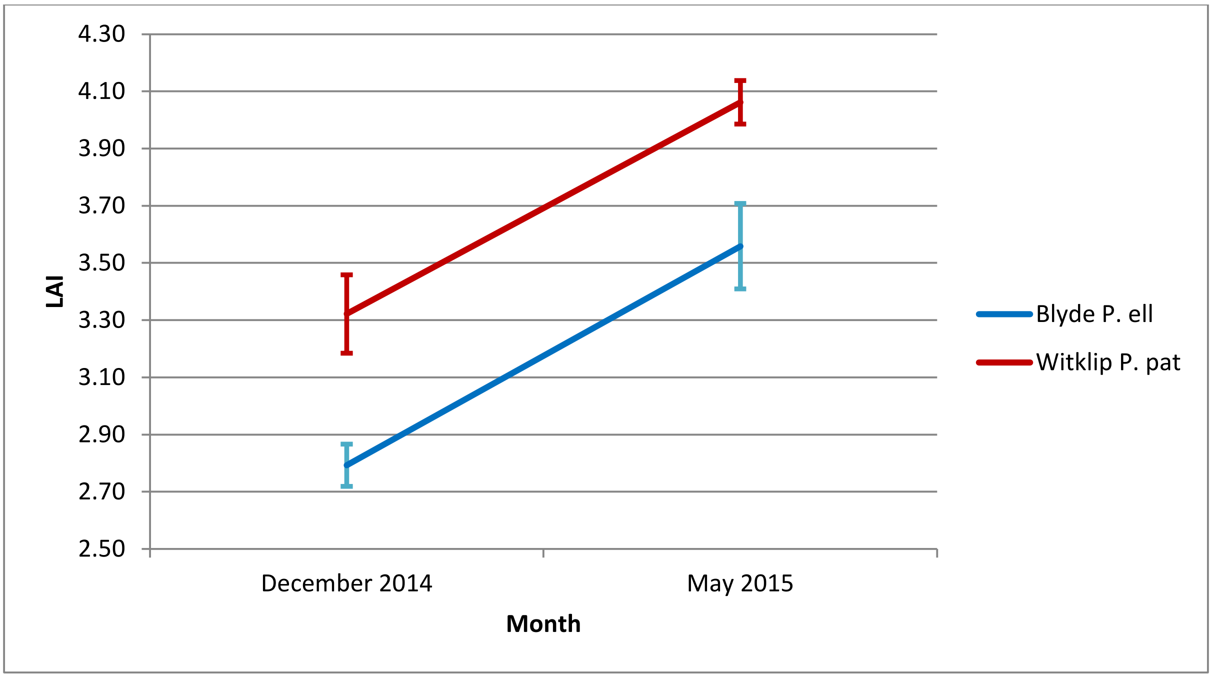

Figure 4.14: Seasonal trend of LAI for trials Blyde and Witklip *P. patula*.

4.3 Nutrients

This section addresses all relevant nutrient analyses in the FF, foliage collected from littertraps and soil nutrients.

4.3.1 Forest Floor Nutrient Content

Forest floor nutrient content was determined by multiplying the average macro nutrient concentration per treatment with the corresponding FF mass.

Nutrient concentrations for both species in this study do not differ significantly with other studies (Table 4.12). The *P. patula* trials in this study correspond quite well with the nutrient concentration found in the study done by Odiwe (2009). Nitrogen in the *P. patula trials,* however, corresponds better with the result of Schutz (1990). Nutrient concentrations for *P. elliottii* were similar to findings by Odiwe (2009) with N, K and Ca being higher in the present study.

Table 4.12: Mean nutrient concentration in the combined FF of *P. elliottii* and *P. patula* for different studies.

Nutrient (%)	*P. elliottii* (Present study)	*P. elliottii* Odiwe (2009)	*P. patula* (Present study)	*P. patula* Schutz (1990)	*P. patula* Odiwe (2009)
N	0.76	0.55	1.24	1.28	0.76
P	0.03	0.03	0.06	0.16	0.04
K	0.07	0.03	0.09	0.10	0.07
Ca	0.46	0.23	0.41	0.28	0.22
Mg	0.07	0.05	0.11	0.08	0.07

Phosphorus in trial Blyde is the only nutrient where the nutrient content remained virtually unchanged with decreasing FF mass, signifying, effectively, a zero loss of this element following burning. This is a consequence of higher P concentrations in the second burnt plots and the fact that only 3 t ha^{-1} was removed during the second burn (Table 4.13). Nutrient concentrations varied considerably as is indicated by the kg ha^{-1} nutrient loss per ton of FF consumed. Nitrogen and calcium show the highest nutrient loss due to higher concentrations of these nutrients occurring in the FF (Appendix 2A). Interesting to note was Witklip *P. patula* losing the most nitrogen even though Berlin and Nelshoogte showed losses more than double the FF mass of Witklip *P. patula*. This can be explained by the higher nutrient concentrations found in the first burn in comparison with the second burn treatments in trial Witklip *P. patula* (Appendix 2A).

Table 4.13: Forest floor nutrient loss through FF mass reduction.

		Kg ha^{-1}				
Trial	Mass loss	N	P	K	Ca	Mg
Blyde	3 851	33 (8.6)	- 0.01 (0.0)	1 (0.2)	20 (5.1)	2 (0.5)
Witklip *P. elliottii*	8 650	56 (6.4)	3 (0.3)	8 (1.0)	59 (6.8)	12 (1.3)
Witklip *P. patula*	7 676	119 (15.5)	7 (1.0)	5 (0.7)	91 (11.9)	11 (1.4)
Berlin	14 070	118 (8.4)	5 (0.4)	23 (1.7)	91 (6.4)	25 (1.8)
Nelshoogte	17 102	53 (3.1)	4 (0.2)	26 (1.5)	101 (5.9)	36 (2.1)

Values outside brackets: Total nutrients loss for each burn.

Values in brackets: Nutrient loss in kg for each ton of FF consumed.

**Grey Shading: Nutrient increasing with a decrease in FF mass.*

Calcium and magnesium are the only two macro nutrients differing significantly between treatments over all 5 trials (Table 4.14).

Table 4.14: ANOVA Table representing significant FF nutrient content differences between treatments.

Nutrient		Df	Sum Sq	Mean Sq	F value	*p-value*
			Berlin			
N	Treatment	2	0.010	0.050	9.662	0.013
	Residuals	6	0.031	0.005		
P	Treatment	2	<0.001	<0.001	11.58	0.009
	Residuals	6	<0.001	<0.001		
K	Treatment	2	0.003	0.001	39.54	<0.001
	Residuals	6	<0.001	<0.001		
Ca	Treatment	2	0.024	0.012	27.7	0.001
	Residuals	6	0.003	<0.001		
Mg	Treatment	2	0.001	0.001	28.45	0.001
	Residuals	6	<0.001	<0.001		
			Blyde			
N	Treatment	1	0.002	0.002	16.65	0.027
	Residuals	3	<0.001	<0.001		
Ca	Treatment	1	0.011	0.001	16.91	0.026

	Residuals	3	0.002	<0.001		
Mg	Treatment	1	<0.001	<0.001	15.26	0.030
	Residuals	3	<0.001	<0.001		
			Nelshoogte			
N	Treatment	2	0.064	0.032	9.271	0.015
	Residuals	6	0.021	0.004		
P	Treatment	2	<0.001	<0.001	18.04	0.003
	Residuals	6	<0.001	<0.001		
K	Treatment	2	0.004	<0.001	228.4	<0.001
	Residuals	6	<0.001	<0.001		
Ca	Treatment	2	0.003	0.014	104.4	<0.001
	Residuals	6	<0.001	<0.001		
Mg	Treatment	2	0.003	0.002	129.1	<0.001
	Residuals	6	<0.001	<0.001		
			Witklip *P. elliottii*			
P	Treatment	1	<0.001	<0.001	9.107	0.095
	Residuals	2	<0.001	<0.001		
K	Treatment	1	<0.001	<0.001	16.38	0.056

	Residuals	2	<0.001	<0.001		
Ca	Treatment	1	0.004	0.004	18.01	0.051
	Residuals	2	<0.001	<0.001		
Mg	Residuals	1	<0.001	<0.001	23.22	0.041
	Treatment	2	<0.001	<0.001		
			Witklip *P. patula*			
N	Treatment	1	0.019	0.012	28.23	0.013
	Residuals	3	0.002	<0.001		
P	Treatment	1	<0.001	<0.001	37.14	0.009
	Residuals	3	<0.001	<0.001		
Ca	Treatment	1	0.012	0.012	55.02	0.005
	Residuals	3	<0.001	<0.001		
Mg	Treatment	1	<0.001	<0.001	9.681	0.053
	Residuals	3	<0.001	<0.001		

**Grey Shading: Weakly significantly p-values*

Berlin and Nelshoogte showed a significant difference between treatment Second burn and Control for all macro nutrients (Table 4.15). This is due to the largest FF mass occurring between these two treatments. The second most significant differences exist between the Second and First burn which also has the second highest FF mass reduction between the two treatments.

Table 4.15: Tukey Contrast Table presenting significant FF nutrient content differences between treatments.

Trial	Treatment	N	P	K	Ca	Mg
Berlin	First Burn - Control	0.119	0.046	0.021	0.224	0.953
	Second Burn - Control	0.011	0.007	<0.001	<0.001	0.001
	Second Burn – First Burn	0.190	0.325	0.006	0.004	0.002
Nelshoogte	First Burn - Control	0.051	0.015	<0.001	0.067	0.372
	Second Burn - Control	0.014	0.002	<0.001	<0.001	<0.001
	Second Burn – First Burn	0.551	0.266	<0.001	<0.001	<0.001

Grey Shading: Significant and weakly significant differences between treatments.

All macro nutrients followed the same trend between treatments and trials (Figure 4.15 – 4.24). Nutrients in the FF decrease with decreasing FF mass except for phosphorus in trial Blyde which remained unchanged due to a small decrease in FF mass and slightly higher P concentration inside the burned treatment. Trials Berlin and Nelshoogte showed the highest nutrient mass due to highest FF formations occurring on these sites and showed a similar trend line over all nutrients.

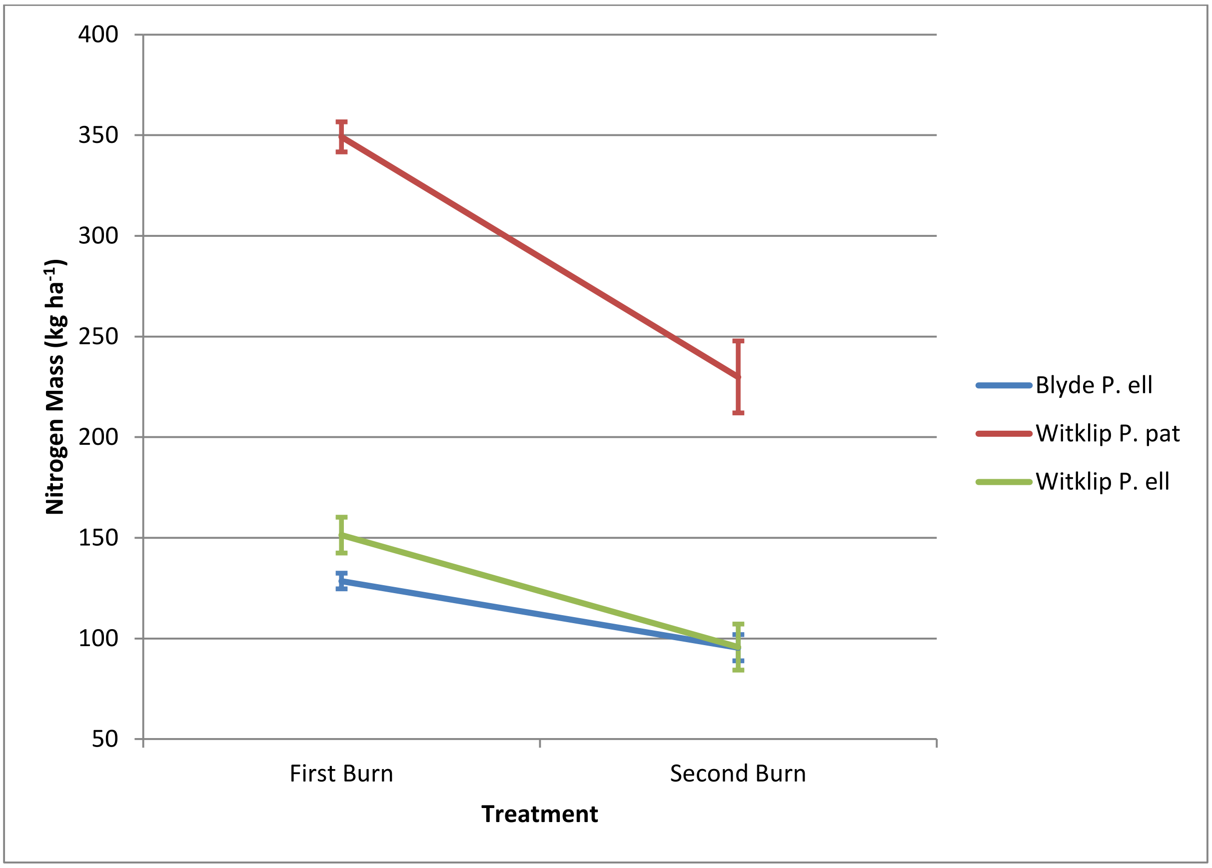

Figure 4.15: Nitrogen content between treatments expressed in kg ha^{-1} remaining.

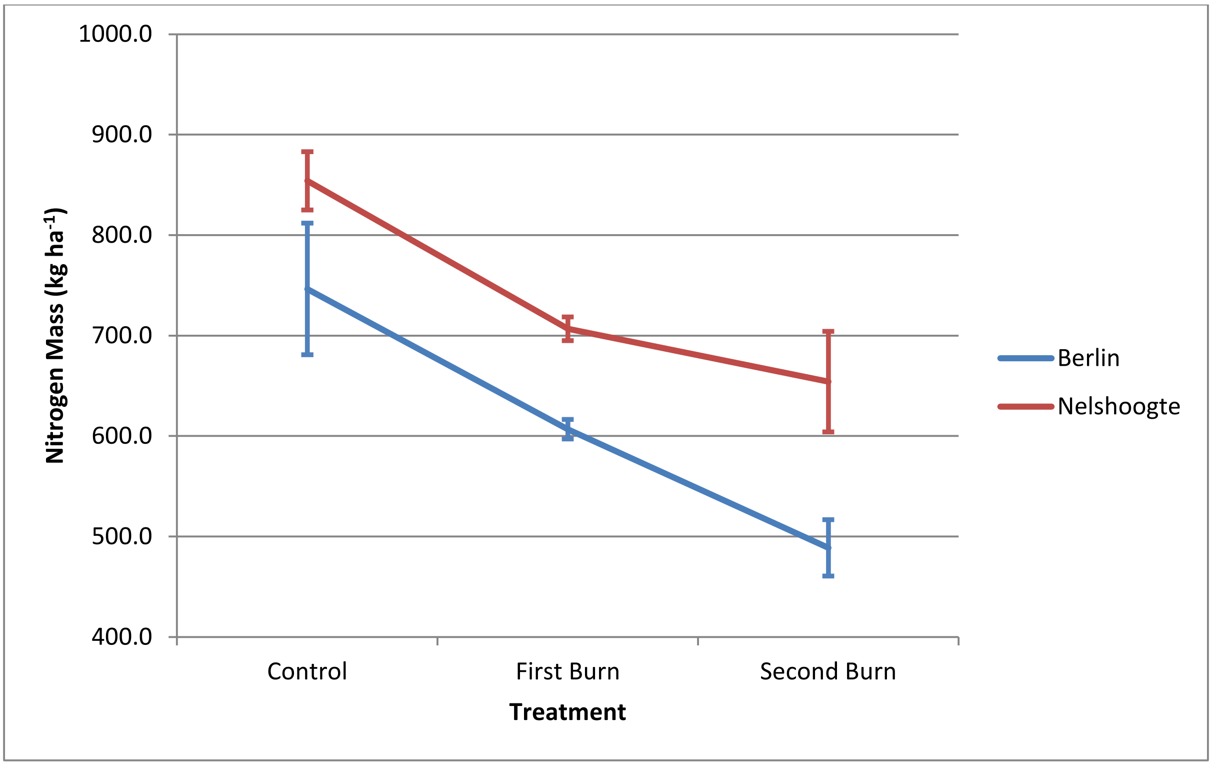

Figure 4.16: Nitrogen content between treatments expressed in kg ha^{-1} remaining.

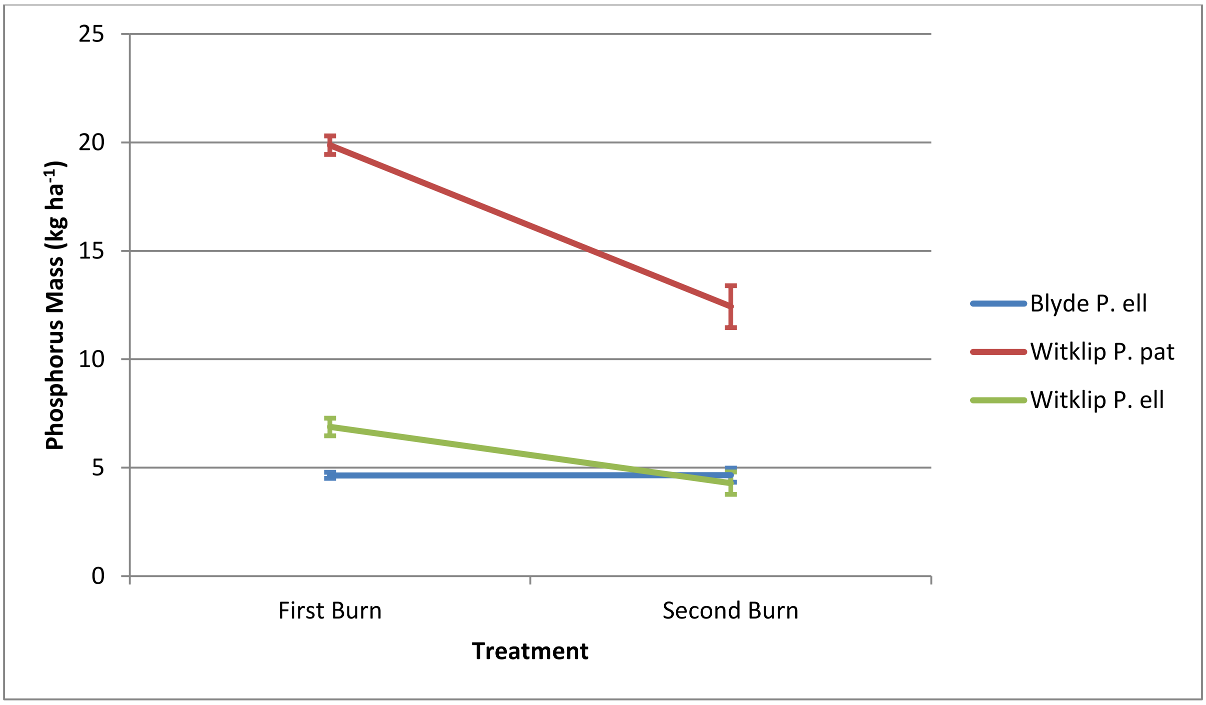

Figure 4.17: Phosphorus content between treatments expressed in t ha^{-1} remaining.

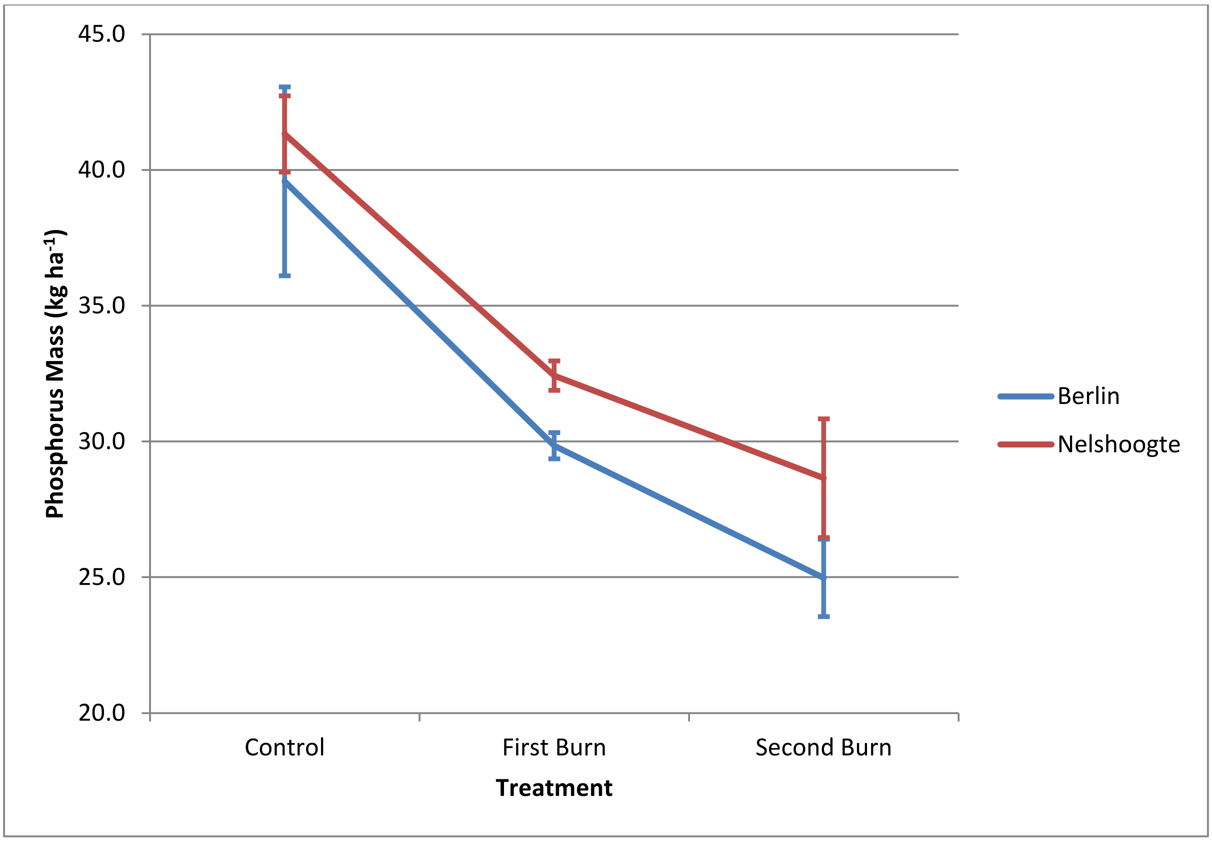

Figure 4.18: Phosphorus content between treatments expressed in t ha^{-1} remaining.

