The effect of modified fuel loads on fire behaviour in *Pinus patula* and *Eucalyptus macarthurii* stands in the Mpumalanga Highveld forestry region of South Africa.

By
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George Campus – Saasveld, March 2013

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Declaration

This thesis was supervised by Prof. J. H. Louw and co-supervised by Dr. C. W. Smith. I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Technology in the Nelson Mandela Metropolitan University, George Campus – Saasveld, George. It has not been submitted before for any degree or examination in any other University.

________________________________________________________________________

Christiaan Frederik Pool.

March 2013
Abstract

The effectiveness of harvesting slash treatments are questionable when wild fires, fuelled by post harvesting slash, burn out of control. In order to quantify effectiveness of various slash treatments, fire behaviour in *Pinus patula* and *Eucalyptus macarthurii* compartments in the Highveld area (Piet Retief) of Mpumalanga, South Africa, were assessed after application of five different post-harvesting slash treatments. Treatments included mulching, chopper rolling, windrowing, removal of slash (inter-windrowing) and broadcasting. Independent fuel and environmental variables were measured prior and during application of fire to the study areas and effects on fire behaviour were compared afterwards. Dependant fire behaviour variables such as the rate of spread, fire temperature and flame height were measured in respective slash treatment plots and compared.

Results of the study indicated that fire behaviour assessed in mulched areas in both the *P. patula* and *E. macarthurii* compartments were significantly less intense when compared to fire behaviour in chopper roll, broadcast and windrow treatments. Fire behaviour in mulched plots compared favourably with areas where harvesting slash was removed (inter-windrow treatment). Comparisons between fuel loads of different treatments also indicated accelerated mineralization of organic material in mulched areas.

Mulching of harvesting slash seems to be an effective method to restrict fire behaviour in post-harvesting compartments and should be considered as part of a fire management strategy.
To my Maker
and to my family
for their support and patience
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CHAPTER 1
INTRODUCTION

Despite technical advancements in fire management, fire losses within the commercial forestry sector of South Africa still escalate. Figures released by Forestry South Africa (FSA) indicate that the average fire damage incurred by the forestry industry more than doubled during the last decade: an average area of 32,418 ha was destroyed annually compared with 14,441 ha/year during the previous decade (Forestry South Africa, 2011). Factors contributing to increased fire damage include:

- Global climate change, which causes adverse weather conditions conducive to veldfire development.
- Poor silviculture practices on plantations, leading to fuel accumulation.
- Economic constraints preventing maintenance and replacement of infrastructure necessary to manage veldfires.
- A lack of competent staff responsible for fire management.
- An unfavourable political climate in some rural areas owing to delayed land restitution, social unrest and unemployment (de Ronde, 2008).

Forestry companies are increasing their efforts to resolve this situation by focusing their fire-management activities on fuel-load management. Prescribed burning activities in some of the major forestry companies, such as Komatiland Forestry (KLF), have more than doubled since 2008 (Bothma, personal communication, 2009). Decision making with regard to controlled burning is, however, becoming increasingly complex owing to an increased risk linked to this activity. Broader ecosystem values, such as maintaining soil quality, are becoming more and more important and need to be considered when decisions are made with regards to applying appropriate fuel-load management methods in commercial plantations (du Toit, et al., 2000).
During 2007, the forestry industry suffered losses amounting to nearly nine billion rand because of veldfires. Damages were calculated in terms of loss of planted forests, equipment and jobs, as well as threatened future income, and caused an estimated reduction of 50% of the provincial gross domestic product (GDP) of Mpumalanga at that time. Events like these are threatening the sustainability of forestry in South Africa (Forestry South Africa, 2011).

The South African forestry industry has shown its commitment to sustained forest management through the adoption of forest certification schemes, such as the Forest Stewardship Council (FSC) system. More than 95% of all commercial plantations in South Africa are currently FSC certified (Forestry South Africa, 2011). In order to retain FSC certification, all management activities of forestry companies have to be FSC-compliant. The mission statement of the FSC includes the following declaration with regard to the environment: “Environmentally appropriate forest management ensures that the harvest of timber and non-timber products maintains the forest's biodiversity, productivity, and ecological processes” (Forest Stewardship Council, 2011).

It is expected that pressure from European environmentalists for greater compliancy with rules and regulations that will regulate fuel-management activities currently threatening sustainability of forest areas will mount. One such activity under scrutiny is prescribed burning of post-harvesting slash (Ottmar, 1985). This statement is supported by the Forest Stewardship Council, especially on sensitive soils (Forest Stewardship Council, 2011; Durgin, 1985).

Prescribed burning, the preferred slash and fuel-load treatment amongst foresters, is continually criticized and some e.g. da Costa (2008) argues that removal of organic material through fire application leads to losses of nutrients and increases the chances of soil erosion on sensitive growing sites. A lack of scientific results regarding fuel-load management strategies has led to renewed interest in the investigation of these practices in the forestry industry. However, the
affordability, effectiveness and ecological implications of these methods with regard to fire
management and sustainable tree growth are inconclusive and need further investigation.

Different post-harvesting slash-management methods are currently employed in the South African
forestry industry. These include prescribed burning, broadcasting, mulching, windrowing,
chopper-rolling and, in some cases, removal of slash for utilization as biofuel. The desirable
outcomes of a post-harvesting slash treatment include the retention and accelerated decomposition
of organic material, ease of silvicultural activities in the compartment, improved weed control, site
sustainability and reduced fire hazard (Norris, 1985). In many cases, the slash-treatment method
preferred by managers is a subjective choice and often long-term ecological and financial
outcomes are disregarded. It is therefore common to find different post-harvest slash-management
methods used in the same area where homogenous environmental conditions prevail. Mulching of
post-harvesting slash is a seemingly effective, although expensive, method of slash management
and is becoming increasingly popular among foresters. Mulching entails the mechanical chipping
of post-harvesting debris to break down and compact fuel loads (da Costa, 2008). The effects of
broadcasting, chopper-rolling, windrowing, prescribed burning and removal of slash have been
studied in the past and fire managers are more familiar with the effects these treatments have on
silviculture activities and fire behaviour (Norris, 1985; Lunt, 1951; Lyon, 1966). Although
mulching is widely applied to dispose of organic slash and to prepare firebreaks, no scientific
measurements have been undertaken to explain fire behaviour in post-harvesting mulched slash or
to compare this with other post-harvesting slash treatments.

It is important that the direct financial cost should not be the primary factor for decision making
regarding treatment of post-harvesting slash, as managers may overlook the ‘value of opportunity
costs’ and the benefits this can generate (Steenkamp, 2008). The effects of mulching,
broadcasting, chopper-rolling, removal of slash and windrowing will be compared in this study to
identify the most desirable fuel-load treatment to change fire behaviour parameters. According to de Ronde, et al. (1990), broadcasting of post-harvesting slash is generally seen as the preferred slash treatment as it is widely practiced and will be regarded as the control in this study. The two species used include Pinus patula (soft wood) and Eucalyptus macarthurii (hard wood). These species represent the most popular commercial genera planted by the forestry industry in South Africa (Forestry South Africa, 2011). The results have the potential to contribute to decision support systems for integrated slash treatment and fire-management strategies in plantation ecosystems.

The objectives of the study therefore are to investigate the following:

- To determine the extent to which fuel- and fire-behaviour variables are affected by post-harvesting slash treatments of broadcasting (control), windrow, inter-windrow, chopper-rolling and mulching.
- To determine the extent to which fuel- and fire-behaviour variables are affected by species of two different genera: Pinus patula and Eucalyptus macarthurii.

The hypotheses with the relevant key questions for this study are as follows:

**Hypothesis 1**

Fuel- and fire-behaviour variables will be the same across different post-harvesting slash treatments.

**Question 1:** To what extent will variables such as rate of spread (RoS), fire temperature and flame length be influenced by different post-harvesting slash treatments?

**Question 2:** How will fuel-class distribution be influenced by different post-harvesting slash treatments?
Hypothesis 2

Fuel- and fire-behaviour variables following different post-harvesting slash treatments will be the same across *Pinus patula* and *Eucalyptus macarthurii* stands.

**Question 1:** To what extent will variables such as RoS, fire temperature and flame length be influenced across *Pinus patula* and *Eucalyptus macarthurii* stands?

**Question 2:** How will fuel-class distribution be influenced across *Pinus patula* and *Eucalyptus macarthurii* stands?
CHAPTER 2

A PERSPECTIVE ON FOREST-FIRE BEHAVIOUR AND POST-HARVESTING SLASH MANAGEMENT METHODS

2.1 INTRODUCTION

Fire behaviour is influenced by several environmental factors; namely fuel, weather and topography. Forest fuels vary over space and time in terms of type, amount and moisture condition. These factors, along with the topography and weather, form the basis of fire-behaviour prediction. In order to assess fire behaviour, it is necessary to understand and determine the extent to which such issues influence this behaviour. Two of these environmental factors, namely weather and topography, are natural factors that cannot be altered by management. The only factor that fire managers can modify is that of fuel and its characteristics. In this study, criteria for weather and topography were determined and may be regarded as being constant throughout the trial period. In practice, fire managers need to consider the topography and weather conditions that prevail in specific areas in order to anticipate fire behaviour under these conditions at any given time. If the anticipated fire behaviour is potentially difficult to control and may threaten life, assets or the environment, managers need to modify fuel types and loads in the area. It is therefore essential to understand these characteristics in terms of the influence of fuel on fire behaviour.

The fuel that are left in compartments after harvesting operations consist of a natural litter layer (duff) created by leave and needle fall as well as the shedding of bark and twigs. During the harvesting process unutilised crowns, bark and branches (harvesting slash) are added to the fuel load (Ottmar, et al., 1985).

This chapter investigates fuel characteristics, as well as the methods commonly used in the forestry industry to treat post-harvesting slash/fuels. This information will provide important
background that will aid fire managers in their selection of an appropriate post-harvesting slash-treatment method to change fire behaviour should forest fires occur.

2.2 FIRE BEHAVIOUR PARAMETERS

Fire behaviour can be defined as the way in which a fire spreads, how fuels ignite, the ability of the fire to create spot fires and the intensity of the fire (Chandler, et al., 1983; Chuvieco, 2003; Teie, 2005). According to Fernández, Loureiro and Botelho (2005), weather conditions, steepness of slope and a reduction in fuel load have a noticeable effect on fire behaviour. Fire-behaviour parameters include fire intensity, RoS, flame height and fire temperature. It is important to understand fire behaviour and the factors influencing this behaviour to predict and measure the affect of fire on the environment (Fernández and Rego, 1998).

Fire intensity: - Fire intensity refers to the rate at which a fire produces thermal energy and is always expressed in terms of heat (calories) or power (watts) (Chandler, et al., 1991; Kennard, 2008)]. According to Kennard (2008), fire intensity is directly proportional to the fuel’s combustion heat, the amount of fuel consumed and the RoS. Fuel, weather and topography thus play a very important role in determining the rate of heat released by a fire. Byram (1959, cited in Chandler, et al., 1983) calculated fire intensity as the product of available fuel energy and the fire’s rate of advance:

\[ I = Hwr, \]

where:

\[ I = \text{fire line intensity (kW/m – the heat output per metre of fire front)}, \]

\[ H = \text{fuel load heat of combustion (kJ/kg)}, \]

\[ w = \text{weight of fuel consumed per unit area (kg/m}^2\text{)} \text{ and} \]

\[ r = \text{rate of spread (m/s)}. \]
Accepting the approximation that the heat value of the plant fuel consumed is approximately 16,000kJ/kg, Luke and McArthur (1978) offer the following calculation:

\[ I = W \times R \times 27, \]

where:

- \( I \) = fire intensity,
- \( W \) = weight of fuel consumed (tonnes/hectare) and
- \( R \) = rate of spread (metres/minute).

This is an important fire parameter as it gives an indication of the amount of fuel consumed by a fire and thus the amount of heat released from fuel.

Intense fires decrease the size of the pool of nutrients needed for tree growth in the medium and long term (Rab, 1996; Gibbons, et al., 2000). Nutrient shortages are created through the process of volatilization as well as erosion and leaching (du Toit, et al., 2004). According to Williams and Gill (1995), repeated burning of surface litter and humus may degrade the physical qualities of soil by reducing the water- and nutrient-holding capacities, crumbliness, aeration and drainage.

*Rate of spread (RoS):* - RoS refers to the horizontal distance that the flame zone moves per unit of time (metres per minute) and refers to the head-fire segment of the boundary between burning and unburned fuels at ground level – the fire perimeter (Kennard, 2008). It refers to the continuous spread rather than the effect of repeated ignitions caused by burning brands or embers falling well ahead of the perimeter (Gill and Knight, 1991). In practice, the rate of perimeter spread may be determined by measuring the position of the perimeter at given intervals or by measuring the time taken to travel given distances (Gill and Knight, 1991). From the perspective of fire management, this is an important parameter as the RoS will determine how fast a veldfire will increase in size (area damaged) and hamper the reaction time of fire.
fighters trying to control the fire. Fires with a fast RoS are also associated with strong winds that can cause more spot fires ahead of the original fire (Chandler, et al., 1983).