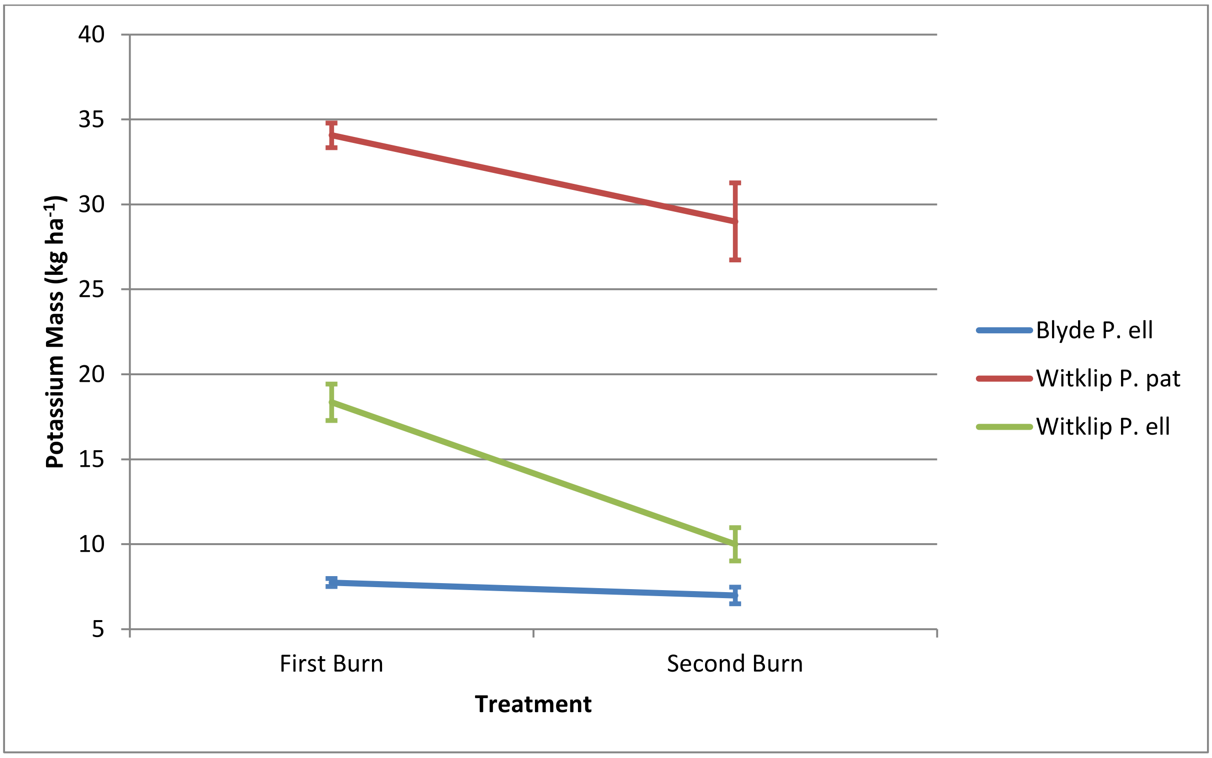

Figure 4.19: Potassium content between treatments expressed in t ha^{-1} remaining.

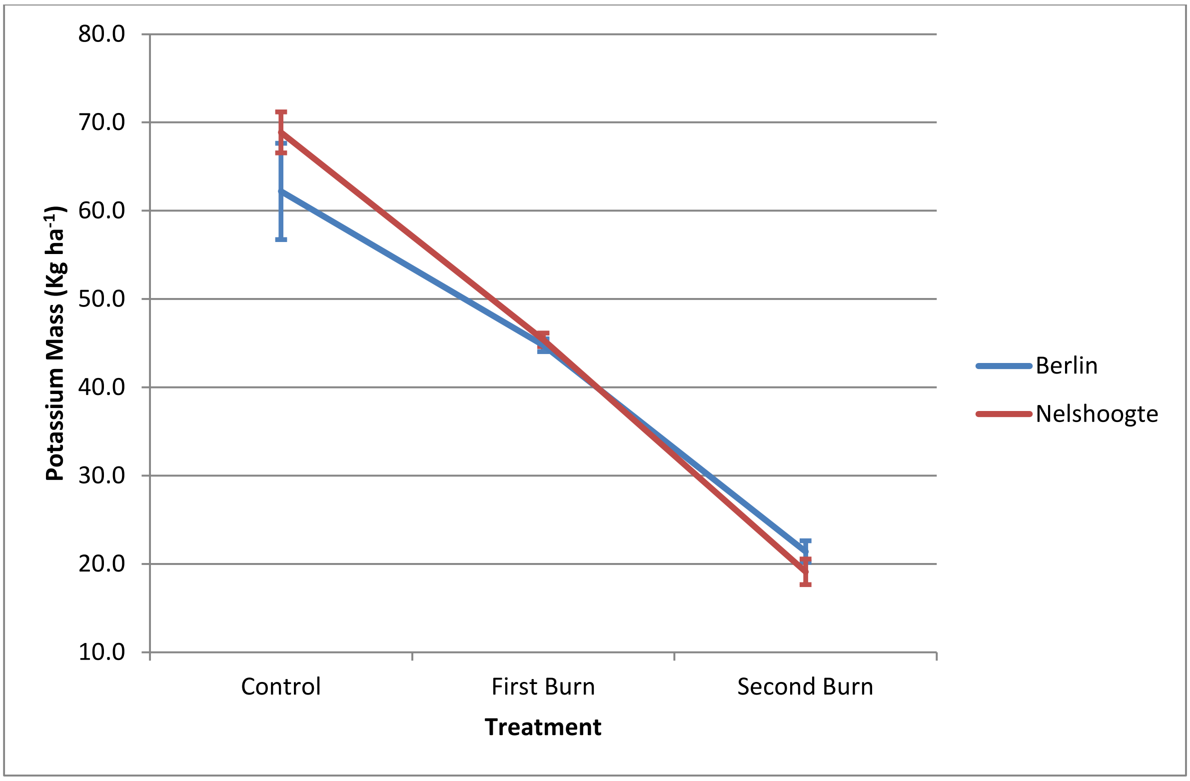

Figure 4.20: Potassium content between treatments expressed in t ha^{-1} remaining.

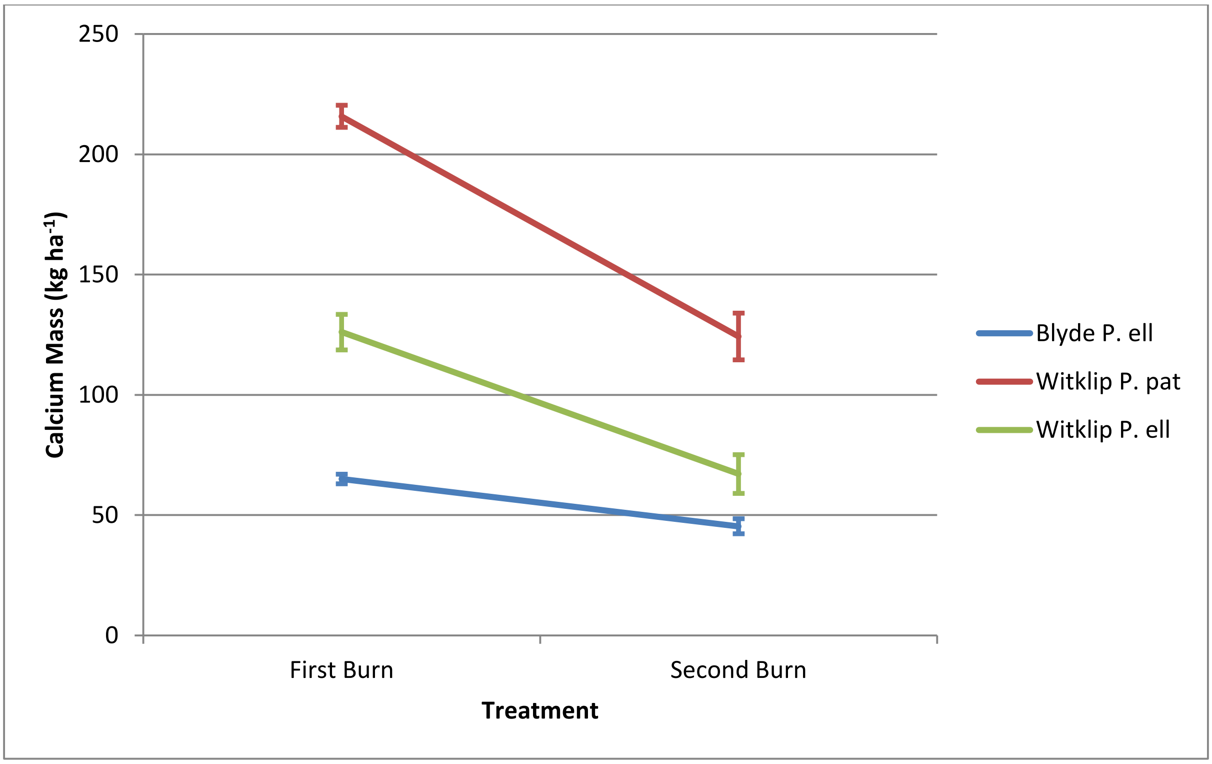

Figure 4.21: Calcium content between treatments expressed in t ha^{-1} remaining.

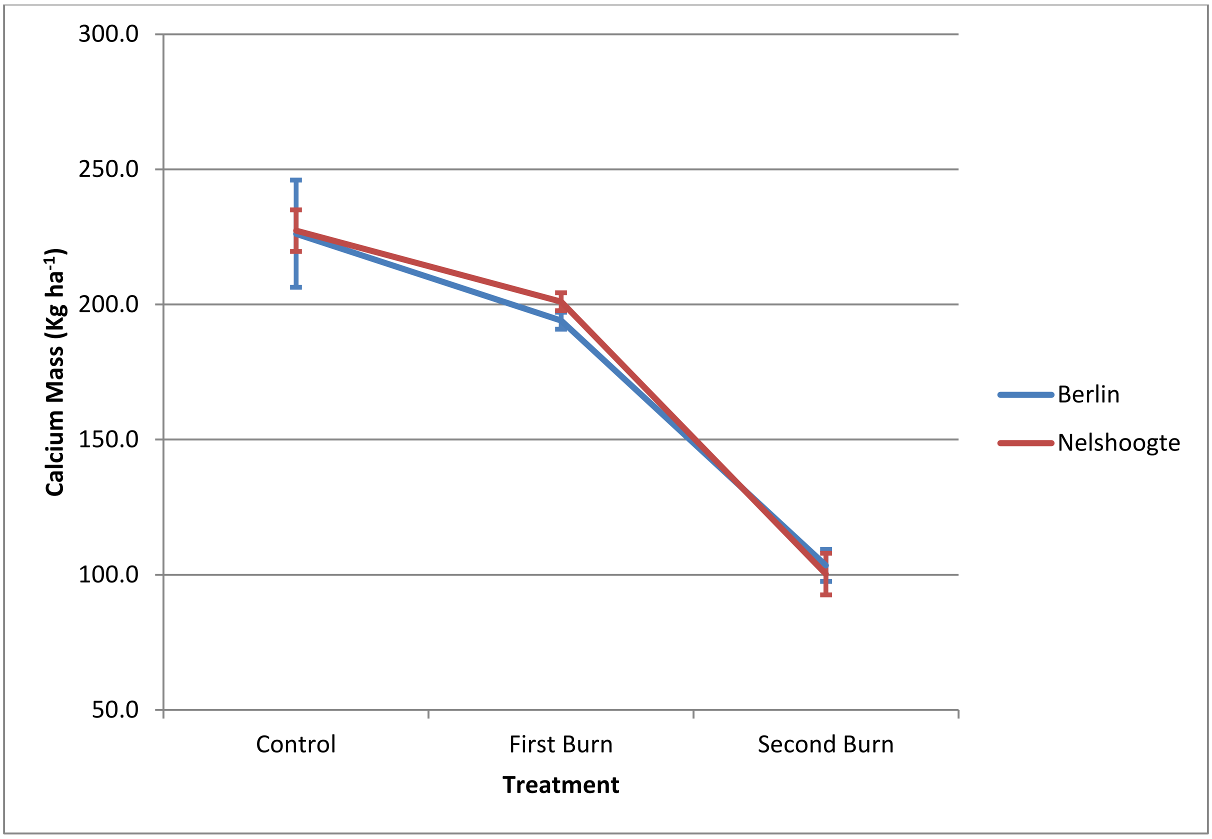

Figure 4.22: Calcium content between treatments expressed in t ha^{-1} remaining.

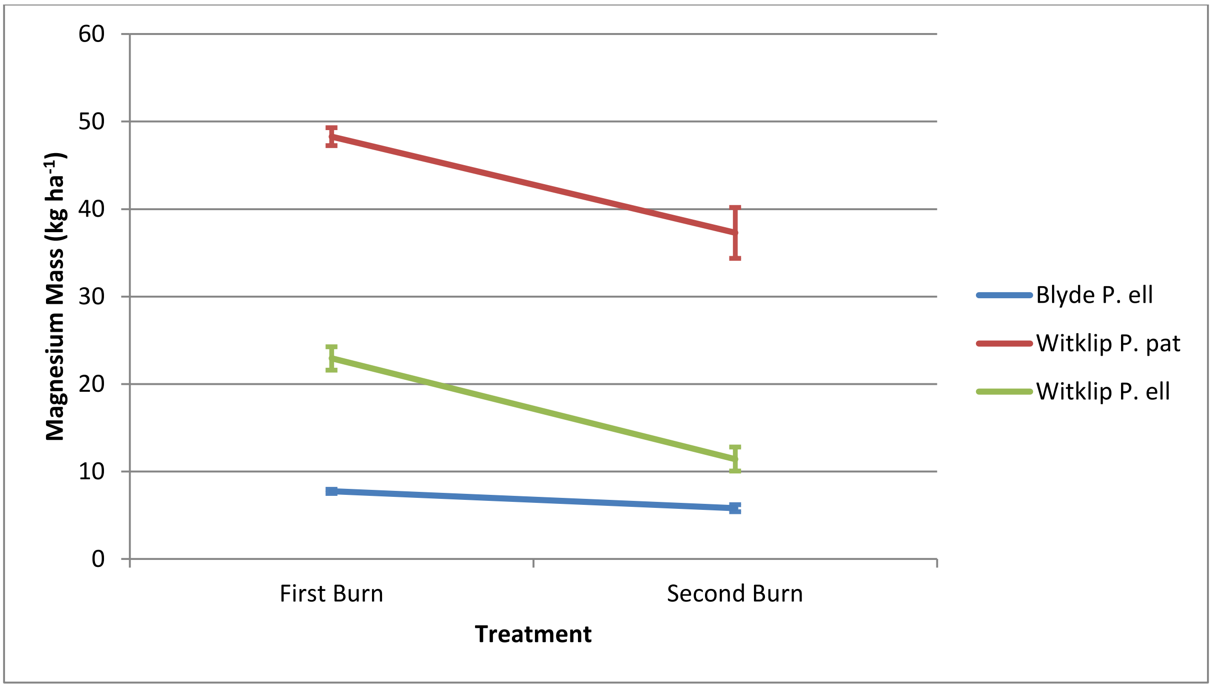

Figure 4.23: Magnesium content between treatments expressed in t ha^{-1} remaining.

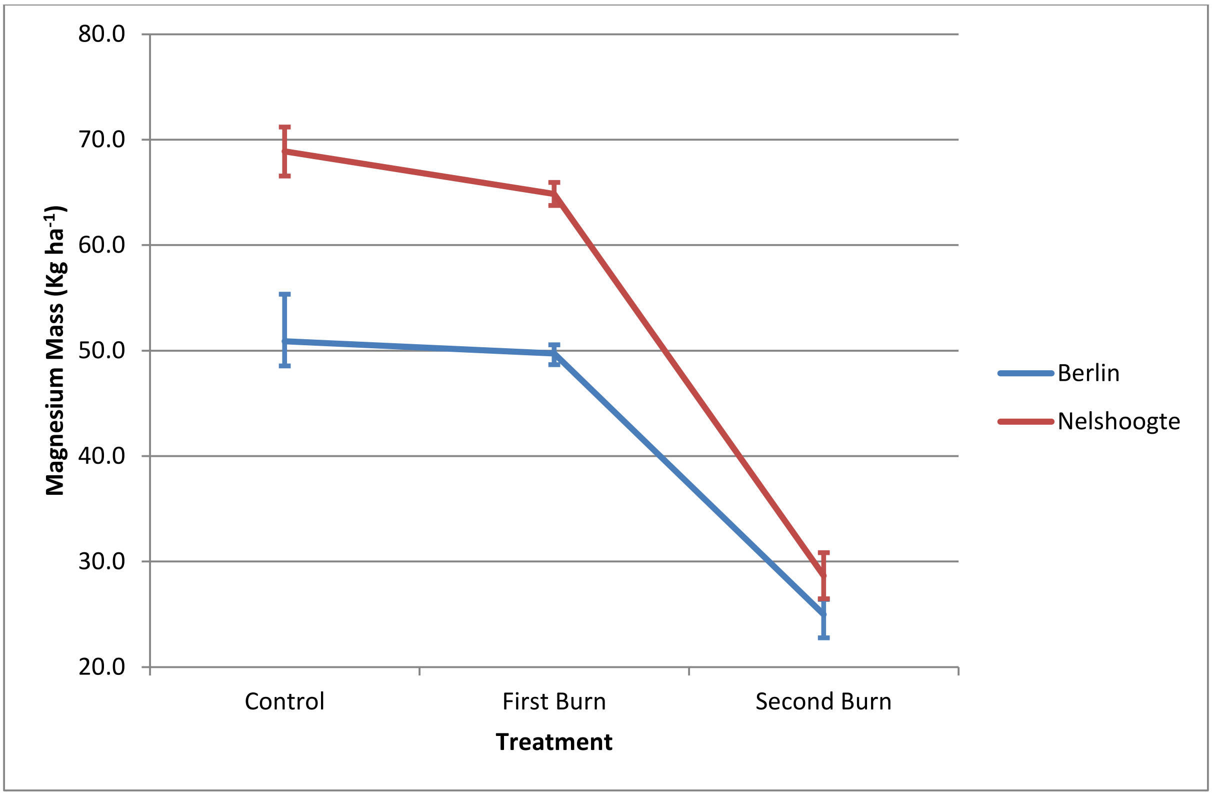

Figure 4.24: Magnesium content between treatments expressed in t ha^{-1} remaining.

4.3.2 Nutrient status of foliar litterfall

Nutrient status of pine foliage was determined from litterfall samples collected during the first two months following treatment implementation. No significant differences are evident between treatments although N during the first month seems to increase in the burnt treatments (Table 4.16 and 4.18).

When compared to actively growing needles, all macro nutrients except calcium are “deficient” for all *P. elliottii* trials and time period (Table 4.16). This can be explained by the ability of plants to translocate macro nutrients from old dying tissue, known as nutrient remobilization (Reuter & Robinson, 1997). Calcium concentration in foliage for *P. elliottii* less than 0.12% is considered deficient. The lowest observed Ca concentration for this species is 0.29%, which is still more than double the deficiency level. Macro nutrient levels in the present study were similar to freshly fallen litterfall nutrient levels recorded by Odiwe (2009) for both species (Table 4.16 & 4.18). Most micro nutrients are considered immobile as they do not have the ability to translocate through the plant (Reuter & Robinson, 1997). All micro nutrients in the *P. elliottii* trials display adequate concentrations (Table 4.17).

Critical micro nutrient levels for *P. patula* could not be found and therefore average nutrient levels from literature were used for comparison (Table 4.19). The current macro nutrient concentrations (Table 4.18) are all relatively similar to those published by Odiwe (2009). When comparing macro nutrient percentage to Schutz (1990), only N and P are below his recordings. This difference can perhaps be attributed to differently aged litter as foliage sampled in the present study was from freshly fallen needles. Zinc is the only micro nutrient that exhibits concentration levels above the average of Schutz (Table 4.19). With the exception of manganese, which in this study displays an average mass of 264 mg kg^{-1} compared to 1169 mg kg^{-1} of Schutz, all other micro nutrient levels are close to the average of Schutz (1990).

Table 4.16: Macro nutrient status of freshly fallen needles during the first two months following treatment implementation for *P. elliottii*.

Trial	Treatment	Time Since Treatment	N	P	K	Ca	Mg
	P. elliottii				%		
Witklip	Burnt	First Month	0.50	0.02	0.05	0.59	0.10
Witklip	Control	First Month	0.39	0.01	0.04	0.42	0.10
Witklip	Burnt	Second Month	0.45	0.02	0.14	0.48	0.13

Witklip	Control	Second Month	0.50	0.03	0.14	0.62	0.16
Blyde	Burnt	First Month	0.75	0.02	0.05	0.38	0.06
Blyde	Control	First Month	0.61	0.02	0.05	0.35	0.05
Blyde	Burnt	Second Month	0.69	0.02	0.03	0.37	0.07
Blyde	Control	Second Month	0.60	0.01	0.05	0.29	0.05
	*Average		0.56	0.02	0.07	0.44	0.09
	*Deficiency levels in canopy		<1.00	<0.10	<0.35	<0.05	<0.04
	Litterfall (Odiwe, 2009)		0.53	0.03	0.06	0.55	0.10

**Reference: (Combination of P. radiata, P. elliottii and P. taeda with consideration of nutrient ratios between conifers, Reuter & Robinson, 1997; Linder, 1995.)*

Table 4.17: Micro nutrient status of freshly fallen foliage during the first two months following treatment implementation for *P. elliottii.*

Trial	Treatment	Time Since Treatment	Mn	Fe	Cu	Zn	B
	P. elliottii				mg kg^{-1}		
Witklip	Burnt	First Month	1152	70	2	17	13
Witklip	Control	First Month	662	74	2	15	12
Witklip	Burnt	Second Month	818	101	2	21	16

Witklip	Control	Second Month	967	111	3	22	18
Blyde	Burnt	First Month	2831	139	3	21	17
Blyde	Control	First Month	3029	125	2	53	17
Blyde	Burnt	Second Month	2869	168	2	51	18
Blyde	Control	Second Month	2447	143	2	42	16
	Average		1847	117	2	30	16
	*Deficient		N.A	N.A	<2	6-10	<8-10
	*Adequate		284	65-404	N.A	10-68	N.A

** N.A: Not available*

** Reference: (Reuter & Robinson, 1997)*

Table 4.18: Macro nutrient status of freshly fallen foliage during the first two months following treatment implementation for *P. patula.*

Trial	Treatment	Time Since Treatment	N	P	K	Ca	Mg
	P. patula				%		
Witklip	Burnt	First Month	0.82	0.05	0.23	0.60	0.20
Witklip	Control	First Month	0.73	0.04	0.22	0.58	0.18
Witklip	Burnt	Second Month	0.68	0.04	0.30	0.64	0.23

Witklip	Control	Second Month	0.66	0.03	0.20	0.52	0.16
	Average		0.72	0.04	0.24	0.59	0.19
	Deficiency levels in canopy		<1.00	<0.10	<0.35	<0.05	<0.04
	Litterfall (Odiwe, 2009)		0.88	0.07	0.25	0.48	0.16
	Litterfall (Schutz, 1990)		1.28	0.16	0.10	0.28	0.08
	Foliar (Schutz, 1990)		2.08 (1.92-2.30)	0.18 (0.16-0.21)	1.04 (0.75-1.32)	0.30 (0.14-0.57)	0.19 (0.12-0.26)

Table 4.19: Micro nutrient status of freshly fallen needles during the first two months following treatment implementation for *P. patula.*

Trial	Treatment	Time Since Treatment	Mn	Fe	Cu	Zn	B
	P. patula				mg kg^{-1}		
Witklip	Burnt	First Month	237	89	3	16	12
Witklip	Control	First Month	257	92	2	17	45
Witklip	Burnt	Second Month	264	74	3	37	15
Witklip	Control	Second Month	296	147	2	42	10
	Average		264	101	3	28	12

Deficient	N.A	N.A	N.A	N.A	N.A
Schutz (1990)	809 (276-2187)	137 (37-291)	7 (2-30)	24 (16-34)	24 (15-38)

** note that Schutz had sampled on some Mn rich areas (dolomite and Chert formations) that are strongly acidic, thus brining manganese ions into the soil solution, resulting in luxury uptake, nearly to the point of toxicity on some sites. The lower level of Schutz's range is a more realistic number for average Mn levels outside of stand on Mn rich geologies.*

4.3.3 Soil Nutrients

In this section soil nutrients will be presented in such a way as to accommodate both treatment differences and the fact that soil sampling occurred during two different time periods (2 months and 5 months after treatment implementation respectively).

All trials were spread out over dolomitic and granitic geological formations. Granite derived soil usually has very high available P and lower carbon content than dolomite derived soils. Soil pH and the nutrients K, Ca and Mg are usually slightly lower in granite than in dolomite derived soils and are considered moderately fertile for the Mpumalanga Escarpment area (Schutz, 1990). Dolomite derived soils have the highest pH and lowest extractable acidity of all soils in the Mpumalanga Escarpment area due to the limestone origin. Available P is relatively low whereas K, Ca and Mg in these soil formations display the highest concentrations in the Mpumalanga Escarpment area (Schutz, 1990).

Clay percentage ranged from 35 – 40 and 20 – 35% in the dolomite and granite derived soils respectively.

Table 4.20: Geology and soil data for all trials.

Trial	Berlin		Blyde	Nelshoogte		Witklip *P. elliottii*	Witklip *P. patula*
Compartment	M29	M31	A87	E28a	E38	B67	M33a
Geology	Dolomite			Granite			
Dominant soil	Kranskop	Inanda	Hutton	Inanda		Hutton	
Texture	ClLm-Cl	ClLm	ClLm – SiClLm	SaClLm -SaCl		MeSa ClLm	SaLm - SaClLm
Clay %	40	35	35	35		25	20
Depth (cm)	60-90	30-60	>150	90-120	120-150	60-90	90-120

Soil pH (KCl) was found to be below 4 (except Witklip *P. patula*) corresponding with average levels recorded by Sugarman (1999) in the Mpumalanga escarpment region (Table 4.21). Schutz (1990) calculated soil pH with H_2O which could explain the higher pH recorded. Effective cation exchange capacity (ECEC) over all trials was high (*circa* 5.66 cmol kg^{-1}) in comparison with mean granite derived forest soils in South Africa of 3.06 (MacLennan, 1998). All the soils are considered mesotrophic with an ECEC above 5, except Witklip *P. elliottii* which is dystrophic (3.29), (Soil Classification Working Group, 1991). All base cations were below the average recorded for granite soils in plantation forestry of South Africa, except Witklip *P. patula* (MacLennan, 1998). Carbon and P were similar to founding's made by Schutz (1990).

Table 4.21: Soil nutrients, pH and carbon content.

Trial	Treatment	(in KCl)	%	mg kg-1	cmol kg-1				%
		pH	N	P	K	Ca	Mg	Na	C
Berlin	Control	3.47	0.33	4.67	0.08	0.32	0.20	0.07	2.57
	First	3.47	0.39	4.33	0.09	0.30	0.22	0.07	2.57
	Second	3.73	0.28	4.67	0.07	0.22	0.24	0.06	N.A
Blyde	First	3.67	0.35	4.67	0.08	0.31	0.07	0.05	2.58
	Second	3.70	0.33	5.33	0.10	0.37	0.13	0.05	2.57
Nelshoogte	Control	3.50	0.38	3.33	0.05	0.10	0.04	0.05	2.55
	First	3.70	0.26	3.33	0.05	0.07	0.04	0.05	2.53
	Second	3.83	0.18	3.00	0.06	0.15	0.15	0.05	2.96
Witklip	First	3.37	0.17	2.67	0.06	0.21	0.11	0.05	1.94
P. elliottii	Second	3.77	0.13	4.00	0.06	0.32	0.15	0.05	1.84
Witklip	First	4.77	0.11	3.33	0.16	3.29	1.00	0.06	1.49
P. patula	Second	4.73	0.14	3.33	0.16	3.15	1.03	0.06	1.71

Sugarman (1990)	Average (KCl)	3.86	N.A	N.A	N.A	N.A	N.A	N.A	N.A
	Granite	*4.90	N.A	6.70	0.10	0.59	0.28	N.A	2.30
Schutz (1990)	Dolomite	*5.00	N.A	3.90	0.12	0.66	0.31	N.A	3.50
	Oaktree	*4.60	N.A	3.40	0.06	0.08	0.08	N.A	5.20
MacLennan (1998)	Granite	N.A	N.A	N.A	0.18	1.80	1.00	0.08	N.A

**pH (H_20)*

***N.A: Data not available*

****Grey Shading: Nutrient content found in RSA Plantation soils.*

As for soil nutrient and pH differences between treatments only soil pH is significantly different (p=0.001) from the rest in the *P. elliottii* trial at Witklip plantation (Table 4.22). Nitrogen and Magnesium show significant differences between the first burn and second burn treatments in trial Nelshoogte. No significant differences of soil nutrients between treatments were observed in the remaining 4 trials. Nitrogen and Magnesium differed significantly between the control plots and the second burnt plots and also between the first burn and second burnt plots for Mg (Table 4.23).

Table 4.22: ANOVA Table presenting soil nutrient and pH differences between treatments.

Trial	Soil Nutrient	Df	Sum Sq	Mean Sq	F value	*p-value*
Nelshoogte	N	2	0.058	0.029	5.736	0.041
		6	0.030	0.005		
	Mg	2	0.024	0.012	13.48	0.010
		5	0.005	0.001		
Witklip *P. elliottii*	pH	1	0.240	0.240	72	0.001
		4	0.013	0.003		

Table 4.23: Tukey Contrast Table presenting significant soil nutrient differences between treatments.

Trial	Soil Nutrient	First Burn - Control	Second Burn - Control	Second Burn – First Burn
Nelshoogte	N	0.179	0.035	0.446
	Mg	1.000	0.020	0.013

**Grey Shading: Significant Difference*

4.3.3.1 Soil pH

Trial Witklip *P. elliottii* shows a significant pH difference between treatments (Figure 4.25) but Blyde and Witklip *P. patula* exhibit almost no difference in soil pH between treatments. It is of interest to note the difference in soil pH between the two species - *Pinus patula* in Witklip has an average soil pH of almost 5 compared to a pH below 4 in the *P. elliottii* trials.

The soil pH for trials Berlin and Nelshoogte shows similar pH values as the *P. elliottii* trials in Figure 4.26. There is a non-significant increase in soil pH with increasing fire frequency. Nelshoogte was almost weakly significant (*p*=0.1) and shows a linear increase in soil pH. Berlin shows a pH increase from the first burn to the second burnt plots two months following treatment implementation.

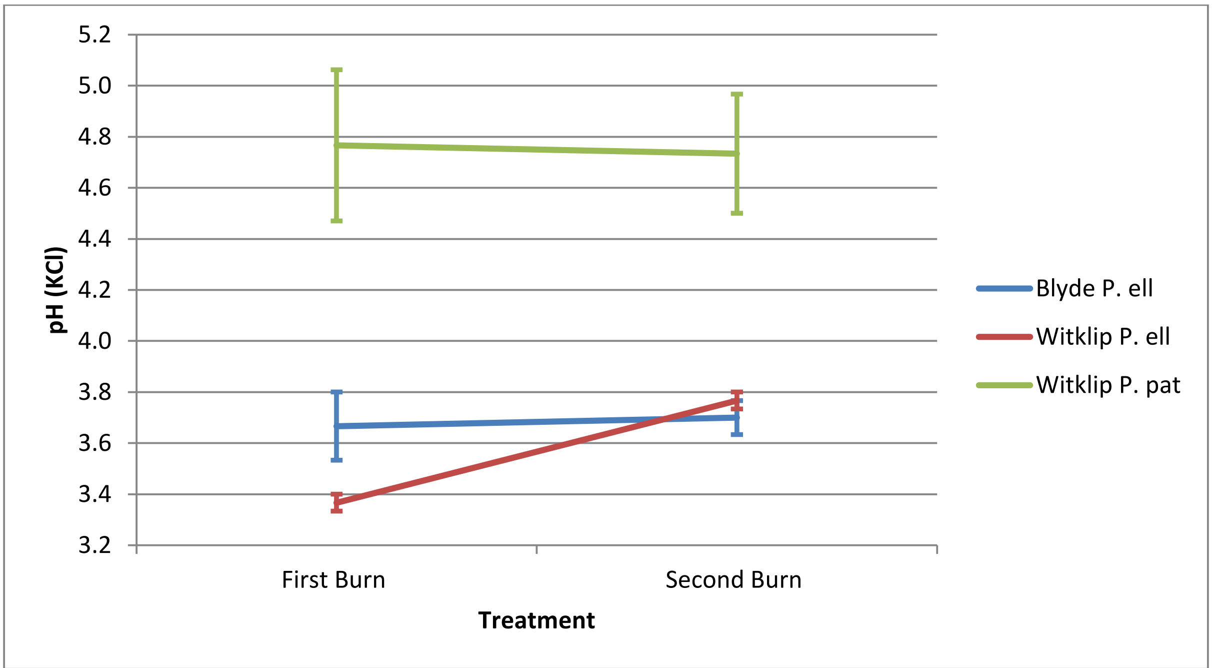

Figure 4.25: Soil pH 5 months following treatment implementation.

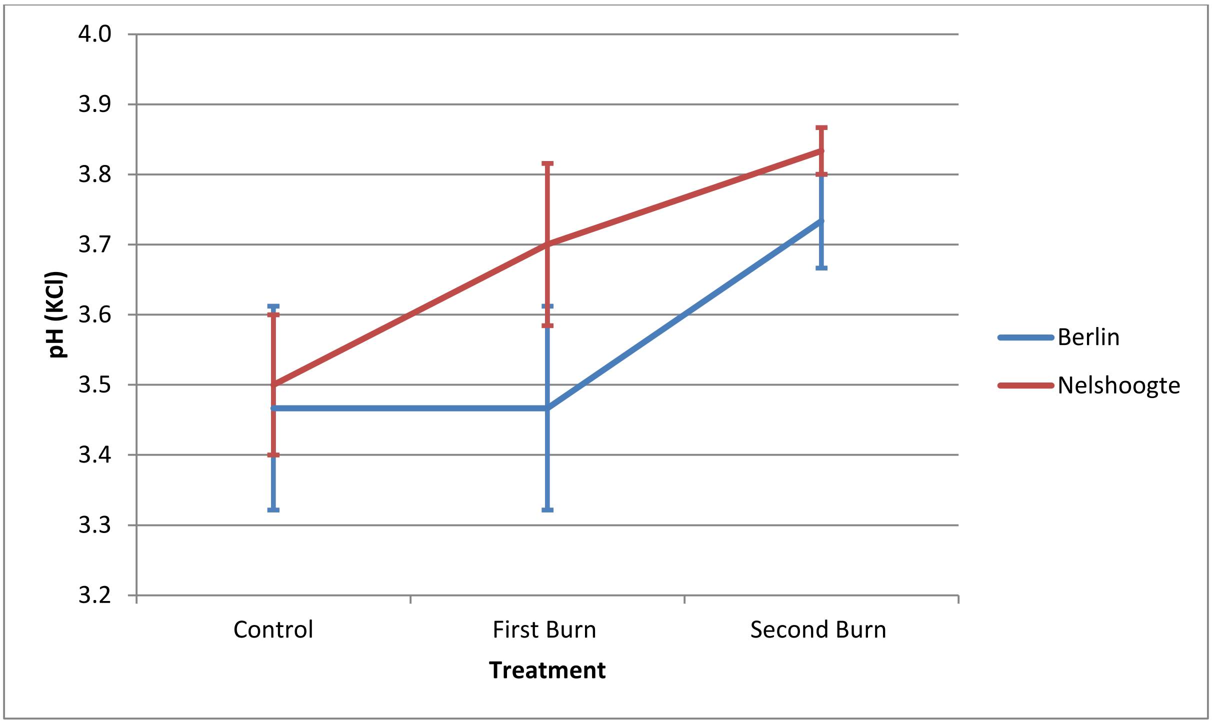

Figure 4.26: Soil pH 2 months following treatment implementation.

4.3.3.2 Macro Nutrients

With regard to macro nutrients, Blyde has the highest total soil nitrogen percentage and phosphorus content in trials sampled 5 months following treatment implementation (Figure 4.27 and 4.29). Total percentage nitrogen decreased significantly (p=0.035) from the control to the second burnt treatment in trial Nelshoogte two months after the second burn treatment (Figure 4.28). Phosphorus content in the trials sampled two months following the second burn treatment (Figure 4.30) are similar to the P content found in the trials sampled 5 months (Figure 4.29) after treatment implementation. The *P. patula* trial in Witklip shows big differences in K, Ca and Mg content in comparison to the rest of the trials sampled 2 and 5 months following treatment implementation (Figures 4.31 – 4.36). The largest difference occurring in Figure 4.33 showing the Ca content of *P. patula* in Witklip exceeding 3 cmol kg^{-1} in comparison with the rest of the trials which has a Ca content less than 0.5

cmol kg^{-1}. Potassium and Ca content in trials Berlin and Nelshoogte followed the same trend from the first to the second burnt treatment (Figure 4.32 and 4.34). In both Figures the nutrient content decreased from the first to the second burnt treatment in trial Berlin and increased for the same treatment in trial Nelshoogte. Figure 4.36 shows a significant increase in Mg content from the control and first burnt to the second burnt treatments at trial Nelshoogte. Nutrient differences between trialsare evident as Blyde has higher N and P concentrations in the soil in comparison with Witklip *P. patula* and *P. elliottii* but changes in K, Ca and Mg concentrations where Witklip *P. patula* records the highest concentrations.

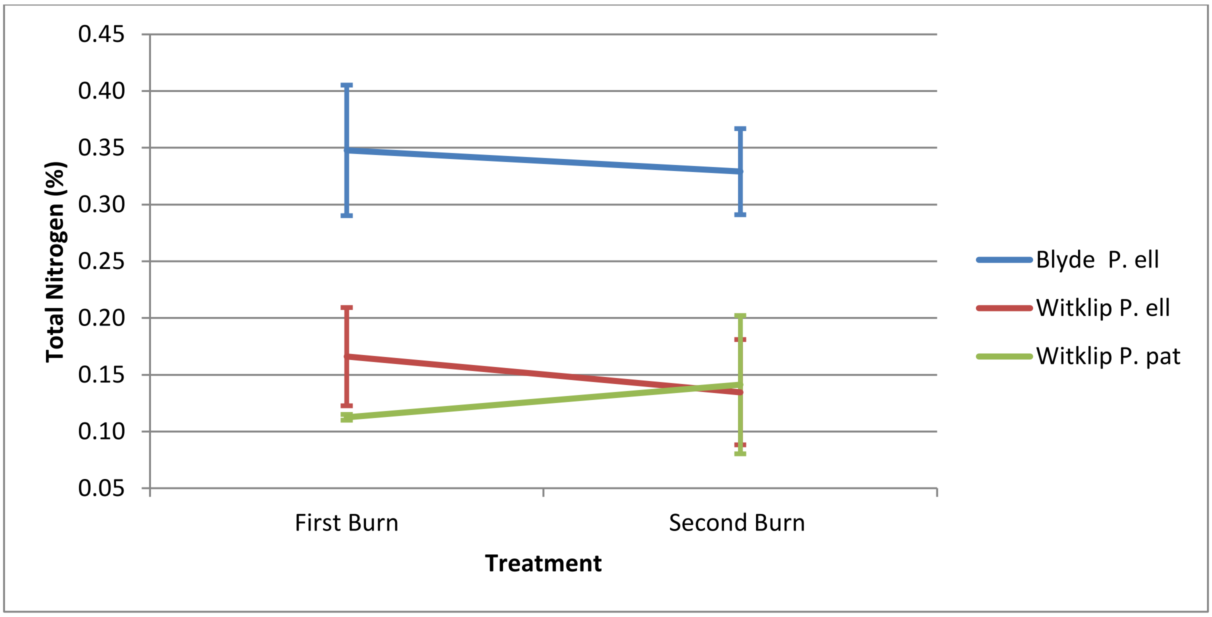

Figure 4.27: Percentage total nitrogen in the topsoil 5 months following treatment implementation.

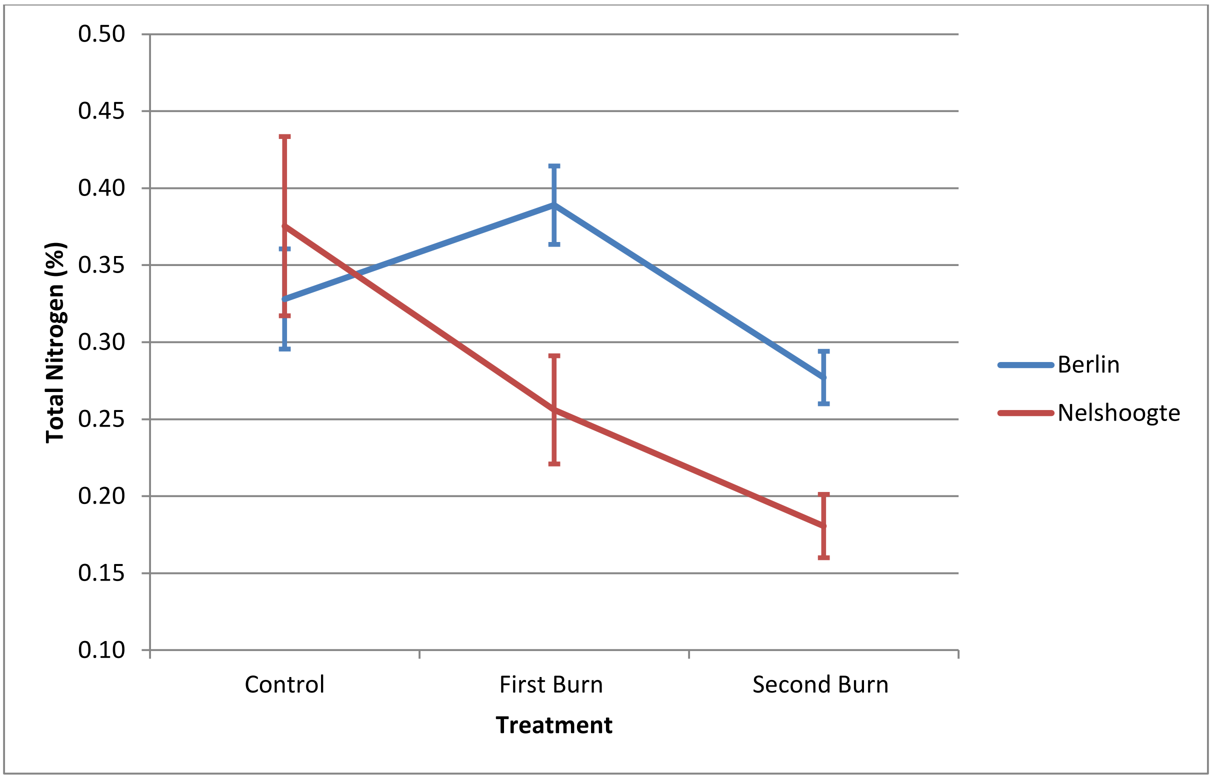

Figure 4.28: Percentage total nitrogen in the topsoil 2 months following treatment implementation.

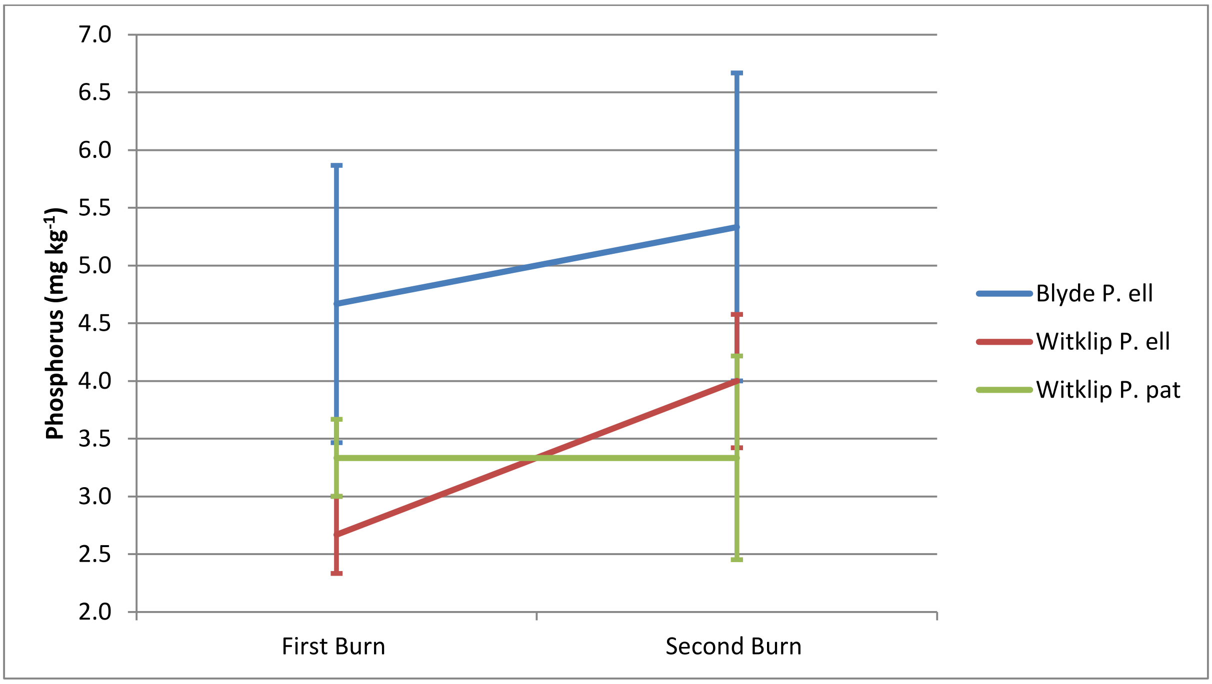

Figure 4.29: Bray #2 extractable Phosphorus concentration in the topsoil 5 months following treatment implementation.