*Flame height*: - Flame dimension and shape may be measured by height, length, depth and angle of the flame. Flame height is used to estimate the radiation intensity of flames, and is directly related to a fire’s RoS (Johnson and Miyanishi, 2001). Johnson and Miyanishi (2001) offer two definitions of flame height: the height of flames at the maximum temperature (which is difficult to measure in veldfires because of varying flame heights); and the vertical distance from the flame base or ground to the time-averaged flame tip. The simplest way to measure a visible flame tip requires height markers to be positioned in the fire. Flame-tip height can be established either by immediate observation or by videotaping the moving fire (Kennard, 2008). For a smoke-covered flame, an infrared camera can be used to penetrate the smoke and measure the maximum flame temperature and visible flame tip (Johnson and Miyanishi, 2001). Visual assessment is often inaccurate (Johnson and Miyanishi, 2001), but is the most common method used (Gill and Knight, 1991). Flame-tip height is an important predictor of the spread of firebrands (small burning/smouldering embers) and the potential for development of spot and crown fires as higher flames elevate firebrands higher (Kennard, 2008).

*Fire temperature*: - Fire temperature refers to the measure of heat released by fuel during combustion. Phrased more scientifically in terms of units, fire temperature is the average kinetic energy of the particles in a sample of matter, expressed in terms of units or degrees designated on a standard scale and an increase in fire temperature increases fire intensity (Gill and Knight, 1991). Dennison, et al., (2006) states that fires with a higher intensity has a higher RoS and a bigger potential to create spot fires.
2.3 FACTORS AFFECTING FIRE BEHAVIOUR

A number of factors affect the way in which a fire behaves. Keeping these in mind, it is possible for the fire manager to either alter them, in the case of fuel characteristics, or plan in such way to compensate for the expected fire behaviour. A fire belt can for example be constructed to prevent a fire to burn on a steep slope that is exposed to wind (Overton, 1996).

2.3.1 Fuel characteristics

Forest fuel may be defined as a fuel complex consisting of a combination of litter types and according to Brown (1974); and Attiwill and Leeper (1987) consist of leaves, bark, twigs, branches and reproductive organs. Fire managers can influence forest fuel by changing the size and shape, arrangement, load, compactness and continuity of fuels, thus intensifying or reducing parameters of fire behaviour. Fuel characteristics that cannot be directly changed by slash treatments include chemical content of fuel, fuel temperature and fuel moisture. However, these characteristics can be directly influenced by changes in weather conditions and indirectly influenced by altering the physical condition of the fuel (Teie, 2005). A discussion of fuel characteristics and their affect on fire behaviour follows this section.

Chemical content: - All fuels contain chemicals which are volatilized when the fuels are heated. Some of these chemicals are more volatile than others and influence fire behaviour when they ignite (Teie, 2005). According to Luke and McArthur (1978), Pinus and Eucalyptus species contain highly volatile resinous and other oily compounds. These chemicals will ignite spontaneously once flashpoint has been reached. Flashpoint refers to the heat stage where these chemicals are gassified. This stage is reached at different temperatures in different chemicals and a higher temperature in green fuels as green fuels contains high concentrations of moisture (Little and Ohmann, 1988).
Fuel moisture content: - The moisture content of fuel reflects the amount of water present in both dead and green fuels at a given time. It is expressed as a percentage of the oven dry weight of the fuel (Teie, 2005). The moisture content of the fuel varies considerably with changes in daily and seasonal weather conditions (for example, through precipitation or lack thereof). Moisture content also depends on the initial moisture content of harvesting slash and the degree of compaction or packing of the fuel. Moisture content of the soil and aspect also influence the moisture contents of fuels. Moisture is lost from fuels through the process of dehydration (Luke and McArthur, 1978). All of these factors vary both on site and between sites. The moisture content of fuel influences the potential for ignition, intensity and the effect of fire duration on the depth of the burn into the litter layer (Teie, 2005).

Dead vegetation shrinks, but it does not lose its basic cell structure and hygroscopic ability. It is therefore able to take in water from the atmosphere through the process of absorption. Fine fuels reach the limit of their water-holding capacity within a few minutes when exposed to high relative humidity, while fuels with a larger diameter seldom reach a condition of complete saturation. Most dead fuels reach their fibre-saturation point when the moisture content is 30-35% of oven dry weight (Luke and McArthur, 1978). Atmospheric moisture is the dominant cause of variations in the moisture content of dead fuels (Teie, 2005).

A higher fuel moisture content of the litter layer will reduce the loss of moisture from mineral. If the moisture of the litter layer declines it will absorb moisture from soil containing high moisture (Teie, 2005).

Size and shape: - Teie (2005) and Luke and McArthur (1978) classified different fuel classes according to their diameter sizes (1-hour fuel: < 6mm; 10-hour fuel: 7-25mm; 100-hour fuel: 26-75mm; 1000-hour fuel: > 75mm). Fine fuels (1-hour fuels) have a high surface-to-volume ratio, which causes them to lose and gain moisture much more rapidly than the bigger fuel classes.
number next to the hour fuel class indicates the time that it will take a fuel to either gain or lose moisture to reach a state of equilibrium with the moisture content of the surrounding atmosphere. The fuel sizes that have the biggest influence on fire behaviour are dead fuels smaller than 75mm and live fuels smaller than 6mm. Because of their larger surface-to-volume ratio, preheating of these fuels is faster and they will therefore ignite more easily than thicker fuels. At the same time, these fuels are light enough to be carried off by strong wind and the convection currents created by the fire. If these fuels are still burning or smouldering while they are being transported, they can cause new fires (spot fires) ahead of the main fire (Luke and McArthur, 1978; de Ronde, 2003; Trollope, et al., 2004; Teie, 2005).

Fuel arrangement: - According to Kent and Coker (2002), fuels are arranged as ground fuels, surface fuels and aerial fuels. Fuels are also arranged horizontally and vertically. Fuels which are densely amassed vertically create a fuel ladder that will allow a surface fire to spread into aerial fuels. Fuels arranged densely in a horizontal manner will make it easy for heat transfer between fuel particles and will increase the spread rate of a fire (Wells, et al., 1979; Teie, 2005). Fuels that are elevated will allow more oxygen to flow between particles and facilitate faster ignition and combustion of fuels. For example veldfires burning in elevated fuels generally produce more heat and have a higher rate of spread (Rowe, 1983).

Fuel load: - Fuel loading/fuel load is the oven-dry weight of all the existing fuels per unit area and is expressed in kilograms per hectare or tons per hectare (Kent and Coker, 2002; Teie, 2005; Geospatial Training and Analysis Cooperative, 2008). Without available combustible fuel, a fire cannot burn. Different types of vegetation and fuel types will generate different fuel loads. The total weight of available fuels in some areas can be high, but if the bulk of the fuel falls into a
large fuel class (for example, large-diameter tree trunks), it may not be able to carry the fire (Teie, 2005).

**Compactness:** Compactness of fuel indicates how close fuel particles (material) are to each other. A compacted fuel load will have small spaces (hence less oxygen) between the fuel particles. This decreases the interaction between oxygen and fuel surface. Compacted fuels are less likely to ignite, thus decreasing the spread rate and intensity of the fire (Rowe, 1983; Trollope, *et al.*, 2004; Teie, 2005). High fuel loads that are compacted will therefore pose a smaller fire hazard than elevated fuels.

### 2.3.2 Weather

Weather is the primary driving force behind changes in fire behaviour. It is important that fire managers are familiar with the underlying dynamics of weather to understand its potential impact on their choice of post-harvesting slash management. As weather cannot be controlled and changes over short, medium and long periods (Wells, *et al.*, 1979; Teie, 2005), the appropriate post-harvesting slash management should be selected to compensate for weather conditions conducive to the start and spread of fires. The five weather elements influencing fire behaviour significantly are briefly discussed below.

**Wind:** Wind is air in motion, varies in speed and direction and is mainly caused by temperature differences on the earth surface. Wind bends flames closer to fuels, accelerating preheating of fuels, changing the direction of fire spread and supplying oxygen to the fire, thus possibly causing fires to ‘spot’ or jump. Compacted fuels are less exposed to wind than elevated fuels and fire behaviour will therefore be less drastic in compacted fuels (Goldammer, 1982; Johnson, and Miyanishi, 2001; Teie, 2005).
Temperature: Diurnal temperature has a direct influence on the temperature of fuels, as well as on relative humidity (RH) in the atmosphere. Latitude, slope, aspect, elevation, the shape of the terrain and the time of day also influence the earth’s temperature. The highest day temperature usually occurs between 14h00 and 16h00 and the lowest temperature just before sunrise (Barrett, 1982; Chandler, et al., 1983; Dyer, et al., 2001; USDA, 2003). Higher surface temperatures cause an increase in fuel temperature, prevalence of winds, atmospheric stability/instability and occurrence of thunderstorm activity (accompanied by strong gusty winds). All four of these effects escalate the chances of both the ignition and the spread of forest fires (Luke and McArthur, 1978; de Ronde, 2003; Trollope, de Ronde and Geldenhuys, 2004; Teie, 2005).

Relative humidity (RH): - Wells, et al. (1979) defined RH as “The ratio of the actual amount of water vapour present in a volume of air at a given temperature, to the maximum amount of moisture that the air could hold at that temperature, expressed as a percentage.” Higher temperatures lower the RH in the atmosphere and cause dead fuel to lose moisture faster. According to Teie (2005), an 11 °C change in temperature could raise or lower the RH by half. Relative humidity is a product of dew point and day temperature, and can be predicted if these two variables are known (Chandler, et al., 1983). In the previous section, mention is made of the ability of different fuel classes to absorb moisture from the atmosphere. Regardless of whether or not moisture has been gained or lost by fuels, thicker fuel classes take longer to reach a state of equilibrium with the air-moisture content. Moist fuels will ignite more slowly and burn with less heat, thus fire will spread more slowly when burning these fuels (Luke and McArthur, 1978; Teie, 2005).

Atmospheric stability: - The United States Department of Agriculture (USDA) (2003) defines atmospheric stability as: “The degree to which the atmosphere resists turbulence and vertical
motion.” Hot surface temperatures, hot surface areas and large fires cause warm, rising, convection columns. These columns cause the atmosphere to become unstable with strong up and down draft winds and thus increase fire behaviour. Unstable atmospheric conditions cause gusty winds that transport fire brands (smouldering material) which can cause spot fires, thus leading to more intense fire behaviour (Luke and McArthur, 1978; Trollope, de Ronde and Geldenhuys, 2004; Teie, 2005). According to Teie, (2005) wind is the weather element influencing fire behaviour the most and controlled burning should not be conducted without a thorough knowledge of the stability status of the atmosphere at the time.

Precipitation: Kennard (2008) define precipitation as any form of water that falls to the earth's surface. The amount of such water falling in a specific area within a specific period can be quantified. Luke and McArthur (1978) indicate that dead fuels will take on water from precipitation through the process of absorption, thus making fuel less flammable. After rains, the soil and dead organic matter on the soil absorb and retain water. The proximity of fuels to the soil and their arrangement will determine how fast moisture can be absorbed and retained by such fuels. Altering the arrangement and size of fuels will have a significant influence on absorption rate. Fine fuels that are closer to the soil will absorb moisture faster than thicker or elevated fuels (Chandler, et al., 1983; Kennard, 2008).

Soil moisture: - The amount of moisture found in soil directly influences fuel moisture. Dead fuel in contact with soil will absorb moisture directly from the soil (Teie, 2005). Fuel with high moisture content will not burn with the same intensity as dry fuel, causes less damage to the environment and is easier to control (Chandler, et al., 1983). Rolando and Little (2006) found that one year after clearfelling, the average monthly moisture content in the soil of the A-horizon of burnt areas in conifer stands was significantly lower than
that of stands where broadcast and chopper-rolled treatments had been used. There was little difference in the soil moisture of the latter two treatments. It may therefore be concluded that soil covered with organic matter retains moisture for longer periods than burnt areas. Iles and Dosmann (1999), found that one season after clearfelling, mineral soil covered by organic mulches had a higher potential of hydrogen [pH] (thus accelerated mineralization), were 6°C cooler and contained 13% more moisture than areas denuded of organic slash.

Soil fauna has been shown to burrow within the soil profile during dry spells, whereas during the wetter periods, the invertebrate fauna spends the majority of its time within the leave litter (Sharon, Degani and Warburg, 2001). After burning, the species density of soil fauna is much lower than that of unburned sites (Decaëns, et al., 2001). The recovery of soil and litter invertebrate fauna densities to levels prior to harvesting and litter removal aided by fire has been shown to take over 27 years (Bird and Chatarpaul, 1986). It can therefore be concluded that soil moisture influences fire behaviour and, hence, the densities of the soil fauna responsible for organic mineralization and nutrient cycling.

2.3.3 Topography

Topography does not feature as a variable in this study and will therefore not be discussed in detail. While topography is the only environmental and site element that stays constant, topographical features, however, influence fire behaviour. Fire behaviour changes contingent on these features or on the relationship of these features to one another. The same fuel located in different areas will burn differently, depending on the amount and angle of solar radiation reaching it (Chandler, et al., 1983; Teie, 2005). Hence, topography has a direct affect on how much solar radiation is absorbed by fuels on the surface of the earth because it determines the angle at which this radiation strikes that surface. According to Teie (2005), topography influences local weather conditions and is a contributing factor determining vegetation type and fuel
characteristics. Topographical features such as elevation, position on slope, aspect, structure of terrain and slope steepness influence fire behaviour directly and should be considered before selecting the most appropriate fuel management method (Johnson and Miyanishi, 2001; USDA, 2003).