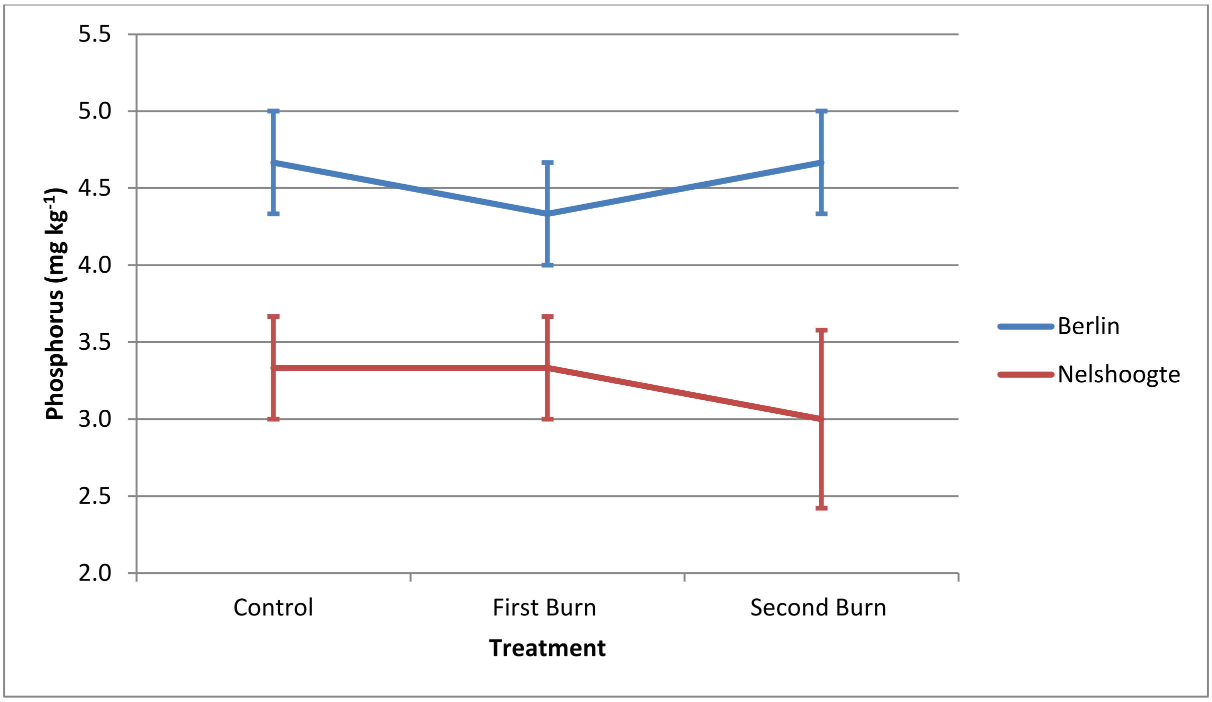

Figure 4.30: Bray #2 extractable Phosphorus concentration in the topsoil 2 months following treatment implementation.

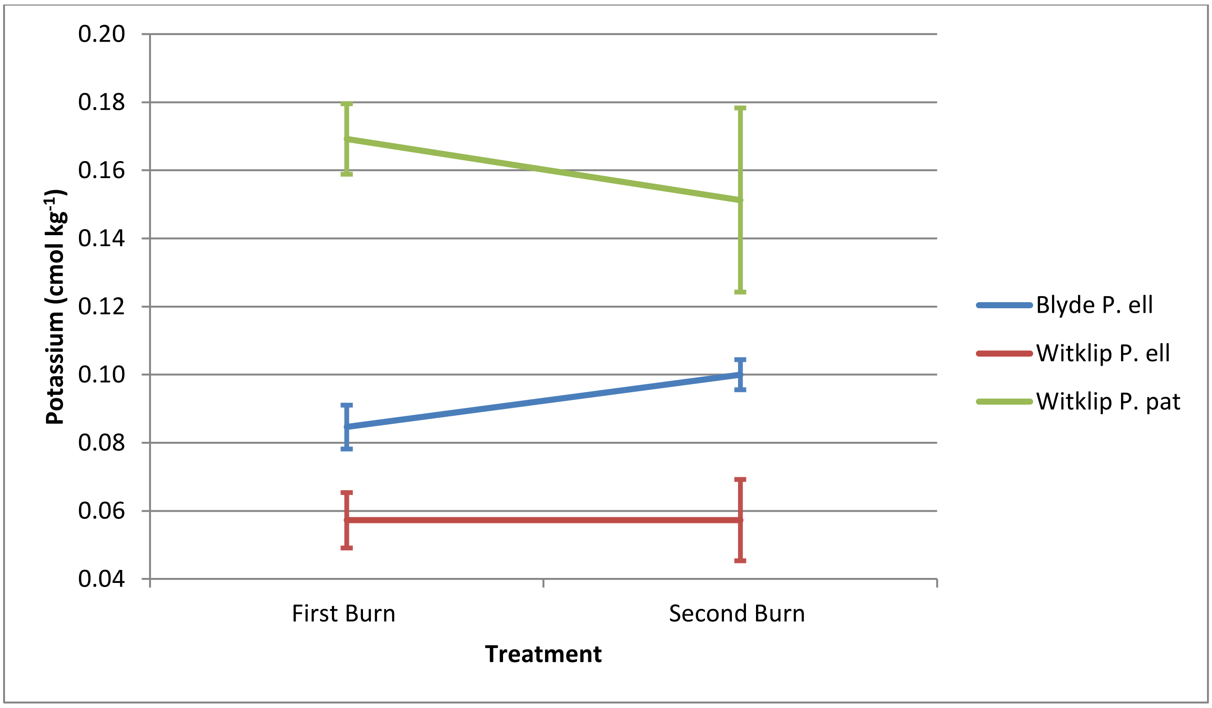

Figure 4.31: Potassium concentration in the topsoil 5 months following treatment implementation.

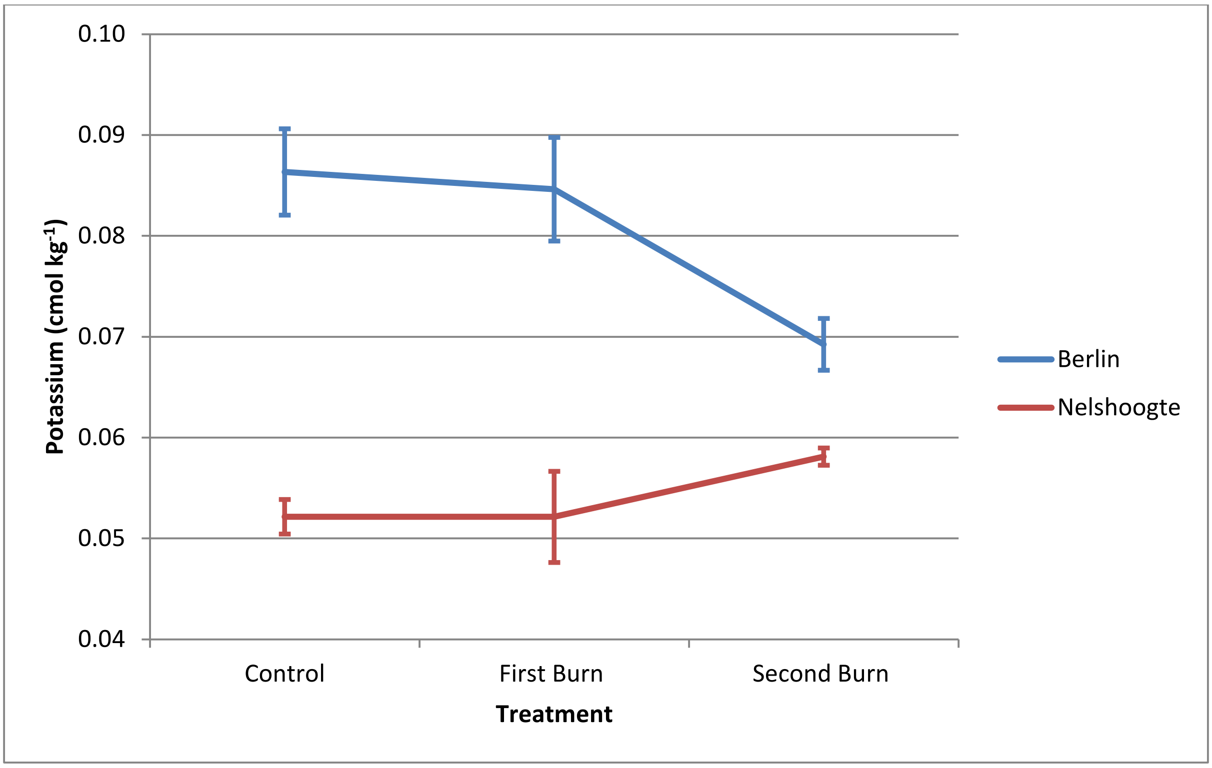

Figure 4.32: Potassium concentration in the topsoil 2 months following treatment implementation.

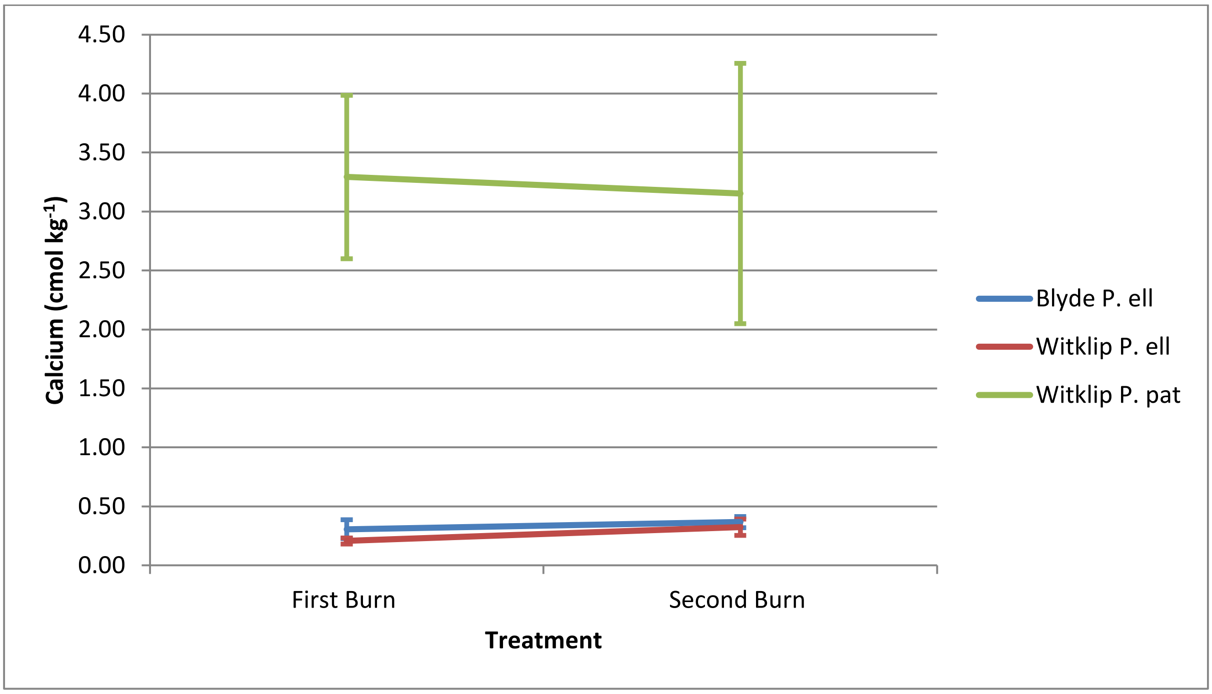

Figure 4.33: Calcium concentration in the topsoil 5 months following treatment implementation.

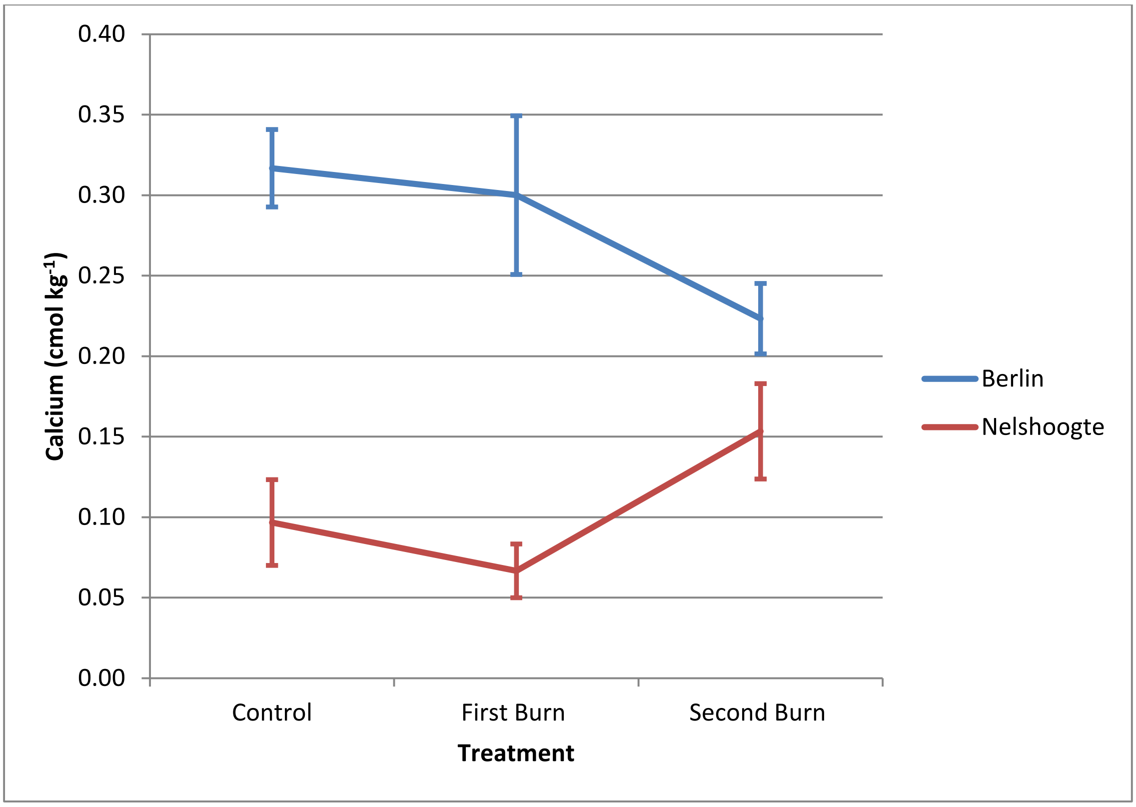

Figure 4.34: Calcium concentration in the topsoil 2 months following treatment implementation.

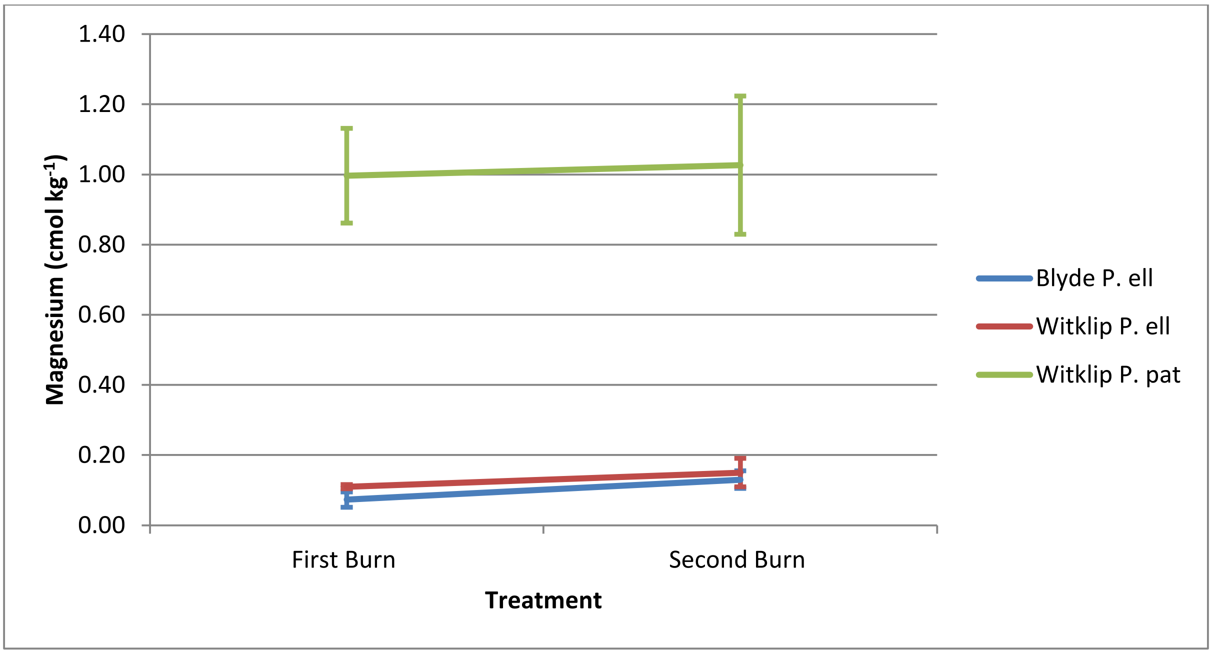

Figure 4.35: Magnesium concentration in the topsoil 5 months following treatment implementation.

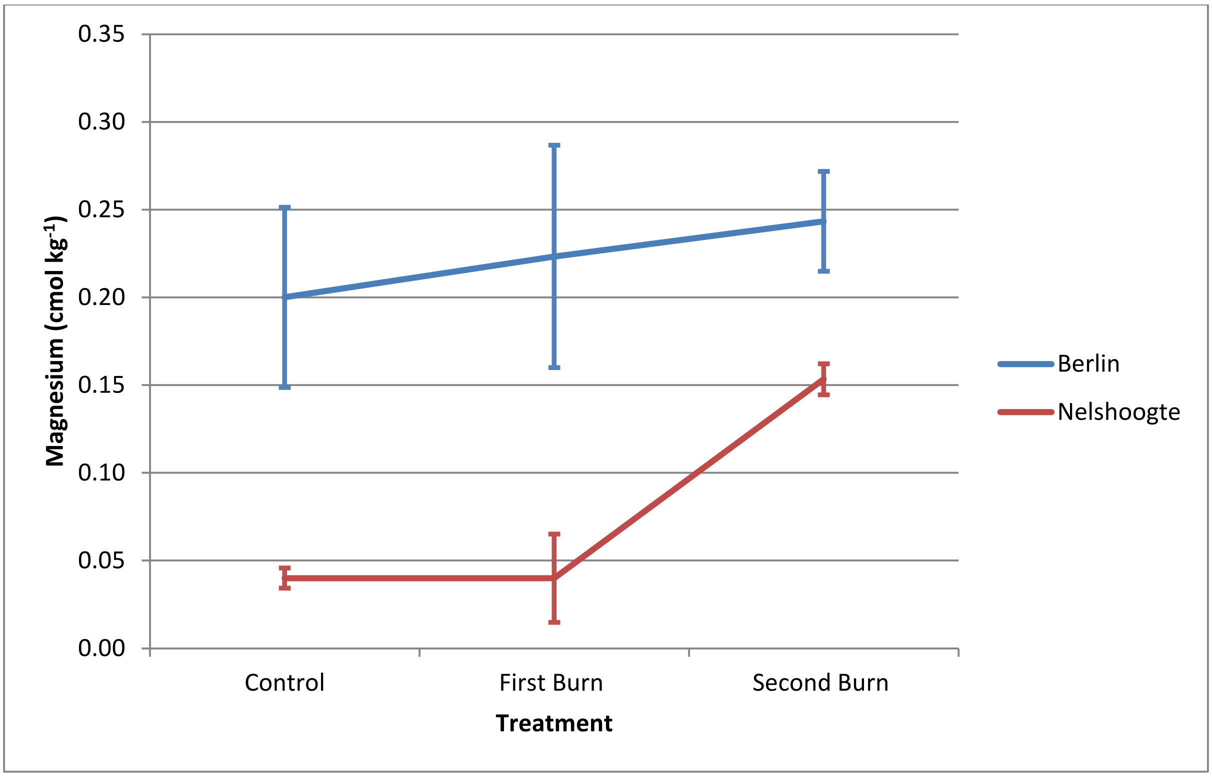

Figure 4.36: Magnesium concentration in the topsoil 2 months following treatment implementation.

4.4 Fireline Intensity

The fire prediction model BehavePlus5 did not produce an output for trial Witklip *P. patula* due to fuel moisture percentage being too high (Table 4.29). The trial did however burn and removed 7.6 t ha^{-1}. Trial Blyde had an average fuel moisture percentage of 30% but due to dried out slash inside the plots, 1 hour fuel moisture was reduced to 15% in the model simulation. According to the model trial Blyde and Berlin would have experienced crown scorch. The model predicts that with a wind speed of 6 km h^{-1}, crown scorch of up to 6.9 m could have occurred in trial Blyde. The model predicts heavy crown scorch in trial Berlin which received no crown scorch. This is due to the lower branches having no needles as a result of the shading out of the higher branches. The wind speeds used in the model were the variance captured during the burning application using a Kestrel and represents the effect wind speed has on fire dynamics.

Table 4.24: BehavePlus5 fire prediction model output for all 5 trials using ambient fuel load, fuel moisture, topographical and climatic conditions across a range of wind speeds measured during the fire event.

Trial	Midflame Wind Speed (km h^{-1})	Rate Of Spread (Max) (m min^{-1})	Heat per Unit Area (kJ m^{-2})	Fireline Intensity (kW m^{-1})	Flame Length (m)	Scorch Height (m)
Berlin	2	1.7	13 510	383	1.2	7.4
	3	2.1	13 510	482	1.3	8.5
	4	2.7	13 510	602	1.5	9.6
	5	3.3	13 510	738	1.6	10.8
	6	4.0	13 510	890	1.8	11.9
Nelshoogte	2	0.6	9 223	96	0.6	2.8
	3	0.9	9 223	136	0.7	3.4
	4	1.2	9 223	183	0.9	3.9
	5	1.5	9 223	238	1.0	4.4
	6	1.9	9 223	298	1.1	4.8

	7	2.4	9 223	364	1.2	5.2
	3	1.8	5 895	175	0.8	4.3
Blyde	4	2.5	5 895	248	1.0	5.2
	5	3.4	5 895	332	1.1	6.1
	6	4.3	5 895	425	1.3	6.9
Witklip	3	0.5	3 952	32	0.4	1.1
P. elliottii	4	0.7	3 952	44	0.4	1.1
	5	0.9	3 952	57	0.5	1.2
Witklip *P. patula*	N.A	N.A	N.A	N.A	N.A	N.A

**Grey Shading: Representing average fire conditions*

4.5 Tree Damage

Tree damage is divided in three categories namely cambium damage, crown scorch and root damage. If areas where the fire burnt through to mineral soil were observed, root damage was automatically assumed. Such areas were investigated to quantify the amount of roots burnt through by grouping each tree accordingly in a specific root damage class. Cambium damage was determined by removing a piece of cambium suspected of damage and placing it in a tetrazolium solution. If resin was observed cambium damage was automatically assumed. Crown scorch was determined by observation after scorched needles turned brown.

4.5.1 Root Damage

Significant differences existed between root damage classes for both (Table 3.4). In trial Berlin, damage class 1 differed significantly (*p*=<0.001) from all other damage classes (Table 4.25). In the Nelshoogte trial damage class 0 and 1 differ significantly from the rest of the damage classes.

Table 4.25: ANOVA representing root damage class differences for trial Berlin and Nelshoogte.

Trial	Df	Sum Sq	Mean Sq	F value	*p-value*
Berlin	4	7554	1888.5	27.44	<0.001
	10	688	68.8		
Nelshoogte	4	2367.9	592	20.75	0.003
	5	142.6	28.5		

Table 4.26: Tukey Contrast Table presenting differences between root damage classes.