2.4 POST-HARVESTING SLASH MANAGEMENT

Post-harvesting slash is generally managed because it hinders silviculture operations in commercial plantations and creates a high fuel load which poses a fire hazard (Christensen and Abbott, 1989). After 50 years of post-harvest slash treatment in the Siskiyou National Forest (Oregon, USA), there was a reduction of almost 50% in burned areas compared with areas where slash was not treated (Radlof, Schopfer and Yancik, 1982). Management of fuel, aims to keep fine fuel loads (fuels <6mm) below 10 tonnes/ha because fine fuels change in moisture content and flammability fastest (Cremer, 2004). Different methods of fuel management modify fire behaviour and tree survival in tree stands (Stephens and Moghaddas, 2005). Different post-harvesting slash-management methods address different aims of fire management, including hazard reduction, biodiversity and soil conservation, ease of silviculture and crop protection (Goldammer, 1982). This, however, presents forest managers with a dilemma, as different post-harvesting slash management methods only address some of these aims (Cremer, 2004). It has been suggested by da Costa, Brown and Venske (2006) that site-specific fuel-load management should remain the most important criterion when selecting the method that will support the most desirable outcome on that site. Factors influencing site-specific Post harvesting slash management include slope, aspect, altitude, weed growth, rainfall, proximity of high fire risks, soil characteristics (pH, texture, absolute levels of phosphorus and nitrogen [P&N]), depth and mass of organic material and accessibility (Louw and Pool, 2008). Sustainability of growing sites requires scientific management of post-harvesting residue to retain nutrients that are locked up in organic
matter (Hall, 1986; Glutz, et al., 2006). In South Africa post harvesting slash is generally burned, mulched, chopper-rolled, windrowed, broadcasted and in some cases removed from the site as biofuels.

*Controlled burning:* Controlled burning of post-harvesting slash remains a cost-effective fire-hazard reduction method, controls weeds under certain conditions and facilitates easy silviculture in commercial plantations (de Ronde, 1992, 1996a; Alegre and Cassel, 1996). While it is assumed that veldfires have a greater affect on forest soils than controlled burning, it is still unknown what effects result from the long-term impact of low-intensity fires on erosion hazard, nutrient status and physical properties of forest soils (Hall, 1986). Controlled burning of post-harvesting slash is strongly opposed by some scientists who suggest that the negative long-term effects thereof outweigh the short-term advantages (Wells, et al., 1979; Keeley, 1981; Rab, 1996; Williams, Gill and Moore, 1998; du Toit, et al., 2000; du Toit, 2003). It is interesting to note that in the central hardwood forests of the USA (Missouri Ozarks), a comparison among areas with no treatment of forest slash (I), prescribed burning of slash (II) and prescribed burning using other fuel-reduction methods (III) revealed a simulated wildfire return interval of 325 years in scenario I, 496 years in scenario II and 637 years in scenario III (Shang, He, Crow and Shifley, 2004).

The case for conservation of organic matter has been sufficiently made to lead to widespread cessation of post-harvesting slash burning between rotations of *Pinus radiata* in Australia (Flinn, et al., 1979). Conservation of organic matter is also widely practised in central Europe, where removal of slash from forest sites has been recognized as having had a major degrading influence on fertility over the past centuries (Cremer, 2004). If prescribed burning is used, a cool, patchy burn that consumes about 50% of the organic material is recommended. Cool burns do less harm to the growing site (Auld and O’Connell, 1991).
**Mulching:** The Longman Dictionary (2002) refers to organic mulch as: “A covering of material made from decaying plants, which is spread over soil to protect plant roots and improve soil.”

In the South African Forestry industry post-harvesting slash, areas overgrown with weeds as well as inter-row areas in compartments are mulched with industrial mulchers. The main aim of these operations is generally fuel reduction with the aim of fire protection in mind. Other benefits identified as a result of mulching includes enriching of the soil by encouraging mycorhizal relationship between certain fungi and plant roots as well as promoting microbial activity by worms and providing insects with food. Despite greater cost associated with residue mulching, it bring due to its beneficial effects on the soil, organic carbon and a higher site nutrient status to growing sites (McLean and Kobayashi, 2009).

Soil moisture has generally been found to be higher under organic mulches and the nature of this practice accelerates the breakdown organic residue, thus ensuring retention of organic material for nutrient recycling, especially Nitrogen and Phosphorous (Norris, 1994; Good, 1996). Thus, mulching results in accelerated decomposition of organic material, better plant health and improved access for easier silviculture operations and weed-growth suppression (McLean and Kobayashi, 2009; Norris, 1994; Little, 2000; Good, 1996). McLean and Kobayashi (2009) suggest that increased heat from accelerated decomposition of mulched organic material might have possible positive effects on the root development of seedlings. Good (1996), supports this statement, mentioning that mulching provides protection from soil erosion and stabilizes temperature in exposed soils.

An important advantage of the mulching of post-harvesting slash is the reduction of vertical fuel distribution through the compaction of fuels, thus making combustion thereof difficult (Glutz, 2006). Mulching further creates the opportunity for mechanization in silvicultural operations and
has to be regarded as a low-risk activity, with minimum impact on the environment (da Costa 2006, 2008; McMaster, personal communication, 2009).

Disadvantages of mulching include high direct cost and the possibility of soil compaction caused by the heavy machinery used (McMaster, personal communication, 2009). Man-made mulch can affect a growing site negatively. Where wooden chips reach a height of over 10cm, the materials underneath are inclined to rot rather than mineralize, preventing aeration and the overall addition of essential elements to the soil. This result in the fauna and flora within the area being negatively affected (Viette, 2009).

Accelerated decomposition of poor quality organic mulch (material with a very high Carbon: Nitrogen ratio) may result in a temporary nitrogen deficiency (Louw, personal communication, 2008). It is generally accepted that mulched post-harvesting slash is more difficult to ignite compared with material remaining after other treatments. However, Steward, Sydnor and Bishop (2003) found that shredded pine bark and pine-bark nuggets ignited 12.5% of the times ignition was attempted, using a burning cigarette butt.

Mulching of post-harvesting slash and other vegetation is a common forestry activity in the United States of America (USA) and is believed to be the most cost-effective and environmentally friendly way to manage high fuel loads (Arola and Miyata, 1980). Robichaud, Beyers and Neary (2000) found that 66% of land users in the USA preferred mulching as a means of rehabilitation of forest sites after big fires. In a chemical, allelopathic and decomposition study conducted on different mulches (including Eucalyptus and Pinus species), it was found that Eucalyptus mulch had a decomposition rate of 21% after a year, while only between 3% and 7% of the other mulches decayed. In the USA, Eucalyptus plantations have been created specifically to produce mulch for landscapers, suggesting that Eucalyptus mulch benefits the soil (Duryea, English and Hermansen, 1999).
Choppe-rolling: - Chopper-rollers vary in size and weight, but are designed to compact and break up post-harvesting slash and other organic material into smaller pieces. The result of chopper-rolling should lead to a reduction in the vertical distribution of fuels, which will make stands more accessible for future silvicultural activities and reduce their flammability (de Ronde, 1996b). Chopper-rolling is not commonly used in South Africa because it is expensive and the expected results are often disappointing, especially in hardwoods (da Costa, 2006). The chopper-rollers used in the South African context weigh between 2.5 and 5.0 tons and are equipped with a variable number of vertical blades placed at 0.3 to 0.5 metre intervals on the roller circumference (Forestry Solutions, 2011).

In Queensland, Australia, chopper-rolling was introduced as a means of reducing fire risk, reducing the environmental impact of traditional slash-management methods and increasing accessibility in stands. It was found that chopper-rolling also saved on expenditure in post-harvesting slash management (Post-harvest care, 1999). Chopper-rolling can be applied both in *Eucalyptus* and *Pinus* compartments. Though stumps may impede the operation, the residue is often split more effectively as the moisture content in the slash decreases (Norris, 1994). Chopper-rolling in *Eucalyptus* compartments, however, was found to be less effective than in softwood compartments (Norris, 1994; da Costa, 2006).

Plant-pit-preparation trials reveal that there is no significant difference in the average size of pits where post-harvest slash has been managed by broadcasting, burning and chopper-rolling. There is, however, a significant variability in pit size and depth in the broadcast treatments because of the close proximity of big slash pieces to the pit area (Rolando and Little, 2006; Steenkamp, 2008).

Broadcasting: - A large proportion of the nutrients of a plantation are concentrated in the leaves, twigs, bark, cambium and roots of the tree. Broadcasting of slash retains organic matter content
on the site and facilitates faster decomposition. At the same time, broadcasting provides a good alternative with regard to reducing fire hazard without burning when compared with situations where no slash management has been done (Kalobokidis and Omni, 1998).

Broadcasting of slash is a labour-intensive operation, where concentrations of post-harvesting slash are distributed evenly across the whole compartment, making access to the compartment easier. Using this method, organic material is distributed evenly within compartments and the vertical distribution of fuels is lowered. Fire behaviour in broadcasted slash is less intense and veldfires are easier to control. For this reason, controlled burning of post-harvesting slash is usually preceded by broadcasting of slash (Burger and Pritchett, 1984).

Windrowing: - Although it is labour intensive to stack post-harvesting slash in rows where the row intervals are pre-determined, this is a common site-preparation and slash-management method in forestry (Burger and Pritchett, 1984). In South Africa post-harvesting slash is often windrowed. This entails movement of large branches into windrows every 5-8 tree rows. The inter-windrow area consists of forest floor, bark and small branches (Rietz and Smith, 2009). The aim of windrowing is to manage post-harvesting residue, improving accessibility to the compartment, retrieving organic nutrients, creating strips with low fuel loads and making re-establishment of the compartment easier (Kalabokidis and Omi, 1998; da Costa, 2006). Disadvantages of windrowing include high concentration of elevated fuels, which can burn very intensely and hamper movement across lines. Breakdown of windrow lines also takes much longer when compared with broadcasting or chopper-rolling (Constandine, 1984; de Ronde, 1994).

A comparison between broadcasting and windrowing Eucalyptus globulus post-harvesting slash revealed that 81%, 67%, 10% and 91% of 1-hour, 10-hour and 100-hour fuels, as well as leaves and litter in the broadcast treatment respectively, were consumed after burning the slash (Fernández, et al., 2004). While in the windrow treatment, the consumption was 91%, 93%, 79%
and 99%. Mean maximum temperatures during burning were measured in degrees centigrade in the litter surface, mineral soil surface and 2.5 and 15 cm below mineral-soil surface. These respective temperatures were 478°C, 204°C, 47°C, 33°C and 27°C in the broadcast treatment and 720°C, 387°C, 68°C, 48°C, and 32°C in the windrow treatment. Overall less residue was consumed by fire in the broadcast post harvesting slash treatment compared to the windrow treatment at a lower average fire temperature. It was found that one year after burning, a soil loss of 2704.2 g/m² occurred in the broadcast treatment and 4116.3 g/m² in the windrow area, making the broadcast post-harvesting slash treatment a more environmental friendly practice (Fernández, Loureiro and Botelho, 2004).

From the sighted literature it is clear that fire behaviour is influenced by various environmental factors. Different post harvesting slash management methods seem to alter fuel characteristics with reported differences on fire behaviour within these treatments (Teie, 2005; Luke and McArthur, 1978; Chandler, et al., 1983). Various advantages and disadvantages resulted from different treatments and cost-benefit seems to be an important consideration influencing choice of treatment method (da Costa 2006, 2008; Glutz, 2006; McMaster, personal communication, 2009). It is generally accepted that fire, when burning at a high intensity, causes more damage to growing sites (Auld and O’Connell, 1991; Wells, et al., 1979; Keeley, 1981; Rab, 1996; Williams, Gill and Moore, 1998; du Toit, et al., 2000; du Toit, 2003). This study will therefore aim to bridge the gap in knowledge about fire behaviour in different post harvesting slash treatments. Manages should therefore be able to make a choice of the most suitable post-harvesting slash management treatment to use, based on fire behaviour measured within different popular treatments.
CHAPTER 3
MATERIAL AND METHODS

3.1 LOCATION OF STUDY AREA
The study area is located within the southern region of the Mpumalanga Province which is a summer rainfall area. For the purpose of this study, a *Eucalyptus macarthurii* compartment (latitude 26° 49’ 31” S and longitude 30° 29’ 30” E) and a *Pinus patula* compartment (latitude 26° 22’ 14” S and longitude 30° 38’ 18” E) were selected. The *E. macarthurii* compartment is situated 30km north-west of Piet Retief in the Iswepi region on Mondi’s Driepan Plantation, at an altitude of 1269m (Figure 3.1). The *P. patula* compartment is situated in the Lothair region of Sappi and is part of the Woodstock Plantation, at an altitude of 1678m (Figure 3.1). Both compartments met desirable criteria in terms of level terrain for easy treatment, ease of protection against fire, easy access, moderate site quality, size (being big enough to lay out a trial) and a similar harvesting time. To meet logistical constraints, both sites selected for this trial had to be in close proximity and had to be representative of the two most important genera in the South African forestry industry.

3.2 SPECIES SELECTED FOR THE TRIAL
The most important commercial forestry species found in South Africa are from the *Pinus* (51% − 650,200 ha) and *Eucalyptus* genera (40.4% − 515,057 ha) (Forestry South Africa, 2011). For this reason, *P. patula* and *E. macarthurii* were selected for this trial. *P. patula* is the most important *Pinus* species in South Africa and *E. macarthurii* is both a popular *Eucalyptus* species and a good representative of all the qualities of the other *Eucalyptus* grown in South Africa (da Costa, 2006). Both these species are fire-prone. Table 3.1 supply information of compartments selected for this trial.
Figure 3.1: *E. macarthurii* compartment in the Iswepi region on Driepan Estate and *P. patula* compartment in the Lothair region on Woodstock Plantation. Insert represents forestry areas in South Africa, Lesotho and Swaziland (Little, 2000).
Table 3.1: Compartment information.