Trial	Root Damage Class					
	1 - 0	3 - 0	4 - 0	2 - 1	3 - 1	4 - 1
Berlin	<0.001			<0.001	<0.001	<0.001
Nelshoogte		0.015	0.008		0.007	0.004

Root damage was observed in trials Berlin and Nelshoogte as clean burnt areas (patches around trees where FF was burnt to the mineral soil) only occurred in these two trials. Figure 4.37 illustrates that in both trials more than 70% of trees were grouped in the root severity damage class of zero and one. Less than 10% of trees received root damage above class two in both trials, bearing in mind that class four is the most severe damage recognised.

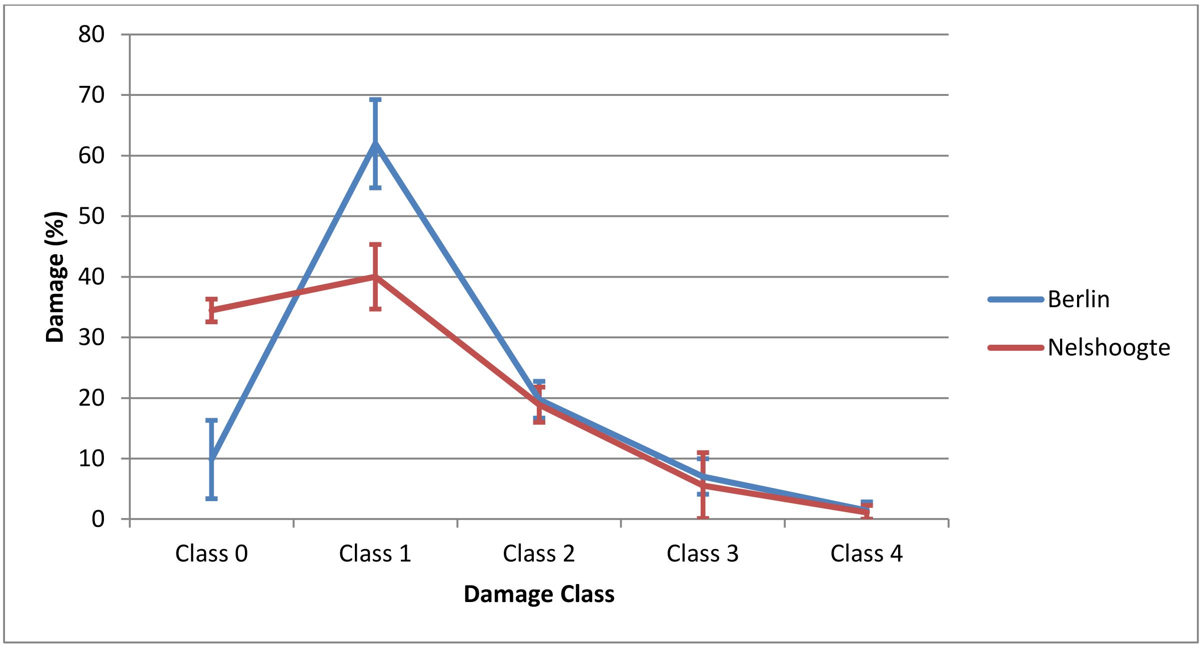

Figure 4.37: Root Damage grouped in severity classes for trials Berlin and Nelshoogte.

4.5.2 Crown Scorch

Crown canopy scorch only occurred inside the Blyde trial. Table 4.26 illustrates the severity of the scorch on trees inside the three different replications. Crown scorch occurred on all three replications and varied from 5-25% of trees inside the trial. The average crown scorch height of the canopy was constant over all three replications (Table 4.25). The total percentage crown scorch per plot was calculated by multiplying the midpoint of the average crown height percentage with the percentage trees scorched per replication. The trial received minor scorch with replication three yielding the highest scorch percentage of only 3%. In replication three, only three percent of the total crown canopy was scorched whilst 1% was scorched in replication one.

Table 4.27: Needle scorch percentage in all three replications of trial Blyde.

Needle Scorch					
Plantation	Species	Rep	Average crown scorch height class (%)	Total Trees with scorch per plot (%)	Total crown scorch per plot (%)
		1	0 - 25	5-10	0.9
Blyde	*P. elliottii*	2	0 - 25	10-15	1.6
		3	0 - 25	15-25	2.5

4.5.3 Cambium Damage

Damage to a portion of the cambium only occurred in trials Berlin and Nelshoogte (Figure 4.38). Nelshoogte received the highest cambium damage where 19% of the trees inside the three replications had resin on the stem following treatment in comparison with 8% found in Berlin. When areas suspected of cambium damage were sampled and tested for both trials no dead cambium tissue was found.

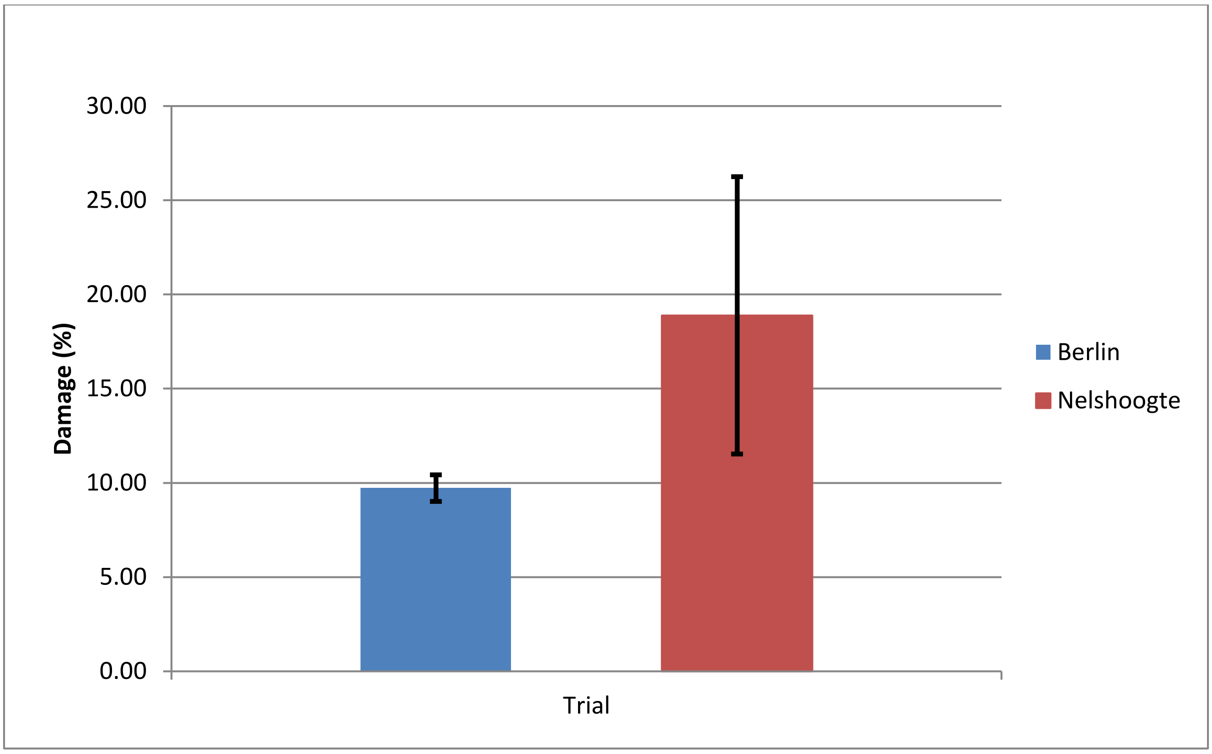

Figure 4.38: Cambium damage observed infield, presented as percentage of all trees showing signs of resin exudation near the base after being subjected to the second burn treatment in trials Belin and Nelshoogte.

4.6 Understorey Growth

Understorey growth was monitored following treatment implementation using the Braun-Blanquet cover abundance scale as described in Chapter 3. Due to unplanned weed control by plantation staff, control plots received different weeding applications and were therefore excluded in the final analysis. The burn 1 treatment was burnt in 2007 and serves as the control whereas the second burnt treatment received treatment implementation 8 months previously (Table 4.27). Both trials Berlin and Nelshoogte received delayed treatment application and was therefore also excluded from the final analysis.

4.6.1 Treatment Differences

Trial Blyde and Witklip *P. elliottii* showed a significant difference in understorey growth between the control and burnt treatments 8 months following treatment implementation (Table 4.27). Trial Witklip *P. patula* showed a non-significant difference in understorey cover. This may be due to species composition as will be discussed in Chapter 5.

Table 4.28: ANOVA output for understorey growth 8 months following treatment implementation.

Trial	Response	Sum Sq	Df	F value	*p - value*
Blyde	Treatment	3.760	1	27.769	0.006
	Residuals	0.542	4		
Witklip *P. elliottii*	Treatment	4.167	1	20	0.011
	Residuals	0.833	4		
Witklip *P. patula*	Treatment	0.510	1	0.266	0.633
	Residuals	7.667	4		

**Grey Shading: Significant Difference*

Figure 4.39 shows the relationship between the treatments and the different trials. The data was recorded during the month of October 2014, eight months following treatment implementation. The *P. elliottii* trial in Witklip plantation shows the highest understorey growth in the control and burned plots. The control treatment inside the *P. patula* trial at Witklip plantation shows a large error bar. This is due to the third replication being across the road and fully covered in *Bidens pilosa* (black jacks).

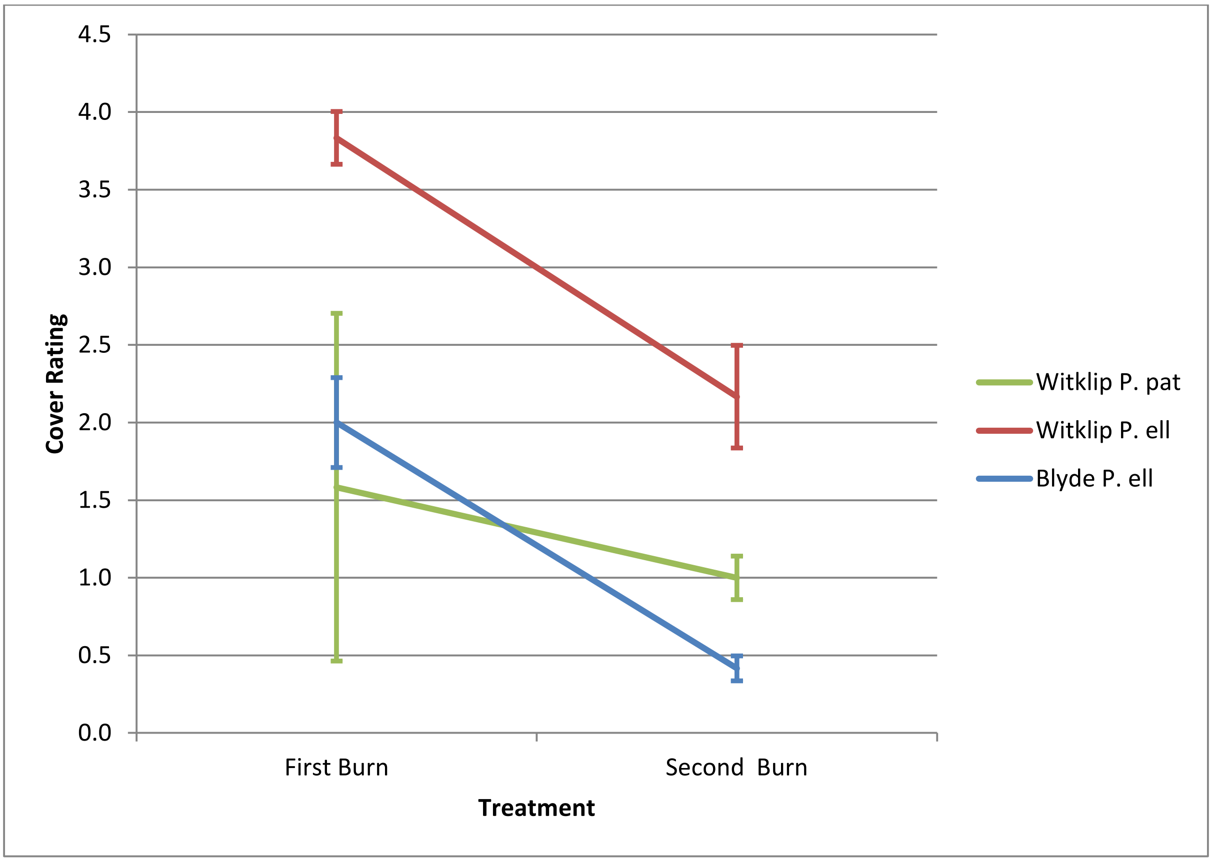

Figure 4.39: Understorey cover between treatments for the trials receiving treatment implementation in February 2014.

4.6.2 Cover Abundance Over Time

Both trials Blyde and Witklip *P. patula* show a significant difference in understorey cover over two different time periods since treatment implementation (Table 4.28). There was no significant interaction between treatment and time following treatment implementation. In Blyde a weakly significant interaction (*p*=0.06) occurred between treatments.

Table 4.29: ANOVA output for understorey cover between treatments over different time periods.

Trial	Response	Sum Sq	Df	F value	*p - value*
Blyde	Time	3.973	1	14.508	0.007
	Treatment	1.373	1	5.012	0.060
	Time:Treatment	0.463	1	1.691	0.235
	Residuals	1.917	7		
Witklip *P. patula*	Time	18.130	1	11.451	0.010
	Treatment	0.255	1	0.161	0.699
	Time:Treatment	0.255	1	0.161	0.699
	Residuals	12.667	8		

**Grey Shading: Significant Difference*

Understorey cover increased with time following treatment implementation (Figures 4.40 and 4.41). In trial Blyde the difference in percentage understorey cover over time between treatments is decreasing whereas the cover abundance inside trial Witklip equalized in April 2015, fourteen months after treatment implementation. Inside both control treatments cover abundance increased with time. This can be explained by seasonality - October is in the beginning of the growth season and with certain understorey species being seasonal, germination and growth had only just started. In contrast, April is at the end of the growing season when all species has germinated and matured, thus increasing cover percentage.

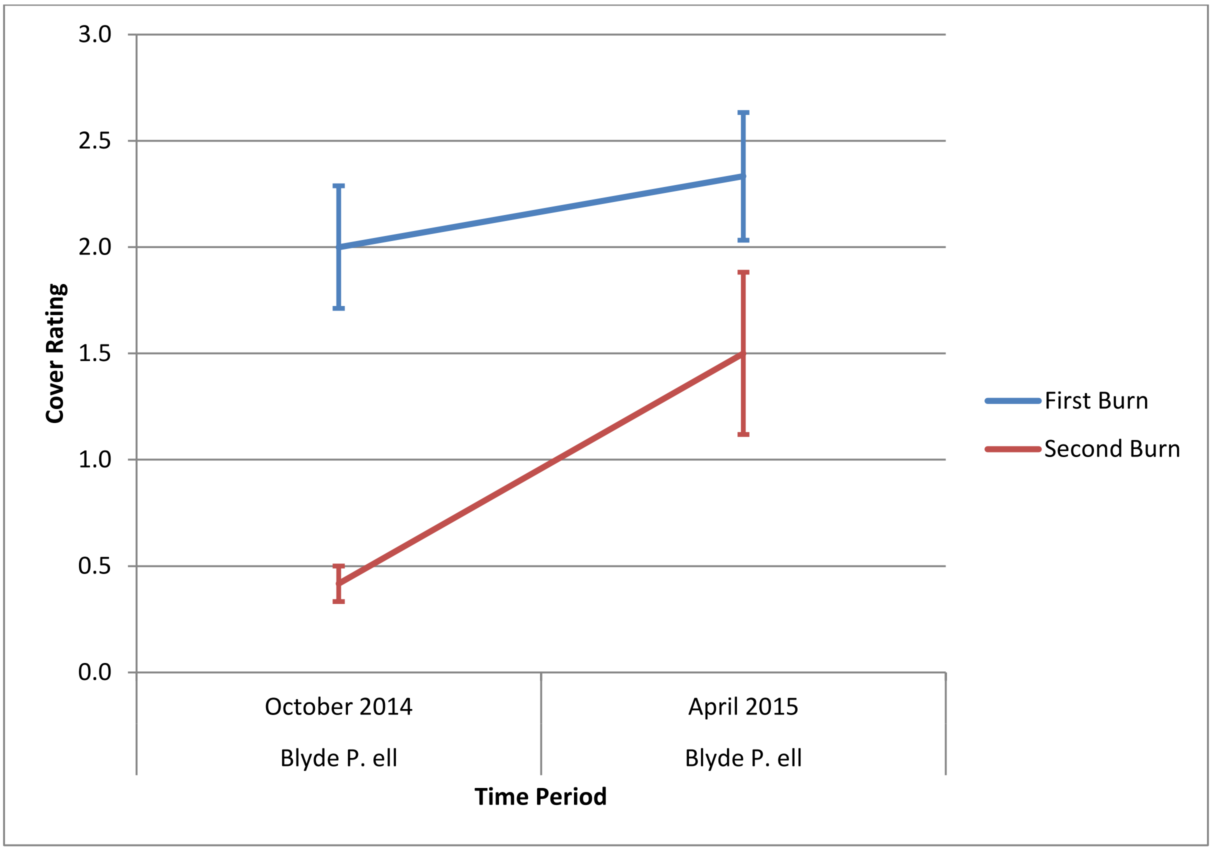

Figure 4.40: The difference in understorey growth over time between treatments for trial Blyde.

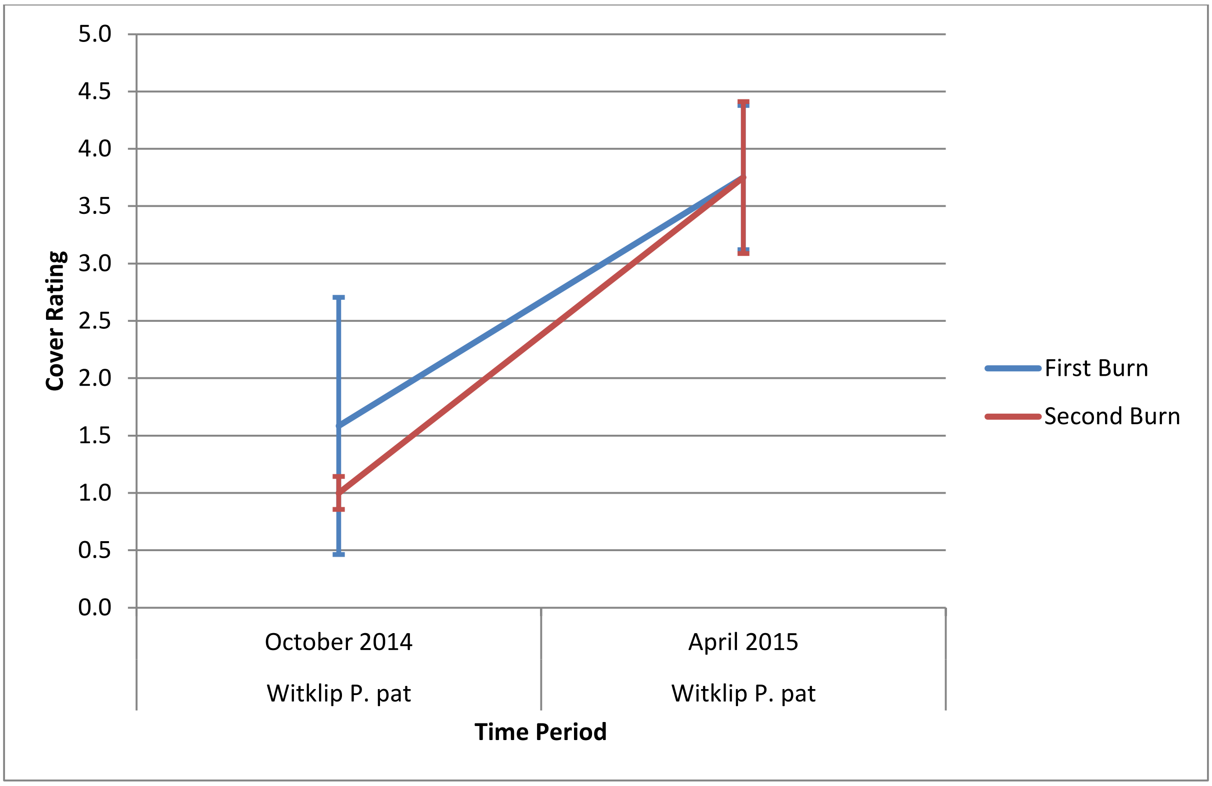

Figure 4.41: The difference in understorey growth over time between treatments for trial Witklip.

5. Discussion

5.1 Forest Floor

5.1.1 Litterfall and Seasonality

Litterfall rates found in the present study correspond with those found in the literature (Table 4.1). Dames *et al.* (1998) found in her study (similar location) litterfall rates of 5.89 t ha^{-1} for *P. patula* saw timber stands aged twenty five. This study found a litterfall rate of 8.82 t ha^{-1} which is lower than that found by Singh (1982) and higher than that found by Lundgren (1978) and Dames *et al*. (1998). Dames did, however, mention litterfall rates were underestimated due to decomposition and theft of littertraps. *Pinus elliottii* litterfall rates were between rates found by Gholz *et al.*, (1985) and De Ronde *et al.,* (1990) differing with only 0.5 and 1 t ha^{-1}. The total dry needle mass for a mature *P. patula* stand is estimated to be around 7 t ha^{-1} (Carlson *et al.,* 2001; Morris, 1986). When using specific leaf area (SLA) for *P. elliottii* (4.8 m^{2} kg^{-1}) and *P. patula* (5 m^{2} kg^{-1} for *P. radiata* due to lack of data), the needle mass for May and December could be calculated using the LAI values obtained (Figure 4.14). Calculated needle mass was 5.8 and 7.3 t ha^{-1} for *P. elliottii* and 6.8 and 8 t ha^{-1} for *P. patula* during December and May respectively corresponding well with values from Carlson and Morris (7 t ha^{-1}). With *P. patula* retaining needles for approximately 2 years (Morris, 1986) and adding the amount of needles retained in the canopy together with the needle fall rate, the amount of needles grown each year can be determined. The sum of needle fall and retained needle mass amounts for 16 t ha^{-1}, indicating the quantity of needle mass available each year. Divided by the 2 year life span of *P. patula* needles it indicates the needle production of mature *P. patula* stands in the specific study is around 8 t ha^{-1} yr^{-1}.

The observation made, that litterfall in the burnt treatments was lower than that in the control plots during the first period after burning and a reversal of this trend switching during the end of the second growing season, may be due to increased leaf production following the ash-bed effect in year one as was found by Birk & Bridges (1989), (Figure 4.1 & 4.3). The ash-bed effect increase nutrient availability, which stimulates canopy growth, and hence, increased litterfall of needles that are shaded out.