<table>
<thead>
<tr>
<th></th>
<th>Iswepi</th>
<th>Lothair</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Species</strong></td>
<td><em>E. macarthurii</em></td>
<td><em>P. patula</em></td>
</tr>
<tr>
<td><strong>Mean annual increment</strong></td>
<td>16.8 t/ha/y</td>
<td>14.7 t/ha/y</td>
</tr>
<tr>
<td><strong>Clear-fell date</strong></td>
<td>04/2009</td>
<td>05/2009</td>
</tr>
<tr>
<td><strong>Tons harvested</strong></td>
<td>120.6 t/ha</td>
<td>267.5 t/ha</td>
</tr>
<tr>
<td><strong>Stems per hectare</strong></td>
<td>1667</td>
<td>1667</td>
</tr>
<tr>
<td><strong>Rotation length</strong></td>
<td>12 years</td>
<td>18 years</td>
</tr>
<tr>
<td><strong>Site quality</strong></td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Slope</strong></td>
<td>0-3%</td>
<td>0-5%</td>
</tr>
<tr>
<td><strong>Silviculture treatment during rotation</strong></td>
<td>Windrows before re-establishment. Two ring-cleans within the first two years and three chemical-weeding operations until canopy closure. Through the rotation: ad hoc chemical weeding and three slashing operations to remove unwanted coppice re-growth.</td>
<td>Burning before re-establishment, ripping plant lines, pre-plant weed control, planting without fertilizer, tending for three years and pruning to two metres at age five.</td>
</tr>
<tr>
<td><strong>MAT (avg.)</strong></td>
<td>25 °C (Jan) 16 °C (Jul)</td>
<td>25 °C (Jan) 16 °C (Jul)</td>
</tr>
<tr>
<td><strong>MAP (avg.)</strong></td>
<td>907 mm</td>
<td>827 mm</td>
</tr>
<tr>
<td><strong>Harvesting method</strong></td>
<td>Motor manual, stripping of bark and cut to length infield</td>
<td>Motor manual, cut to length infield</td>
</tr>
<tr>
<td><strong>Date of post harvesting slash management</strong></td>
<td>All treatments 05/2009</td>
<td>Windrow, inter-windrow and broadcast: 05/2009, Chopper-roll and mulch: 10/2009</td>
</tr>
<tr>
<td><strong>Date of fire</strong></td>
<td>02/02/2010</td>
<td>03/02/2010</td>
</tr>
</tbody>
</table>

A period of nine months passed between the harvesting of the *E. macarthurii* compartment and its fire treatment. Trees were felled manually in strips and debarked and cross cut in the compartment before extraction by tractor and trailer to a nearby depot. Post-harvesting slash
management of all the plots in the *E. macarthurii* compartment took place within a month of clear felling. Fuel loads were measured five months after harvesting in the *E. macarthurii* compartment. A period of eight months passed between the harvesting of the *P. patula* compartment and its fire treatment. Trees were felled manually in strips and cross cut in the compartment before extraction by tractor and trailer to a nearby depot. The broadcasting and windrowing treatments were done within a month after clearfelling and chopper-rolling and mulching operations took place four months after clearfelling. Fuel loads were measured four months after harvesting in the *P. patula* compartment. The intention was to burn shortly after measuring the fuel within the compartments but due to an abnormal raining season that lasted longer than usual, burning had to be postponed until early February 2010.

### 3.3 BIOPHYSICAL ENVIRONMENT

The topography of the area is flat with gently rolling terrain and the gradient generally does not exceed 20-35%. The altitude of the region varies between 1200m and 1700m above sea level. This area is situated in a warm-temperate region, with hot, wet summers and dry, cold winters (Harrison, 1983; SA Weather Service, 2011). As the area is known for heavy frost in winter, only cold-tolerant *Eucalyptus* species are grown in the region. The average maximum temperatures in January and July are approximately 25°C and 16°C respectively. The minimum temperature during July varies from below 0°C to 4°C. Approximately 85% of the rainfall occurs between October and March and the annual rainfall varies between 750mm and 900mm. Most of the rain is in the form of thunder showers and the region has the highest number of lightning strikes in South Africa at 12-14 flashes per km² per year⁻¹ (SA Weather Service, 2011). The area is known for the periodic droughts it experiences, which lead to extended fire seasons. The high fire-occurrence season is during August and September, and strong north-west Bergwinds can be expected during this period (SA Weather
Service, 2011). Berg-wind conditions are accompanied by a low RH, which increases fire danger.

Figures 3.2-3.5 illustrate the variation in monthly and average rainfall figures for the study area.

Soils within the study area show relatively little variation in general morphology (Council for Geoscience, 1997).

**Figure 3.2:** Monthly rainfall for Woodstock Plantation, Lothair, compared with the average monthly rainfall over five and eighteen years (du Toit, personal communication, 2009).

**Figure 3.3:** Variation in annual rainfall for Woodstock Plantation, Lothair (du Toit, personal communication, 2009).
The dominant lithology of the Iswepi area includes potassic granite and gneiss. The main soil types in the area include red massive or weakly structured soils and red-yellow and greyish soils with low to medium base status. According to Smith (personal communication, 2009), these soils represent a significant portion of the soils of this forestry region. In the Lothair area, the underlying geology is mainly granite (79%) with dolerite (16%) and minor sandstone formations (5%) (Council for Geoscience, 1997). The dominant soil group is deeper than 600mm, with red and yellow-brown apedal subsoil horizons.
The natural vegetation of the area can be divided into two types: KaNgwane Montane grassland that is found in the Iswepi area and Eastern Highveld grassland found in the Lothair area (South African National Biodiversity Institute, 2005). A natural fire regime, of annual to bi-annual frequency, with fire occurrence in early to late spring, is customary with this vegetation type.

### 3.4 PLOT DESIGN, LAYOUT AND TREATMENTS

A total of five treatments were implemented, i.e. broadcasting, mulching, windrowing (rows and inter-rows) and chopper-rolling. All treatments were replicated three times. The trials were 6.27 ha in size and consisted of 15 plots (Figures 3.6 and 3.7). Each trial was laid out in a rectangle, 190m x 330m. Individual treatment plots were 50m x 50m and designed as indicated in Figure 3.8. A buffer row of 10 was included in each treatment plot, resulting in an inner measurement plot of 30m x 30m. Four sampling points were established in the middle of each 30m x 30m plot, where fire behaviour was measured (Figure 3.8).