Litterfall was the highest during winter with spring and summer (Figure 4.6) recording the lowest falls. Dames *et al.,* (1998) found litterfall rates to peak in spring (three months of litterfall combined) which does not correspond to the results of this study – in fact it indicates the exact opposite (Table 4.2). Over all three trials litterfall peaked during June with a mean litterfall rate of 1.2 t ha^{-1} compared to 0.4 t ha^{-1} during

September (Figure 4.1 – 4.5). This seasonal trend recorded corresponds with LAI measurements. Leaf area index increased from December to May. This is a result of litterfall peaking during winter and the trees only starting to develop new needles in the beginning of the growing season. The month of May is at the end of the growing season when full needle growth has been achieved, thus explaining the higher LAI. This could also explain the high needle fall during June. The trees have a maximum mass of needles at the end of the growing season and consequently loose the most needles during the first few months following on from the growth season as found by Morris (1995). The seasonal increase in needle fall during winter is a result of the decrease in precipitation and temperature (Figure 3.7 & 3.9), (Chave *et al.,* 2010; Lehtonen *et al.,* 2008; Yang *et al.,* 2005). In this specific study however precipitation would most likely be the main contributor to increased needle fall as daily temperatures remain moderate between seasons (Figure 3.7). With low rainfall trees will start experiencing water stress and through the shedding of needles evapotranspiration and consequently water demand is reduced. A similar annual pattern of LAI reductions during dry winters and LAI increases during wet summers was documented for Eucalyptus in KwaZulu-Natal province (Du Toit *et al,* 2008).

5.1.2 Litterfall and Crown Scorch

Blyde was the only trial that received crown scorch following the burn treatment (Table 4.26 and Figure 4.1). Suspended fuel due to slash and the openness of the compartment most likely caused the higher intensity fire resulting in the occurrence of crown scorching. Average crown scorch height varied between 10-20% of the crown in trees subjected to scorch and resulted in a significant litterfall increase of 0.54 t ha^{-1} during the first month following the treatment. This increase only lasted for the first month after the fire. It is interesting to note that the control treatment lost 0.75 t ha^{-1}

more needles over the first 12 months than the burnt treatment. This indicates minor crown scorch does not increase total litterfall which signifies minimal change in cumulative litterfall and tree stress. De Ronde (1983) found similar results for *P. elliottii* in the Southern Cape. Litterfall increased with 0.8 t ha^{-1} during the first month from the control to the burnt treatment in a stand with a scorch percentage of 25%. In areas subjected to 75% scorch litterfall rates of 3.7 t ha^{-1} were recorded one month following treatment implementation. Trees subjected to severe crown scorch will lead to defoliation of trees causing stress and even death (De Ronde, 1982). *Pinus elliottii* is however considered to be one of the most fire tolerant species, which has been known to resprout after total crown scorch (de Ronde, 2008; de Ronde 1982). With minimal crown scorch observed in the present study combined with the high fire tolerance of *P. elliottii* planted in trial Blyde, no significant tree stress and growth differences are expected for the trial.

No crown scorch was detected in the *P. patula* trials through physical observation and litterfall rates, although trial Berlin seems to show increased litterfall after the first month following treatment implementation (Figure 4.5). With no crown scorching detected in trial Nelshoogte and increased litterfall occurring in the burnt plot, tree stress could be the main factor for two reasons. Although Berlin received the highest fire intensity, the Nelshoogte burn had a slower rate of spread and higher FF formation, which would increase time exposed to the fire through the slower rate of spread and longer smouldering time therefore increasing stress to trees (Table 4.29). It may also be that some needles were only partially damaged and not scorched, in which case the trees still decided to shed them.

The fact that no crown scorch occurred in the *P. patula* trials could be explained by their increased crown height compared to *P. elliottii*. Due to denser crown development under *P. patula* stands, more shading out of the bottom needles occur, resulting in clean lower branch whorls. It was estimated that the crown height in these stands is 3 - 4 meters higher up the stem compared to *P. elliottii,* resulting in a crown height of 10 - 13 meters. With the rule of thumb ratio between flame length and crown scorch being 1:6 it indicates that a flame length of 2 m is required to inflict damage in these *P. patula* stands (De Ronde *et al*., 2004).

5.1.3 Forest Floor Reduction

An increase in FF mass between treatments as a result of increased litterfall after treatment implementation was not found in the present study. This can probably be ascribed to the fact that the prescribed burns were of low intensity (Table 4.29). With high intensity burns resulting in high crown scorch and tree stress, higher litterfall rates may occur, as found by De Ronde (1983), and may counter the initial objective of FF reduction. The FF mass was significantly reduced in all trials with an average reduction of 12.9 t ha^{-1} and 6.3 t ha^{-1} in *P. patula* and *P. elliottii* trials respectively (Table 4.5). These results are similar to FF reductions in stands with minimum crown scorch of 11 t ha^{-1} recorded by De Ronde (1983). Forest floor mass for trials Berlin and Nelshoogte showed a non-significant decrease from the control to the first burnt treatments which was burnt 7 years ago, indicating the reduction in FF mass is maintained for some period after under-canopy burning. When calculated as percentage loss of original mass, *P. elliottii* (31%) lost a slightly larger proportion than *P. patula* (27%). The *Pinus elliottii* FF generally burns more easily than *P. patula* as was experienced in the present study, probably due to the difference in needle morphology and higher resin content which could explain the higher percentage mass loss in burnt treatments for *P. elliottii*. Shorter thicker needles of *P. elliottii* result in increased aeration, providing more oxygen and together with higher resin content and consequently flammable turpentine enhance fire intensity (Teshome, 2011; Coppen & Hone, 1995). Fibrimor FF layers were found in *P. patula* trials Berlin, Nelshoogte and to some extend in Witklip as described in Chapter 2.2.1. Although a clear increase in FF load with altitude was not found in the present study due to age and trial differences, Witklip *P. patula* showed a 47% lower FF than the combined average FF mass of medium and high altitude trials Berlin and Nelshoogte indicating an altitudinal effect on FF development.

The desired FF mass of approximately 11 t ha^{-1} (McArthur, 1971 cited in De Ronde *et al.,* 1990) was achieved in trial Blyde with Witklip trials nearing the optimal figure. The lower FF mass observed in the medium altitude trial (Blyde) in comparison with the low altitude trial (Witklip *P. elliottii*) may be a result of the age difference with Blyde being 7 years younger combined with the fact, trial Blyde is adjacent to grassland (Figure 3.3) and received a relative hot burn in 2007. The first two factors allow more sunlight to penetrate the crown canopy increasing ground temperature and increasing FF breakdown (Schutz, 1990; Dames, 1996). The higher intensity under-canopy burn would have further decreased the FF mass substantially and together with the increased FF breakdown explain the low FF mass observed in trial Blyde. With more sufficient FF breakdown usually occurring after under-canopy burning, FF build-up will be countered, resulting in a more balanced and lower fire risk environment, thus achieving the main goal of implementing under-canopy burning (De Ronde *et al.,* 2004; Fisher & Binkley, 2000; Covington & Sackett, 1984; Schoch & Binkley, 1986). Under-canopy burning thus contributes to FF mass reduction through the short term physical loss associated with the burning and secondary longer term loss through the increased FF breakdown.

5.2 Growth

Treatments had no significant effect on growth (Appendix 5A) for both *P. elliottii* and *P. patula* trials 12 and 4 months after treatment implementation as was also found by Bird & Scholes (2005), De Ronde (1988) and Reinhardt & Ryan (1988). Blyde shows an annual average BA increment in the first and second burnt treatment of 1.59 and 1.66 m^2 ha^{-1} respectively (Figure 4.12). Witklip *P. patula* showed an increment of 1.13 and 1.12 m^2 ha^{-1} in the first and second burnt treatment respectively corresponding well with literature (Kotze & Du Toit, 2011). De Ronde (1983) and Bird *et al.,* (2005) found a significant reduction in growth increment in compartments subjected to high intensity under-canopy burns. De Ronde (1988) and Bird *et al.,* (2005) respectively classified high intensity burns as events when tree scorch higher than 75% and fireline intensity greater than 761 kW m^{-1} occur. Fireline intensity in the present study ranged from 32 – 890 kW m^{-1} with an average of 283 kW m^{-1} over all trials (Table 4.29). Needle scorch below 25% occurred only in trial Blyde (Table 4.26). Differences in growth recorded between trials Blyde and Witklip *P. patula* may be due to higher N and P content and age differences resulting in more growing space being available after thinning and hence higher diameter growth (Figure 4.27 and 4.29).

Significant growth increment differences occurred between season's winter and summer. No interaction was found between season and treatment. Summer had a 61% higher growth increment rate for trials Blyde and Witklip *P. patula* combined than for winter. Significant LAI differences between seasons correspond with decrease in growth during winter months. Litterfall peaks during winter following the summer rainfall season resulting in lowered LAI values and hence, more sunlight passing through the canopy (Figure 4.14), (Morris, 1995; Dames, 1998). Growth is directly related to light interception by the crown canopy for photosynthesis purposes (Dovey, 2004; Turnbull *et al.,* 1988). This effect is confirmed by the higher growth rates with increasing LAI recordings during the growth season, observed in the present study.

With cambium and root damage only occurring in trials Berlin and Nelshoogte, which received the second burnt treatment during May 2015, growth responses as a result of treatment for these two trials could not be determined. The initial growth increment 4 months after treatment implementation shows a non-significant variation in growth between the first and second burn treatments. This growth increment occurred during the winter months when very little growth normally occurs and clear patterns in increment are not yet visible. Delayed growth increment effects may develop as a result of stress from cambium and root damage due to the smouldering effect (Scott, 2001; Varner *et al.,* 2009). Continued monitoring, through the use of dendrometers on trees with the same competition factor, over consecutive growth seasons, will be carried out to determine if significant growth differences occurred between treatments.

5.3 Nutrients

5.3.1 Forest Floor

Forest floor nutrient concentrations are similar to that found by Odiwe (2009) and Schutz (1990) as shown in Table 4.12. Within trials, no significant difference or clear patterns between treatments were observed regarding FF nutrient concentrations except for Ca which showed a non-significant decrease from the first to the second burn treatment (Appendix 2A). Nutrient loss due to under-canopy burning is directly related to FF mass consumption. Berlin and Nelshoogte showed a significant macro nutrient loss between the second burn and control treatments due to the largest FF consumption occurring between these treatments (Table 4.15). Witklip *P. patula* had the highest N loss although Berlin and Nelshoogte lost more than double the FF mass

(Table 4.13). This is a result of N concentrations decreasing from the first to the second burn treatment in trial Witklip *P. patula* and increasing for trials Berlin and Nelshoogte resulting in higher N losses when multiplying with FF mass loss. N and Ca showed the highest concentrations in the FF whilst P concentration was the lowest of all macro nutrients (Table 4.12). Witklip *P. patula* showed an N loss of 15.5 kg ha^{-1} in comparison with the average of the remaining 4 trials of 6.6 kg ha^{-1} for each ton of FF consumed. The amount of nutrients lost through under-canopy burning must be viewed in context - mor FF formations results in nutrient lockup when nutrients are not recycled to the soil Schutz, 1990 and Dames *et al.,* 1998). When a wildfire occurs in such stands, the whole FF and tree stand is lost. With the highest nutrient content occurring in the duff layer (Ross, 2004) and under-canopy burning, burning of only the top FF layer comprised of the Litter layer, and a small portion of the Fermentation layer, minimum nutrients are lost to the system in the short term and are protected in the long term (De Ronde *et al.,* 2004). The ash-bed effect furthermore increases nutrient availability as nutrients are released from the litter into the soil. Microbial activity additionally increases with increasing pH resulting in faster breakdown of the FF (Fisher & Binkley., 2000; Covington & Sackett, 1992; Geldenhuys *et al.,* 2004).

5.3.2 Nutrient loss to the system

The major nutrient loss to forest plantations is through harvesting and high intensity prescribed burning operations, such as slash burning for re-establishment purposes (Morris, 1986). The single major nutrient input to the system is through atmospheric deposition (Du Toit and Scholes, 2002; Morris, 1986; Dovey *et al.,* 2011). Combining nutrient losses of harvesting and under-canopy burning for mature pines and subtracting the sum of two operations with the mean atmospheric deposition over rotation age the amount of nutrient loss to the system through these nutrient depletion operations can be estimated (Table 5.1). Slash burning was not incorporated due to the following reason: consecutive under-canopy burns reduce fuel loads substantially and incorporating average nutrient loss of slash burns (consuming the slash and most of the FF) into nutrient loss calculations, would thus overpredict, as FF mass will be much lower in the compartment when slash is burned. Harvesting of a 30 year old pine stand with an initial stocking of 1220 sph, thinned three times with a final stocking of 250 sph were used. The compartment had a timber volume of 329 m^3 ha^{-1} with the thinning's incorporated into the nutrient loss associated with harvesting (Carlson & Allan, 2001). Under-canopy burning data from the present study was used, incorporating the average nutrient concentrations and FF mass removed over all 5 trials, summed for three under-canopy burns. Atmospheric deposition collected and averaged from numerous studies in Africa and South Africa was calculated over 28 years and used as nutrient input to the system (Dovey *et al.,* 2011).

The results show N loss from the two combined operations is highest at 9.04 kg t^{-1} of FF consumed followed by Ca (7.48 kg t^{-1}) with P the least (0.45 kg t^{-1}). Nitrogen and Ca loss to the system is highest (118 and 154 kg ha^{-1} respectively) and K increases with 89 kg ha^{-1} over 28 years (Table 5.1). Phosphorus and Mg loss is small losing only 13 and 56 kg ha^{-1} respectively. For every cube of timber and ton of FF consumed, 4.21 kg ha^{-1} of N is lost to the system. The calcium loss is very high due to high concentrations occurring in the system indicating an abundance of the nutrient, which suggests the system will remain sufficient for some time. The main concern however is the N loss to the system and care must be taken to avoid depletion of this critical important nutrient in tree growth. Atmospheric deposition varies considerably with regards to location as wind and industrial operations, such as mines play a fundamental role in nutrient deposition (Dovey *et al.,* 2011). To be able to determine the input and output of nutrients in a specific plantation, accurate atmospheric deposition rates need to be determined.

Knowing the nutrient input to the system, nutrient loss can accordingly be controlled through number of under-canopy burns and the mass of HR and FF consumed (which will be less in slash burn operations subjected to UCB) as nutrient loss is directly related to organic material consumed.

If large quantities of nutrients are still lost to the system, fertilization can be used to rectify the loss as excluding slash burning and/or under-canopy burning where fuel reduction is necessary will result in higher fuel loads. The higher fuel loads and fire risk would lead to increasing number of fires which will result in much higher nutrient loss combined with all the social, environmental and financial degradation accompanied by such events.

Table 5.1: Nutrient budget representing nutrient loss through harvesting with 3 thinning's included in a pine stand age 30, 3 under-canopy burns in *P. patula* stands and the combined average atmospheric deposition for Africa and South Africa over 28 years.

		kg ha^{-1}					
		N	P	K	Ca	Mg	Reference
HR & 3 Thin	329 m^3 ha^{-1} (Vol)	209 (0.64)	26 (0.08)	58 (0.17)	84 (0.25)	45 (0.14)	Carlson & Allan, 2001
UCB (3)	10 (t ha^{-1}) x3	252 (8.40)	11 (0.37)	31 (1.03)	217 (7.23)	43 (1.43)	Present study
Total		461 (9.04)	37 (0.45)	89 (1.20)	301 (7.48)	88 (1.57)	
Deposition	28 years	342	24	178	147	32	Dovey *et al.*, 2011
Nutrient Loss (Rotation)		118	13	-89	154	56	
Nutrient Loss (yr^{-1})		4.21	0.46	-3.18	5.50	2.00	

Brackets: Nutrient loss per ton of FF consumed and per m^3 of timber.

Grey shading: Nutrient increase to the system.

5.3.3 Freshly Fallen Litter

Foliar nutrient status could unfortunately only be determined for needles collected from littertraps. This means that all macro nutrients that were analysed for, except Ca, were deficient as plants have the ability to remobilize macro nutrients from old dying tissue (Reuter & Robinson, 1997). Micro nutrients and Ca are not as mobile as macro nutrients resulting in very little remobilization of these nutrients. Remobilization is primarily dependent on the ease with which nutrients move through the xylem (Reuter & Robinson, 1997). In theory nutrient deficient trees should yield even lower nutrient concentrations in foliage after remobilization in comparison with nutrient sufficient trees. Odiwe (2009) presented fresh litter nutrient concentrations of *P. elliottii* for nutrient sufficient trees, which corresponds with litterfall nutrient concentrations found in the present study indicating *P. elliottii* trials for the study were most probably nutrient sufficient (Table 4.16). These nutrient concentrations may alternatively indicate the nutrient status of *P. elliottii* as conventional methods require fresh needle sampling, which is very time consuming.

In the present study the objective of recording the nutrient status of needle fall was to determine if there were any significant differences in nutrient concentration between treatments one and two months following treatment implementation (Appendix 3A). The results show no significant differences between treatments, but trial and month differences were evident. In the second burn treatments, N shows a clear increase after the first month (0.11, 0.14 and 0.09%) compared to the control treatment which decreased with 0.05 in trial Witklip *P. elliottii* and increased with 0.09 and 0.02% in Blyde and Witklip *P. patula,* respectively during the second month. This could be a result of increased inorganic N uptake by the trees through the thermochemical transformation of organic to inorganic N, called pyrolysis, which has widely been documented (Covington & Sackett, 1992; Carter & Foster, 2004; Schoch & Binkley, 1986; Hatten *et al.,* 2012). However, the fact that this phenomenon only occurs during the first month after treatment implementation suggest that it is most probably a result of stress and partly damaged needles being shed by the trees before remobilization of nutrients could occur as slight increases in litterfall were observed for all trials (Figure 4.1 - 4.5). The rest of the macro nutrients showed very little increase during the first month after the burn treatment, except for Ca, which shows variable increases between months and treatments ranging from 0.02 – 0.17%. No clear patterns are obvious between the treatments in the second month.

Micro nutrients for both species varied considerably but with no clear pattern. All micro nutrient levels were found to be adequate. Although Mn nutrient levels for *P. patula* (264 mg kg^{-1}) were lower than adequate Mn nutrient level for *P. elliottii* (284 mg kg^{-1}), these levels are still far above the critical Mn level of pines which is usually below 10 mg kg^{-1} (Reuter & Robinson, 1997).

5.3.4 Soil Nutrients

All trials occurred on either granite- or dolomite-derived soils. Dolomite-derived soils are generally considered more fertile than granite-derived soils (Schutz, 1990). Some treatment differences did occur but were non-significant due to small sample sizes which, in turn, was the result of a cost issue as samples from a total of 45 plots had to be analysed.

5.3.4.1 Soil pH, N & P

A significant increase (p=0.001) in soil pH was recorded after treatment implementation in trial Witklip *P. elliottii* (Table 4.22). Modest increases in soil pH were also recorded for all trials except Witklip *P. patula.* Soil pH usually increase after prescribed burning as ash from plant material are high in ions of the macro nutrients (Fisher & Binkley, 2000). Witklip *P. patula* shows a pH value that is 1 unit higher than the other remaining trials (Table 4.21). Schutz (1990) found average soil pH (H_2O) units under *P. patula* stands in Mpumalanga of 4.90 and 5 in granite- and dolomite-derived soils respectively. It is a known fact that pH measured in H_2O is higher than pH measured in KCl, due to the displacement of acid cations from the exchange complex by the salt solution. For example, Sugarman (1999) recorded the average pH in a KCl-solution to be 0.8 units lower than in a H_2O solution. Sugarman (1999) recorded pH levels ranging from 3.74 – 4.10 in the Mpumalanga escarpment area under pine plantations, measured in KCl, which correspond to the low pH levels recorded in the present study (Table 4.21). Sugarman (1999) concluded that the soils seem to have reached the Al-buffer range and that pH levels are highly unlikely to decrease further. Forest soils usually have a pH value ranging from 3.5 – 6.0 placing the plantation soils in the present study at the very bottom range of soil acidity for forestry (Binkley, 1985).

Total N was similar between treatments five months after treatment implementation except for trial Witklip *P. patula,* which shows a slight increase from the first to the second burn (Figure 4.27). However, two months following treatment implementation in trials Berlin and Nelshoogte, both trials experienced a reduction in total N in the second burn treatment (Figure 4.28). Nelshoogte shows a significant decrease in total N between the control and second burn treatment (Table 4.23). This can be explained by the low volatilization temperature for N of 200 °C which would have resulted in a low N content in the ash, thus decreasing the potential N flow from the FF to the soil, as was found by De Ronde (1988) and Fisher & Binkley (2000). Berlin and Nelshoogte were burnt under dry conditions causing smouldering of the FF for days after the burn, which resulted in areas with total FF consumption. This most likely explanation is the significant loss in total N recorded in trial Nelshoogte. It probably also explains why no increase in total N was recorded in the present study as was the case in numerous other studies (e.g. De Ronde, 1992; Binkley *et al.,* 1992; Wells, 1971; Grogan *et al*., 2000). A meta-analysis of data by Wan *et al.* (2001) showed that inorganic N is the only soil-N form that consistently increases after a fire and that total N does not seem to change significantly - their analysis lends some support to the findings in the present study.

P shows an overall increase from the first to the second burn treatments. P levels in the trials Berlin, Blyde and Witklip *P. elliottii* increased from the first to the second burn treatment, while they decreased in Nelshoogte and remained the same in Witklip *P. patula* (Table 4.21). Interesting to notewas the higher P levels at trial Berlin and Blyde compared to the other tree trials. This is interpreted as the result of the underlying dolomite in these trials, which yields higher nutrient concentrations than granite-derived soils (Schutz, 1990). The higher P levels recorded are probably a result of increased microbial activity, soil pH and heat-induced P conversion to plant available form (Certini, 2005; Hatten *et al.,* 2012; Fisher & Binkley, 2000; Carter & Foster, 2003). However, the major mechanism for the increased P availability probably stems from the increase in soil pH from a very low initial level, which is responsible for the formation of sparingly soluble P compounds in soil. The highest P increase was recorded in the trial showing the highest pH increase (Witklip *P. elliottii*) confirming the role of pH in P availability. Geldenhuys *et al. (*2004), Fisher & Binkley (2000) and Schutz (1990) showed that granite-derived soils with a higher sand content than dolomite-derived soils are on average more depleted in nutrients than dolomite-derived soils, with the result that small changes in soil chemistry are more prominent in these soils with their lower buffer capacity.

5.3.4.2 Effective Cation Exchange Capacity

All trials exhibit a low ECEC (5.66) and can be considered mesotrophic. The ECEC showed no significant difference between treatments. Higher ECEC usually occurs with increased soil pH through deprotonation which decrease the positive charge and increase the negative charge of molecules (Edmeades, 1982). Such a significant, but temporary increase in ECEC was noted by du Toit *et al.* (2008) after a slash burn and subsequent increase in soil pH. Mean ECEC values tended to decrease slightly from the first to the second burn treatments with only trial Nelshoogte showing an increase. P and Na stayed constant between treatments but differences were noticeable in Ca and Mg content (Table 4.21). Mg in all five trials tended to increase after the second burn treatment with a significant increase occurring in trial Nelshoogte. Three out of the five trials showed an increase in Ca. The differences were highest in the granite-derived soils, again probably as a result of the lower buffer capacity compared to the dolomite-derived soils. The increase in cations is most probably a result of the ash bed effect with ash containing high levels of base cations (Binkley & Fisher, 2000; Geldenhuys *et al.,* 2004). Witklip *P. patula* displays very high levels of Ca and Mg in comparison to the other trials. From a geological viewpoint this does not make sense as this site is situated on a granite-derived soil although small geological differences may occur, which could explain this phenomenon. The answer may, however, lie in the climate difference as Witklip is the lowest altitude site at a 1000m above sea level. The lower altitude site has warmer average temperatures and lower moisture content than the rest of the trials (Figure 3.7 & 3.9). This will result in more efficient breakdown of the FF explaining the lower carbon percentage and FF mass. The drier conditions will furthermore inhibit leaching which could explain the higher Ca and Mg in trial Witklip *P. patula*. This interpretation, however, does not agree with the Witklip *P. elliottii* trial exposed to the same climatic conditions which does not show Ca and Mg differences compared to the rest of the trials. There may, however, also be other purely site-related reasons for the observed differences such as the fact that *P. elliottii* is usually planted on poorer sites than *P. patula*.

5.4 Stand Damage

Crown scorching was directly related to litterfall rates and was therefore discussed with litterfall rates in section 5.1.2.

5.4.1 Root Damage

Root damage only occurred in trials burnt during autumn due to low moisture content of the FF resulting in smouldering and complete FF consumption around trees where higher and better aerated fuel occurs thus exposing the mineral soil around trees (Scott, 2001; Sacket & Haase, 1998). Root damage can lead to tree stress, reduced growth, secondary damage or death and usually has a delayed effect on trees (Scott, 2001; Varner *et al.,* 2009). In the present study root damage was mostly restricted to non-woody medium roots where 70% of trees in both trials lost four or less medium size roots (Figure 4.37). A root was considered damaged when it was burnt through. Only 10% of trees received root damage where coarse or very coarse roots were burnt through. Scorch and resin bleeding did occur on larger roots but was in most cases restricted to small sections of the upper parts of the root. Fine roots smaller than 1mm in diameter occur as a network throughout the FF but were not regarded in the damage assessment as determining the amount of fine roots lost would be impractical. The larger roots damaged will have a greater negative effect on the tree due to the structure of root system. Smaller roots are highest in abundance and connect to larger roots of lower abundance. With large root damage the small root systems connected to the large root will also be damaged in other words, the larger the roots, the larger the extent of roots that are damaged. Root damage leading to tree stress, growth decrease and also death is positively correlated with the duration of exposure of the top soil to the lethal tissue temperature of 60 °C (Varner *et al.,* 2009). The duration of the smouldering effect will thus determine the extent of root- and consequently tree-damage. In view of the relatively small number of large-diameter roots killed during the burning treatment it is the author's opinion that tree damage would most likely to some extent result in delayed growth through water stress and as carbohydrates will be used to replenish damaged roots to the expense of tree growth (Varner *et al.,* 2009).

5.4.2 Cambium Damage on Stem Wood

Cambium damage, as with root damage, only occurred in trials Berlin and Nelshoogte, a result of burning during the end of autumn. Nelshoogte suffered the highest percentage cambium damage (19%) compared to 10% in trial Berlin (Figure 4.38). The reader is reminded that resin exudation was observed after burning, but that all the apparently damaged cambia tested were found to be alive (Section 4.4.3). De Ronde (1986) using tetrazolium as a method of detecting cambium damage showed that living cells were still present even though resin and discoloration of the cambium occurred on the stem beneath the bark. With all trees in his study being semi-mature, bark thickness was well developed thus protecting the cambium and limiting cambium damage to areas subjected to long periods of smouldering (De Ronde, 1982). Bark thickness together with structural, physical and chemical properties play a vital role in the extent of cambium damage (De Ronde, 1982; Odhiambo *et al.,* 2013). Cambium damage usually occurs on the leeward side of stems, where vortices increase the heating duration, and increases with stem diameter (Michaletz & Johnson, 2007). Cambium damage in the present study did not only occur on the leeward side of trees, an observation that can probably be attributed to the smouldering effect, which caused both the temperature and the duration of heating to vary considerably between trees. Resin covering the whole circumference of the stem, which would indicate severe cambium and tree damage, was not detected. When cambium damage occurs around the whole tree, carbohydrates generated by the canopy through photosynthesis will be cut off from the root system resulting in root death, water stress and ultimately tree death (Michaletz & Johnson, 2007). The difference in cambium damage observed between trials in the present study could also be a result of slope differences. Berlin has a steeper slope, which increased the fire's rate of spread and decreased the fire resistance time at stem level, as was reflected by the fire prediction model. Lower fire resistance times would have resulted in shorter times, in which the cambium was subjected to lethal temperatures resulting in less cambium damage (Table 4.29).

Root damage was more severe than cambium damage in the present study and tree stress and slower growth rates would mainly be attributed to root damage, although cambium damage would still contribute to a lesser extent.

5.5 Understorey Growth

A significant difference was evident between the first and second burn treatments 8 months following treatment implementation, except for Witklip *P. patula* (Table 4.27). Interesting to note is the effect that exposed soil had on understorey growth. Germination of *Setaria megaphylla* was much more aggressive in the firebreaks around the research plots (Appendix 4A). This observation corresponds to the findings of De Ronde *et al.* (2004) who concluded that partial consumption of the FF will lead to patchy regrowth due to minimum stimulation of the seedbed. Witklip *P. patula* was covered in *Bidens pilosa* (Blackjack) in plots 3b1 and 3b2, an annual herb growing up to 100 cm and originating from South America (Directorate Plant Production, 2011). These two plots, located on the opposite side of the road, had very rapid Black jack regrowth after the first and second burn treatments. This is the cause of the long error bars in Figure 4.39, as understorey coverage was very low in the remaining 4 plots.

The same regrowth species composition recurred after the second burn treatment in all trials, with certain species, such as *Setaria megaphylla* (Grass) resprouting immediately, indicating an initial change in species diversity due to delayed growth response between species. The findings in the present study correspond to the results of Rego *et al.,* (1990), who found no significant difference in species diversity and Busse *et al.,* (2000) reporting a slight increase in species diversity after prescribed burning.

The growth pattern observed from October 2014 to April 2015 in both trials Blyde and Witklip *P. patula* was the same. The second burn treatments had significantly lower understorey coverage than the first burnt plots in October 2014 but, by April 2015, showed a growth increase back to the levels of the first burn treatment, which served as the control. The second burn treatment in Witklip *P. patula* reached the same cover density as the first burn treatment 18 months after treatment implementation corresponding to literature examples, which indicate that herbaceous species normally show irregular response and return to pre-burn levels (De Ronde, 1988; Busse *et al.,* 2000; Rego *et al.,* 1990).

The observed seasonal trend recorded an increase in regrowth from October to April, which is expected as most species are annual herbs germinating in spring and reaching maturity during autumn.

5.6 Under-canopy Burn Intensities

Pinus elliottii trials burnt much easier than *P. patula* trials. The *P. patula* trial in Witklip burnt easier than the high altitude sites probably because of the drier climatic conditions favouring burning, even though the burn struggled somewhat and had to be reignited a few times due to high moisture content of the fuel. The high altitude sites could only be burnt successfully during the end of autumn under very dry conditions. Even so, this resulted in smouldering that continued for days and consumed the entire FF around the base of most trees. This was the result of insufficient moisture in the duff layer caused by lack of rain. This effect highlights the importance of optimal burning conditions. As a result of the long thin needles of *P. patula,* which cause dense FF formations that are not well aerated, optimum conditions for burning *P. patula* are very seldom reached if wind speeds of around 10 km h^{-1} are not present to supply oxygen and carry the fire over the FF, as described to the author by the Fire Risk Manager of KLF, Mr. Ben Bothma (pers. comm., 2014). Trial Berlin was subjected to the highest intensity fire according to the fire prediction model (Table 30). Trial Nelshoogte had the highest FF reduction; this may be explained by the higher initial FF formation increasing smouldering duration. With slower rate of spread predicted for Nelshoogte, FF consumption could have increased even further.

5.7 Fire Prediction Model

The fire prediction model is a useful tool in predicting to some extent what could or had occurred during a fire. The model is not perfect as all influencing factors cannot always be sufficiently accommodated by the model. For trial Blyde, the model predicted the highest crown scorch height of 6.9 m, which corresponded with the crown damage and litterfall differences actually recorded in the present study. The model is very sensitive to fuel moisture and therefore did not deliver an output for Witklip *P. patula* with litter layer fuel moisture of 45%. All prescribed under-canopy burns are considered moderate to low intensity burns with the fireline intensities predicted to be below 250 kW m^{-1} on average for all trials except Berlin (Hollis *et al.,* 2011; Bird & Scholes, 2005; Van Wagtendonk, 1996). Fireline intensities below 1000 kW m^{-1} are considered suitable for under-canopy burning (Bird, 2001 cited in Ross, 2004). Wind speed plays a big role in fire intensity as is indicated by the model output. In trial Blyde scorch height increased from 4.3 to 6.9 m as wind increased from 3 to 6 km h^{-1} and FLI from 175 – 425 kW m^{-1}.

The fuel model used in the present study is the combination of a model made for *P. patula* ST stands in South Africa, adjusted with site specific conditions (Appendix 6A), (Ross & du Toit, 2004).

6. Conclusions

6.1 Forest Floor

6.1.1 Litterfall

Under-canopy burning increased litterfall during the first month after treatment implementation with a significant increase evident in trial Blyde. This was a result of light crown scorch occurring in that specific trial. Under-canopy burning had no significant effect on litterfall in mature *P. elliottii* and *P. patula* trials form 2 months onwards after treatment implementation and did thus not contribute to an increase in FF formation. There was some evidence (Figure 4.1 & 4.3; Section 4.1) in the burnt trials indicating an increase of litter production in the second growing season following the prescribed burn, which may be a result of the ash-bed effect. The litterfall rate varied between species with *P. patula* producing the highest litterfall rate. Litterfall in *P. patula* trials was estimated to account for approximately half of the total crown needle mass, indicating that the needle production is around 8 t ha^{-1} yr^{-1}, with the species retaining a similar quantity of needles per ha. The observed seasonal trend shows that litterfall peaks during winter when rainfall is at its lowest and this suggests that trees are probably subjected to some degree of water stress.

6.1.2 Forest floor reduction

The FF in all 5 trials was significantly reduced by under-canopy burning. The FF mass of *P. elliottii* was on average reduced by 31% and with 27% for *P. patula*. *Pinus patula* had on average a higher FF formation before burning than *P. elliottii*. The FF mass for *P. elliottii* as well as for the Witklip *P. patula* trial was close to the desired mass of approximately 11 t ha^{-1} after the second burn treatment. Very high FF formations of 70 t ha^{-1} were observed in the high altitude *P. patula* trials and this suggests that repeated burning will be required to achieve the optimal mass. A non-significant FF reduction was noticeable from the control to the first burn treatments in trials Berlin and Nelshoogte. These first burn trials were burnt during 2007, which suggests the burnt application has a longer term effect on the FF loading. Under-canopy burning is therefore very effective in reducing FF formation.

6.2 Growth

We observed significant differences in growth rates between sites and between trees representing classes of low, medium and high competition according to the Hegyi competition index. This was expected (a) because site indices differ markedly and (b) because large trees with lower competition are known to use a disproportionate quantity of resources in a stand. However, we observed no significant growth differences or clear pattern among the different burn treatments at 4 and 12 months after treatment implementation. This is probably the result of the low intensity burns, which caused minimum damage and stress to trees, as was found in numerous other studies. The short period over which growth was monitored could also have contributed to the apparent non-significant growth rate. Trial Berlin and Nelshoogte suffered cambium and root damage due to smouldering, which should have a delayed effect on growth, although this could not be detected within the available 4 dry month period after treatment implementation. Significant growth differences were observed during winter and summer with winter showing a 61% lower growth rate compared to summer, corresponding with litterfall and LAI values.

6.3 Nutrients

6.3.1 Forest Floor

No significant FF nutrient concentration differences were observed between treatments. Nutrient loss was directly related to FF mass consumption. Nitrogen and calcium show the highest nutrient loss due to higher concentrations of these nutrients in the FF. Berlin and Nelshoogte show a significant nutrient loss of all 5 macro nutrients. Although significant nutrient losses occurred in the FF, these nutrients build up with the increasing FF and remain unavailable for the trees. Under-canopy burning removes only the top litter layer, while keeping the duff layer intact. The latter contains the largest nutrient pool and also increases microbial activity and consequently FF breakdown, thus enhancing nutrient availability. Wild fires will remove many more nutrients from the system and thus, by reducing the fire risk with under-canopy burning, nutrients remaining in the FF will be preserved. Furthermore, atmospheric depositions provide an annual nutrient input to the system, decreasing the nutrient loss associated with prescribed burning (Table 5.1). The main concern is loss of N (9.04 kg t^{-1} of FF consumed) and care must be taken to avoid depletion of this critical important nutrient through better understanding of nutrient input and output dynamics and adjusting forestry operations accordingly.

6.3.2 Freshly Fallen Litter

A definite but non-significant increase in N was observed in the burn treatments during the first month following treatment implementation. This was most probably the result of premature shedding of needles after treatment implementation before remobilization of nutrients could have occurred. This observation is supported by the fact that the increase in nutrient concentration was not observed during the second month after treatment implementation. Had this occurred, it would have suggested an increase in nutrient uptake as a result of the ash-bed effect. The rest of the macro nutrients showed a small but consistent increase during the first month after the second burn treatment. Micro-nutrient concentrations varied considerably and no clear patterns were observed. Nutrient concentrations in freshly fallen needles of *P. elliottii* correspond to concentrations of nutrient sufficiency, suggesting that trees of this species, in the present study, were most likely not macro-nutrient poor.

6.3.3 Soil Nutrients & pH

Modest increases in soil pH were observed in all second burn trials except Witklip *P. patula*. Witklip *P. elliottii* showed a significant increase in soil pH. Soil pH in the present study was found to be very acidic (< 4) in comparison with other forest soils. A non-significant overall increase in P occurred in the second burn treatment, most probably due to the increase in soil pH. Total soil N remained constant between treatments, 5 months after treatment implementation. Trials Berlin and Nelshoogte showed a decrease in total N with the latter decreasing significantly 2 months after treatment implementation and may be a result of the smouldering effect in the FF. All soils except Witklip *P. elliottii* can be considered mesotrophic and no significant difference in the ECEC was observed between treatments. K and Na tended to stay relatively constant between treatments with differences noticeable in Ca and Mg concentrations. A significant increase in Mg was observed in the second burn treatment of trial Nelshoogte. The differences in Ca and Mg were most pronounced in the granite-derived soil, which could be a result of the lower buffer capacity compared to dolomite-derived soils. The increase in cations may be the result of the high levels of base cations contained in ash known as the ash-bed effect.

6.4 Stand Damage

Crown, cambium and root damage were observed in the present study. Although pronounced crown scorch was only observed in trial Blyde, where a significant increase in needle fall was observed during the first month after treatment implementation, all trials showed some increase in needle fall during the first month after treatment implementation. This can be ascribed to low stress levels and/or partly damaged needles causing additional needle shedding. Cambium and root damage was only observed in trials Berlin and Nelshoogte where smouldering of the FF occurred. All cambium samples suspected of fire damage were alive when tested, even though resin bleeding occurred. Root damage was observed around most trees in trials Berlin and Nelshoogte where complete FF consumption occurred. Root damage was mostly restricted to non-woody, medium size roots with only 10% of coarse and very coarse roots being damaged. In view of the relatively small number of large-diameter roots killed during the burning treatment it is the author's opinion that tree damage would most likely to some extent result in delayed growth through water stress and as carbohydrates will be used to replenish damaged roots to the expense of tree growth (Varner *et al.,* 2009).

6.5 Understorey Growth

A significant difference was evident between treatments 8 months after treatment implementation, except for Witklip *P. patula*. Species composition did not change after treatment implementation although certain species did resprout faster than others. A significant difference in cover abundance was observed between the first and second burn treatments. The understorey growth in both trials recovered to near their pre-burn levels with increasing time - in trial Witklip *P. patula* it actually recovered to the same level. The increase in cover abundance between the first and second burn treatments reflects the change of seasons.

6.6 Under-canopy Burning

All under-canopy burns can be considered to be of low to moderate intensity. *P. elliottii* burnt much easier compared to *P. patula*. This is most probably due to the difference in needle morphology and the higher resin content of *P. elliottii*. Under-canopy burning was conducted during May 2015 when fuel moisture was already very low, which resulted in smouldering and areas of complete FF consumption. This was a result of the difficulty experienced in burning *P. patula* under optimal burning conditions. Smouldering was directly related to FF mass, with smouldering increasing with FF depth. Trial Berlin received the highest FLI (600 kW m^{-1}) according to the Behave fire prediction model although Nelshoogte received the highest FF reduction. This was the result of the slower spread rate and thus increased fire resistance time, which, together with increased smouldering duration associated with the higher FF mass, increased FF consumption in trial Nelshoogte. Scorch height increased with flame length, which was directly related to FLI. Although scorch height in trial Berlin was predicted to reach 11.9 m and trees pruned to only 9.5 m, no scorch occurred. This anomaly can be explained by the increased crown height observed in the *P. patula* trials, in which the lower branch whorls are deprived of needles due to very dense crown development shading out the bottom needles.

7 Recommendations

The main objective of the study was to determine the effectiveness of under-canopy burning in reducing FF formations and shed some light on the sustainability thereof.

Based on the results obtained in the present study, the author suggests that under-canopy burning under mature pine trees in Mpumalanga can successfully be implemented without any major negative impacts on the trees and environment. Several other researchers have also presented data to support this conclusion (Fisher &Binkley, 2000; Binkley *et al.,* 1992; De Ronde, 1988, 1992). None of the factors monitored in the specific study had a prolonged, significantly negative effect on the tree stand with only slight changes observed. The evidence obtained does support the sustainability of the application. This is however only valid if under-canopy burning is conducted under ideal conditions, avoiding additional damage such as root and cambium damage which was experienced in the present study. Furthermore must care be taken to ensure all combined nutrient exporting operations do not deplete the nutrient budget significantly and if the case, supplements and more sufficient operations would be required.

Even though chronosequence plots were used in this study, it would be advantageous to be able to conduct longer term monitoring to effectively determine all the possible long term impacts of prolonged under-canopy burning. Because of the inevitable time restrictions on the duration of this study, tree growth, tree damage and needle fall in these trials will continue to be monitored beyond the scope of the thesis to determine any delayed treatment effects.

In particular, a better understanding of the effect of root, cambium and crown damage on tree health and tree growth caused by prolonged under-canopy burning, as manifested over time, should be gained. The intended continuous monitoring of the trials used for this study as stated above will address these issues to some extent.

Based on the outcome of this study, further research is proposed in order to determine and predict nutrient input and output to the system as a result of burning, specifically nitrogen, as this aspect is currently one of the main factors contributing to the resistance by industry to use this application more freely. A need therefore exists to determine the difference in nutrient loss between compartments, which received adequate fuel reduction through under-canopy burning before slash burning is applied and slash burning under normal fuel load quantities. Atmospheric deposition monitoring is important in this regard as it constitutes a major nutrient input flux. While we have presented some evidence of changes in nutrient pools, little is known about nutrient dynamics. The relative availability and the tree uptake of macro nutrients following repeated under-canopy burning should thus be investigated more closely. This study has also shown that understorey species were not changed by under-canopy burning with species returning to pre-burn levels, on average, after 14 months. Further research is recommended to determine best practise under-canopy burning methods designed specifically to suppress the main problematic understorey species.

Because of the difficulties experienced with burning underneath *P. patula* specifically, more effective methods of burning of these species need to be researched. New pine hybrids may have different FF structures. There is a need to quantify the effect of repeated under-canopy burning on carbon stocks that are sequestered in plantation forests. This should include changes in FF, understorey vegetation, as well as topsoil carbon.

There is clearly a need for more extensive long-term research on the effect of the use of prolonged under-canopy burning on a number of other related issues, such as the long-term social and environmental impacts and economic sustainability.

Reference

Anderson, HE. 1982. Aids to determine fuel models for estimating fire behaviour. *USDA Forest Service General Technical Report INT – 122.* Intermountain Forest and Range Experiment Station, U.S. Department of Agriculture. 22 pp.

Baker, TG and Attiwill, PM. 1985. Loss of organic matter and elements from decomposing litter of Eucalyptus obliqua L'Hérit. and *Pinus radiata* D. Don. *Australian Forest Research 15: 309-319.*

Binkley, D., Campoe, OC., Gspaltl, M. and Forrester, DI. 2013. Light absorption and use efficiency in forests: Why patterns differ for trees and stands. *Forest Ecology and Management 288: 5-13*.

Binkley, D., Richter, D., David, MB. and Caldwell, B. 1992. Soil chemistry in a Loblolly/Longleaf pine forest with interval burning. *Ecological Applications 2(2): 157-164.*

Bird, TL. and Scholes, MC. 2005. Prescribed under-canopy burning in Pinus patula plantations of the Mpumalanga Highveld: The effects of fire on tree growth. *Southern African Forestry Journal 204(1):3-13.*

Birk, EM. and Bridges, RG. 1989. Recurrent fires and fuel accumulation in even-aged Blackbutt (*Eucalyptus pilularis*) forests. *Forest Ecology and Management 29: 59 - 79.*

Bridgett, JA., Van Wilgen, BW., Kruger, FJ., Forsyth, GG., Jayiya, TP. and Kruger, L. 2003. A new approach to wildland fire management in South Africa. *CSIR, Stellenbosch.*

Brown, AA. and Davis, KP. 1973. *Forest fire: control and use. 2nd edition. The Bark Beetles, fuels, and fire bibliography*. McGraw-Hill, New York.

Busse, MD. Simon, SA. and Riegel, GM. 2000. Tree-Growth and understorey responses to low-severity prescribed burning in thinned *Pinus ponderosa* Forest of Central Oregon. *Forest Science 46(2): 258-268.*

Campbell, CR., & Plank, CO. 1998. Preparation of plant tissue for laboratory analysis, in Kalra, Y.P. (ed.). *Handbook of reference methods for plant analysis. Boca Raton: CRC Press*. pp 37-49.

Carlson, C. and Allan, R. 2001. A pilot study into above ground biomass of a mature *Pinus patula* stand. *ICFR Bulletin Series 20/2001,* Institute for Commercial Forestry Research, Pietermaritzburg. 41 pp.

Carter, MC. and Foster, CD. 2004. Prescribed burning and productivity in southern pine forests: a review. *Forest ecology and management 191: 93-109.*

Chandler, C., Cheney, P., Thomas, P., Trabaud, L. and Williams, D. 1983. *Forest fire management and organization.* Fire and forestry volume 1. John Wiley and Sons, New York.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L. and Williams, D. 1983. *Forest fire management and organization.* Fire and forestry volume 2. John Wiley and Sons, New York.

Chave, J., Navarrete, D., Almeida, S., Álvarez, E., Aragão, LEOC., Bonal, D., Châtelet, P., Silva-Espejo, JE., Goret, JY., Von Hildebrand, P., Jiménez, E., Patino, S., Penuela, MC., Phillips, OL., Stevenson, P and Malhi, Y. 2010. Regional and seasonal patterns of litterfall in tropical South America. *Biogeosciences 7: 43-55.*

Certini, G. 2005. Effects of fire on properties of forest soils: a review. *Oecologia 143: 1-10.*

Coppen, JJW. and Hone, GA. 1995. Gum naval stores: turpentine and rosin from pine resin. Non-wood Forest products 2. Food and Agriculture Organization of the United Nations, Rome.

Covington, WW. and Sackett, SS. 1984. The effect of a prescribed burn in southwestern Ponderosa pine on organic matter and nutrients in woody debris and forest floor. *Forest Science 30(1): 183-192.*

Covington, WW. and Sackett, SS. 1992. Soil mineral nitrogen changes following prescribed burning in ponderosa pine. *Forest Ecology and Management 54: 175-191.*

DAFF. 2011. Blackjack production guideline. *Directorate Plant Production, Pretoria.*

Dames, JF. 1996. *Litter accumulation in Pinus patula plantations and the role of ectomycorrhizal fungi in a forest ecosystem.* Unpublished PhD thesis. University of the Witwatersrand. 206 pp.

Dames, JF., Scholes, MC. and Straker, CJ. 1998. Litter production and accumulation in *Pinus patula* plantations of the Mpumalanga Province, South Africa. *Plant and Soil 203: 183-190*.

Davies, C. 2010. *A climate change handbook for north-eastern South Africa.* Climate change Group, Council for Scientific and Industrial Research, Pretoria.

De Ronde, C. 1980. Controlled burning under pines - A preliminary fuel classification system for plantations in the Cape. *South African Forestry Journal 113: 84-86.*

De Ronde, C. 1982. The resistance of *Pinus* species to fire damage. *South African Forestry Journal 122: 22-27.*

De Ronde, C. 1983. Controlled burning in pine stands in the Cape: The influence of crown scorch on tree growth and litterfall. *South African Forestry Journal 127: 39-41.*

De Ronde, C. 1988*. Preliminary investigations into the use of fire as management technique in plantation ecosystems of the Cape Province*. Unpublished MSc thesis. University of Natal. 179 pp.

De Ronde, C. 1992. *The Impacts of Management on Nutrient Cycling in Plantation Forestry in the Southern Cape.* Unpublished PhD thesis. University of Stellenbosch. 280 pp.

De Ronde, C. 1993. Spatial Variation of Forest Floor Loading in Pine Stands of the Tsitsikamma. *South African Forestry Journal 166: 1-8*.

De Ronde, C. 2008. Guidelines for prescribed burning for the specific vegetation types assessed within the FIRE PARADOX community. Deliverable D9.1-4 of the Integrated project “Fire Paradox”, Project FP6-018505. European Commission, 41p, plus 25 pp Appendices.

De Ronde, C. 2007. Prescribed burning inside Pinus pinaster stands: considering surface fire fuel beds, comparisons with other Pinus species and the relative resistance to fire damage. In: Leone V. (ed.), Lovreglio R. (ed.). *Proceedings of the international workshop MEDPINE 3: conservation, regeneration and restoration of Mediterranean pines and their ecosystems.* Bari: CIHEAM. 85-91 pp.

De Ronde, C., Bohmer, LH. and Droomer, AEC. 1986. Evaluation of wildfire damage in pine stands. *South African Forestry Journal 138: 45-50.*

De Ronde, C., Goldammer, JG., Wade, DD. and Soares, R. 1990. Prescribed burning in industrial pine plantations. In: Fire in the tropical biota. *Ecosystem processes and global challenges (Goldammer, JG. ed.)*. Ecological Studies 84, Springer-Verlag, Berlin-Heidelberg-New York. 216-272 pp.

De Ronde, C., Trollope, WS., Parr, CL., Brockett, BH. and Geldenhuys, CJ. 2004. Fire effects on flora and fauna. In: Wildlands Fire Management Handbook for Sub-Sahara Africa. Goldammer, JG. and De Ronde, C. (Eds.): 60-87.

Ditomaso, JM., Brooks, ML., Allen, EB., Minnich, R., Rice, PM. and Kyser, GB. 2006. Control of invasive weeds with prescribed burning. *Weed Technology 20: 535-548.*

Dovey, SB. 2005. *Above-ground allometry, biomass and nutrient content of Acacia mearnsii across four ages and three sites in the Kwazulu-Natal midlands.* Unpublished MSc thesis. University of KwaZulu-Natal. 106 pp.

Dovey, SB., Du Toit, B. and De Clercq, E. 2011. Nutrient fluxes in rainfall, throughfall and stemflow in Eucalyptus stands on the Zululand coastal plain, South Africa. *Southern Forests 73(3&4): 193-206.*

Du Toit B Dovey SB Smith CW, 2008. Effects of slash and site management treatments on soil properties, nutrition and growth of a Eucalyptus grandis plantation in South Africa. In *Nambiar, E.K.S. (ed.) Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 2-9 November 2006*. Centre for International Forestry Research (CIFOR), Bogor, Indonesia. Pp 63-78.

Du Toit, B. and Scholes, M. 2002. Nutritional sustainability of Eucalyptus plantations: A case study at Karkloof, South Africa. *South African Forestry Journal 195: 63-72.*

Du Toit, B. and Fischer P.M., 2011. Nutrient losses resulting from prescribed burning in semi-mature pine stands, Mpumalanga. 5th International Wildland Fire Conference, Sun City, South Africa, 9-13 May 2011.

Edmeades, DC. 1982. Effects of lime on effective cation exchange capacity and exchangeable cations on a range of New Zealand soils. *New Zealand Journal of Agricultural Research 25: 27-33.*

Erickson, HE. and White, R. 2008. Soils under fire: Soils research and the joint fire science program. *General Technical Report, USDA.*

Fecko, RM., Walker, RF., Frederick, WB., Johnson, DW. and Miller, WW. 2008. Influence of mechanized thinning and prescribed underburning on radial growth of Jeffrey pine. *Journal of sustainable forestry 26(1): 19-60.*

Fisher, RF. and Binkley, D. 2000. *Ecology and Management of Forest Soils*. Third edition. John Wiley and Sons, Inc. New York. 494 pp.

Forsyth, GG., Kruger, FJ. and Le Maitre, DC. 2010. National veldfire risk assessment: analysis of exposure of social, economic and environmental assets to veldfire hazards in South Africa. Report No. CSIR/NRE/ECO/ER/2010/0023/C. CSIR Natural Resources and the Environment CSIR, Fred Kruger Consulting CC, Stellenbosch.

FSA, 2003-2010. Report on commercial timber resources and primary roundwood processing in South Africa. Forestry Technical and Information Services, Pretoria.

Garrison-Johnson, M. 2002. Development of nutrient status in forest soils. *Forest Resources Department.* University of Idaho, Moscow.

Geldenhuys, CJ., Van Wilgen, BW., Bond, WJ., Van der Vijver, ADM. and De Ronde, C. 2004. Fire effects on the maintenance of biodiversity, soil and nutrients. In: Wildland fire management Handbook for Sub-Sahara Africa. Goldammer, JG. and De Ronde, C. (Eds.). 88-113 pp.

Gholz, HL. and Fisher, RF. 1982. Organic matter production and distribution in Slash Pine (*Pinus elliottii*) plantations. *Ecology 63: 1827-1839.*

Gholz, HL., Fisher, RF. and Prichett, WL. 1985. Nutrient dynamics in slash pine plantation ecosystems. *Ecology* 66(3): 647-659.

Gonzalez-Benecke, CA., Jokela, EJ. and Martin, TA. 2012. Modeling the effects of stand development, site quality, and silviculture on leaf area index, litterfall, and forest floor accumulations in Loblolly and Slash pine plantations. *Forest Science 58(5): 457-471.*

Gregoire, N. and Fisher, RF. 2004. Nutritional diagnoses in loblolly pine (*Pinus taeda* L.) established stands using three different approaches. *Forest Ecology and Management 203: 195-208.*

Grogan, P., Bruns, TD. and Chapin, FS. 2000. Fire effects on ecosystem nitrogen cycling in a Californian bishop pine forest. *Oecologia 122: 537-544.*

Hatten, J., Zabowski, D., Ogden, A., Theis, W. and Choi, B. 2012. Role of season and interval of prescribed burning on ponderosa pine growth in relation to soil inorganic N and P and moisture. *Forest Ecology and Management 269: 106-115.*

Hollis, JJ., Anderson, WR., McCaw, WL., Cruz, MG., Burrows, ND., Ward, B., Tolhurst, KG. and Gould, JS. 2011. The effect of fireline intensity on woody fuel consumption in southern Australian eucalypt forest fires. *Australian Forestry 74(2): 81-96.*

Huffman, DW., Stoddard, MT., Springer, JD., Crouse, JE. and Chancellor, WW. 2013. Understorey plant community responses to hazardous fuels reduction treatments in pinyon-juniper woodlands of Arizona, USA. *Forest Ecology and Management 289: 478-488.*

Hunt, SM. and Simpson, JA. 1985. Effects of low intensity prescribed fire on the growth and nutrition of a Slash pine plantation. *Australian Forestry of Research 15: 67-77.*

ICFR 1998. Annual research report 1998. MacLennan, L. (ed.) Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Iglay, RB., Leopold, BD. and Miller, DA. 2014. Vegetation responses to fire and herbicide in intensively managed, mid-rotation pine. *Forest Ecology and Management 328: 69-78.*

Iglay, RB., Leopold, BD., Miller, DA. and Burger, LW. 2010. Effect of plant community composition on plant response to fire and herbicide treatments. *Forest Ecology and Management 260: 543-548.*

Kent, M. and Coker, P. 1992. *Vegetation Description and Analysis: A Practical Approach*. John Wiley & Sons: New York.

Kotze, H. and Du Toit, B. 2012. Silviculture of industrial pine plantations in Southern Africa. In: Bredenkamp, BV. and Upfold, SJ. (eds) *Southern African Forestry Handbook.* Southern African Institute of Forestry (5th edn). South Africa. pp 123-139.

Lehtonen, A., Lindholm, M., Hokkanen, T., Salminen, H. and Jalkanen, R. 2008. Testing dependence between growth and needle litterfall in Scots pine – a case study in northern Finland. *Tree Physiology 28: 1741-1749.*

Linder, S. 1995. Foliar analysis for detecting correcting nutrient imbalances in Norway spruce. *Ecological Bulletins 44: 178-190.*

Lundgren, B. 1978. Soil conditions and nutrient cycling under natural and plantation forests in Tanzanian highlands. *Swedish University of Agricultural Sciences.*

Maggs, J. 1988. Organic matter and nutrients in the forest floor of *Pinus elliottii* plantation and some effects of prescribed burning and superphosphate addition. *Forest Ecology and Management 23: 105-119.*

Mackensen, J. 1999. Nutrient management for industrial tree plantations (HTI) in Indonesia. A practical guidance towards integrated nutrient management. *Tropical Forest Research.*

Marshall, DJ., Wimbley, M., Bettinger, P. and Stanturf, J. 2008. Synthesis of knowledge of hazardous fuels management in Loblolly pine forests. *General technical report SRS-110.* United Stated Department of Agriculture.

McDowell, NG., Adams, HD., Bailey, JD. and Kolb, TE. 2007. The role of stand density on growth efficiency, leaf area index, and resin flow in southwestern ponderosa pine forests. *Canadian Journal of Forest Research 37: 343-355.*

Michaletz, ST. and Johnson, EA. 2007. How forest fires kill trees: A review of the fundamental biophysical processes. *Scandinavian Journal of Forest Research 22: 500-515.*

Monleon, VJ. and Cromack, K. 1996. Long-term effects of prescribed underburning on litter decomposition and nutrient release in ponderosa pine stands in central Oregon. *Forest Ecology and Management 81:143-152.*

Moreira, F., Delgado, A., Ferreira, S., Borralho, R., Oliveira, N., Inacio, M., Silva, JS. and Rego, F. 2003. Effects of prescribed fire on vegetation structure and breeding birds in young *Pinus pinaster* stands of northern Portugal. *Forest Ecology and Management 184: 225-237.*

Morris, AR. 1984. A comparison of soil nutrient levels under grassland and two rotations of Pinus patula in the Usutu Forest, Swaziland. In: IUFRO symposium on site and productivity of fast growing plantations. *South African Forestry Research Institute .* Pretoria. pp 881-892.

Morris, AR. 1986. *Soil fertility and long term productivity of Pinus patula in the Usutu Forest, Swaziland.* Unpublished PhD thesis. University of Reading. 398 pp.

Morris, AR. 1993. Forest floor accumulation, nutrition and productivity of *Pinus patula* in the Usutu forest, Swaziland. *Commonwealth Forestry Review 72(2): 114-117.*

Morris, AR. 1995. Forest floor accumulation, nutrition and productivity of *Pinus patula* in the Usutu Forest, Swaziland. *Plant and Soil: 271-278.*

Odhiambo, B., Meincken, M. and Seifert, T. 2014. The protective role of bark against fire damage: a comparative study on selected introduced and indigenous tree species in the Western Cape, South Africa. *Trees 28: 555-565.*

Odiwe, AI. 2009. *Effects of late rotation fertilization and nutrient cycling on pine plantation productivity in the Mpumalanga province of South Africa.* Unpublished PhD thesis. University of the Witwatersrand. 220 pp.

Phillips, RJ. and Waldrop, TA. 2008. Changes in vegetation structure and composition in response to fuel reduction treatments in the South Carolina piedmont. *Forest Ecology and Management 225: 3107-3116.*

Pretzsch, H. 2009. *Forest dynamics, growth and yield.* Springer-Verlag Berlin Heidelberg. 295-297 pp.

Reeb, J. and Milota, M. 1999. Moisture content by the oven-dry method for industrial testing. *Oregon State University Corvallis, OR.*

Rego, FC., Bunting, SC. and Da Silva, JM. 1991. Changes in understorey vegetation following prescribed fire in maritime pine forests. *Forest Ecology and Management 41: 21-31.*

Reinhardt, ED. and Ryan, KC. 1988. Eight-year tree growth following prescribed under-burning in a western Montana Douglas-fir/Western Larch stand. *Intermountain Research Station.* 387, United States Department of Agriculture.

Reuter, DJ. and JB. Robinson. 1997. *Plant Analysis: An Interpretation Manual (2nd edition).* CSIRO Publishing.

Ross, T. and Du Toit, B. 2004. Fuel load prediction and characterisation for the development of fuel models for *Pinus patula* plantations in South Africa. *ICFR Bulletin 12: 1-24., Institute for commercial Forestry research, Pietermaritzburg, South Africa.*

Ross, T., Du Toit, B. and Dovey, S. 2005. Nutrient pools in slash loads in *Pinus patula* sawtimber and pulpwood stands in South Africa. *ICFR Bulletin 10: 1-25. Institute fore commercial Forestry research, Pietermaritzburg, South Africa.*

Ross, TI. 2004. *Fuel load characterisation and quantification for the development of fuel models for Pinus patula in South Africa.* Unpublished MSc thesis. University of Stellenbosch. 138 pp.

Sackett, SS. and Haase, SM. 1998. Two case histories for using prescribed fire to restore Ponderosa pine ecosystems in northern Arizona. *Pacific Southwest Research station.* United States Department of Agriculture.

Schoch P. and Binkley, D. 1986. Prescribed burning increased nitrogen availability in a mature Loblolly pine stand. *Forest ecology and management 14: 13-22.*

Schutz, CJ. 1990. *Site relationships for Pinus patula in the eastern Transvaal escarpment area.* Unpublished PhD thesis. University of Stellenbosch. 334 pp.

Schulze, RE. 2007. South African Atlas of Climatology and Agrohydrology. *Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 7.2*

Scott, DW. 2001. Review of the prescribed fire program on emigrant creek ranger district. *Blue Mountains Pest Management Service Centre.* United States Department of Agriculture.

Singh, B. 1982. Nutrient content of standing crop and biological cycling in *Pinus patula* ecosystem. *Forest Ecology and Management 4: 317-332.*

Soil Clasification Working Group. 1991. A taxonomic system for South Africa.

Sugarman, DR. 1999. *Soil chemical properties in pine plantations of different ages in the eastern escarpment region of South Africa.* Unpublished MSc thesis. University of Cape Town. 78 pp.

Symstad, AJ., Newton, WE. and Swanson, DJ. 2014. Strategies for preventing invasive plant outbreaks after prescribed fire in ponderosa pine forest. *Forest Ecology and Management 324: 81-88.*

Teie, W. C. (2009). *South African Edition: Fire Manager's Handbook on Veld and Forest Fires.* Strategy, Tactics and Safety – 2nd Edition. South Africa: Southern African Institute of Forestry.

Teshome, T. 2011. Analysis of resin and turpentine oil constituents of *Pinus patula* grown in Ethiopia. *Ethiopian e-Journal for Research and Innovation Foresight 3(1): 32-43.*

The Non-Affiliated Soil Analysis Work Committee, 1990. Handbook of standard soil testing methods for advisory purposes. Sunnyside 0132, Pretoria: *Soil Science Society of South Africa.*

Trading Economics. 2014. [Online]. Available: http://www.tradingeconomics.com/south-africa/population [2014, March 16].

Trollope, WSW., De Ronde, C. and Geldenhuys, CJ. 2004. Fire Behaviour. In: Wildland Fire Management Handbook for Sub-Sahara Africa. Goldammer JG. and De Ronde, C. (Eds.). pp 27-59.

Turner, MG., Tinker, DB., Romme, WH., Kashian, DM. and Litton, CM. 2004. Landscape patterns of sampling density, leaf area, and aboveground net primary production in postfire Lodgepole pine forests, Yellowstone national park (USA). *Ecosystems 7: 751-775.*

Van der Sijde, JHR. 2003. *The assessment of fire history in plantations of Mpumalanga North.* Unpublished MSc thesis. University of Stellenbosch. 209 pp.

Van Wagtendonk JW. 1996. Use of a deterministic fire growth model to test fuel treatments. *National Biological Service.* El Portal, California.

Varner, JM., Putz, FE., O'Brien, JJ., Hiers, JK., Mitchell, RJ. and Gordon, DR. 2009. Post-fire tree stress and growth following smouldering duff fires. *Forest Ecology and Management 258: 2467-2474.*

Vose, JM., Sullivan, NH., Clinton, BD. and Bolstad, PV. 1995. Vertical leaf area distribution, light transmittance, and application of the Beer-Lambert Law in four mature hardwood stands in the southern Appalachians. *Canadian Journal of Forest Research 25: 1036-1043.*

Wan, S., Hui, D. and Luo, Y. 2001. Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis. *Ecological Applications 11(5): 1349-1365.*

Wells, CG. 1971. Effects of prescribed burning on soil chemical properties and nutrient availability [and Comments by William L. Pritchett], *Proceedings of the Prescribed Burning Symposium. Charleston, SC.* USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC. p. 86-99.

Yang, YS., Guo, JF., Chen, GS., Xie, JS., Gao, R., Li, Z. and Jin, Z. 2005. Litter production, seasonal pattern and nutrient return in seven natural forests compared with a plantation in southern China. *Forestry 78(4): 403-415.*

Appendix 1A

The FF mass table used in predicting the FF depth-mass regression used for *P. elliottii* in the study (KLF, pers. comm., 2014).

Litter Depth (mm)	SPECIES	
	P. elliottii; P. taeda	P. patula
	Litter mass	(Tonnes/ha)
5	2.5	2.8
10	4.9	5.2
15	7.4	7.2
20	10	9
25	12.4	10.7
30	15	12
35	17	14
40	20	16
45	22	18
50	25	20
55	27	22
60	29	24
65	31	26
70	33	28
80	37	31
90	41	34
100	45	37
Add 2 tons per ha for litter density		

Appendix 2A

Table representing the combined FF nutrient concentrations for each trial and treatment.

Trial	Treatment	N	P	K	Ca	Mg
Berlin	Control	1.32	0.07	0.11	0.40	0.09
	First Burn	1.22	0.06	0.09	0.39	0.10
	Second Burn	1.37	0.07	0.06	0.29	0.07
Blyde	First Burn	0.83	0.03	0.05	0.42	0.05
	Second Burn	0.82	0.04	0.06	0.39	0.05
Nelshoogte	Control	1.24	0.06	0.10	0.33	0.10
	First Burn	1.09	0.05	0.07	0.31	0.10
	Second Burn	1.37	0.06	0.04	0.21	0.06
Witklip P. pat	First Burn	1.23	0.07	0.12	0.76	0.17
	Second Burn	1.11	0.06	0.14	0.60	0.18
Witklip P. ell	First Burn	0.66	0.03	0.08	0.55	0.10
	Second Burn	0.67	0.03	0.07	0.47	0.08

Appendix 3A

ANOVA table presenting macro nutrients in fresh fallen needles collected during the first two months after treatment implementation.

ANOVA (Type Ⅱ test)					
Nutrient	Response	Sum Sq	Df	F value	*p*-value
Nitrogen	Month	0.0040	1	0.1944	0.6710
	Treatment	0.0133	1	0.6426	0.4459
	Month:Treatment	0.0065	1	0.3149	0.5901
	Residuals	0.1660	8		
Phosphorus	Month	<0.001	1	0.0417	0.8434
	Treatment	<0.001	1	0.3750	0.5573
	Month:Treatment	<0.001	1	0.0417	0.8434
	Residuals	<0.001	8		
Potassium	Month	0.0040	1	0.3572	0.5666
	Treatment	0.0008	1	0.0738	0.7928
	Month:Treatment	0.0003	1	0.0266	0.8746
	Residuals	0.0903	8		
Calcium	Month	0.0000	1	0.0000	1.0000

	Treatment	0.0065	1	0.3421	0.5748
	Month:Treatment	0.0021	1	0.1117	0.7468
	Residuals	0.1528	8		
Magnesium	Month	0.0010	1	0.2010	0.6658
	Treatment	0.0007	1	0.1346	0.7233
	Month:Treatment	0.0001	1	0.0150	0.9057
	Residuals	0.0401	8		

Appendix 4A

Setaria megaphylla growth in the firebreaks due to exposed soil stimulating germination.

Appendix 5A

ANOVA table presenting diameter increment between treatments over twelve months of growth in trial Blyde and Witklip *P. patula*.

Blyde DBH Increment				
	Df	Sum Sq	F value	*p*-value
Treatment	1	0.045	0.0672	0.7957
Residuals	198	133.913		
Witklip *P. patula* DBH Increment				
Treatment	1	0.499	0.8485	0.3584
Residuals	158	92.939		

Appendix 6A

Input data from each trial used in the fire prediction model BehavePlus5 in predicting fire behaviour.

Description	Unit	Berlin	Blyde	Nelshoogte	Witklip P. ell
1-h fuel load	t ha^{-1}	16	5	17	4
10-h fuel load	t ha^{-1}	0.8	1	0.7	0.9
100-h fuel load	t ha^{-1}	0.1	0.1	0.1	0.1
Live herbaceous fuel load	t ha^{-1}	0.0	0.0	0.0	0.0
Live woody fuel load	t ha^{-1}	0.0	0.0	0.0	0.0
1-h SA/V	m^2 m^3	6562	6562	6562	6562
Live herbaceous SA/V	m^2 m^3	4921	4921	4921	4921
Live woody SA/V	m^2 m^3	4921	4921	4921	4921
Fuel bed depth	m	0.15	0.2	0.1	0.07

Dead fuel moisture of extinct.	%	31	31	31	31
Dead fuel heat content	kJ kg^{-1}	18622	1.8622	18622	18622
Live fuel heat content	kJ kg^{-1}	18622	18622	18622	18622
1-h moisture	%	12	15	10	20
10-h moisture	%	20	20	20	25
100-h moisture	%	30	30	30	30
Live herbaceous moisture	%	50	50	50	50
Live woody moisture	%	50	50	50	50
Midflame wind speed (upslope)	km h^{-1}	2 – 6	2 – 7	2 - 7	3 - 5
Air temperature	°C	27	28	26	26
Slope steepness	%	30	0	0	10