Plot treatments were allocated randomly in both trials, but because of the presence of rocks in the Lothair trial area, the three plots with the fewest rocks were selected for the mulching treatment as rocks can cause excessive damage to the blades of the mulcher. Mulched strips, 20m in width, were created between all plots for ease of access and to facilitate safe burning of individual plots. Smaller 30m x 30m plots, where fire behaviour measurements were taken, were established within the bigger plots. The fire was set on the edge of the bigger plots and allowed to gain sufficient momentum to reach fire behaviour that was comparable to that of a natural fire by the time it reached the inner measurement.

Note that Plots 12 and 14 from the Iswepi trial had to be moved because of a road that passed through the compartment.
Figure 3.6: Experiment layout in *E. macarthurii* compartment.

Figure 3.7: Experiment layout in *P. patula* compartment.
Trial areas were investigated for homogeneity of environmental and site conditions. The trials were laid out so that the narrow side faced the dominant, north-west [NW] wind direction (Figures 3.6 and 3.7). This was done to ensure a safe burn as burning was started on the north-western side of the trial areas, leaving a narrow boundary to guard against fires escaping.

**Figure 3.8:** Plot design – a smaller 30m x 30m plot, containing four sampling points, within a bigger 50m x 50m plot.

### 3.4.1 Broadcast, windrow and inter-windrow treatments

Broadcast treatments were implemented manually. The forest floor was left intact and all post-harvesting slash (consisting of large branches, tops small branches and in the *Eucalyptus* trial bark) was spread evenly across the treatment plots.

Windrows treatments were implemented manually. The forest floor was left intact and all large harvesting slash (large branches and tops) removed to windrows placed 5m apart. in both trials were set out at five-metre intervals, with a row width of between 1.2 and 2.7m (Figure 3.9).

The area between the windrows was used as the inter-windrow treatment between windrows. Fine fuels (1h and 10h) fuels were often left behind in the inter-row area, adding to its fuel load, but thicker material (> 10h fuels) were removed.
3.4.2 Mulch

An AWHI UZN700A mulcher, powered by a 240 horsepower [HP] direct-drive Deutz/Cummins engine, was used for mulching in the Iswepi trial. The mulcher was drawn by a V8 Kumito rubber-wheeled Caterpillar horse. The blade configuration of the mulcher head works with a hammer action and has a working width of two metres. Figure 3.10 shows the result of the mulching action.

An AWHI FM600 mulcher head, mounted in front of a D7 bulldozer (Figure 3.11), was used during the Lothair mulching trial. The power pack powering the mulcher head produced between 100 and 150 HP and was mounted on the back of the bulldozer. The blade configuration of the mulcher head had a hammer action and a working width of two metres. The results produced by the working action of the two mulchers were the same.
3.4.3 Chopper-roll

Chopper-rolling was done with a twin-drum chopper-roller that weighed 2.5 tons. The blades of the chopper-roller were 23cm long and mounted 20cm apart on the drum. Individual drums were 1.3m in length (Figure 3.12). The chopper-rolling used the same horses as were used for the mulching.
3.5 MEASURED VARIABLES

Before the burning operations were attempted, fuel load, fuel-bed depth and fuel moisture were measured as these three variables have an influence on fire behaviour. Fuel loads were measured four months after harvesting in the *P. patula* compartment (09/2009). During the burning treatment, the RoS, fire temperature, flame length and the fire danger index (FDI) were recorded.

3.5.1 Weather conditions and fire danger index

The fire danger index (FDI) indicates the potential fire behaviour according to weather conditions in an area and FDI readings are reflected on a scale of 1-100 Luke and McArthur (1978). According to Chandler, *et. al.* (1983), weather conditions experienced at any specific moment directly influence fire behaviour more than any other factor. Burning operations therefore had to take place under similar weather conditions to obtain comparable fire-behaviour results, according to changes in the weather variables: wind speed, temperature, relative humidity and precipitation. During the burning of the plots, the FDI was constantly monitored to ensure that prevailing weather conditions remained similar. A deviation of 10 FDI points from the average was allowed as an acceptable variation under the burning conditions.

The FDI system used was the one customized from Luke and McArthur (1978), which is currently used in South Africa. The FDI is calculated by considering the day temperature, relative humidity and wind speed, and adjusting these in accordance with a rainfall-correction factor. Weather variables were measured with a Kestrel 3000 hand-held weather station at each plot just before fire was applied.

3.5.2 Fuel load

Fuel load and forest-floor mass were determined using the line-intersect method developed by Brown (1974) and applied by Ross (2004) in *P. patula* stands for sawtimber and pulpwood stands
in the summer-rainfall regions of South Africa. **Equation 3.1** from the model to predict forest-floor mass is as follows:

\[ LM = 0.70(LD) - 8.71 \]

where:

- \( LM \) = forest-floor mass (t ha\(^{-1}\))
- \( LD \) = forest-floor depth (mm)

**Equation 3.2** from the model as applied by Ross (2004) calculates the mass (t ha\(^{-1}\)) of the 1-, 10-, and 100-hour fuel classes:

\[ M(1-, 10-, 100-hr) = 1.23 \times n \times d^2 \times s \times a \times c \times l \]

where:

- \( M(1-, 10-, 100-hr) \) = the mass (t ha\(^{-1}\)) of the 1-, 10-, and 100-hr fuels (fuels corrected to dry weight)
- \( n \) = the number of intersections in each fuel class
- \( d^2 \) = the squared average quadratic mean diameter of each fuel class
- \( s \) = the density of each fuel class
- \( a \) = the non-horizontal correction factor of each fuel class
- \( c \) = the slope correction factor of each fuel class
- \( l \) = the total line length of each fuel class

**Equation 3.3** from the model as applied by Ross (2004) calculates the mass (t ha\(^{-1}\)) of the 1000-hour fuel class:

\[ M(1000-hr) = 1.23 \times \sum d^2 \times s \times a \times c \times l \]

where:

- \( M(1000-hr) \) = the mass (t ha\(^{-1}\)) of the 1000-hr fuels (fuels corrected to dry weight)

The squared average quadratic mean diameters (\( d^2 \)) and average density values (\( s \)) for each size class for *P. patula* (Brown, 1974) and *E. macarthuri* (Banks, 1954), as well as the non-horizontal correction factors (\( a \)) used in these equations, are summarized in Table 3.2 below.
Table 3.2: Squared average quadratic mean diameters ($d^2$), average density values ($s$) and non-horizontal correction factors ($a$) for equations 2 and 3 (Banks, 1954; Brown, 1974).

<table>
<thead>
<tr>
<th>Size class (cm)</th>
<th>Average $d^2$ (cm)</th>
<th>$a$</th>
<th>$s$ (g/cm$^3$)</th>
<th>$s$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$P.$ patula</td>
<td>$E.$ macarthurii</td>
</tr>
<tr>
<td>0 – 0.6 (1 hour)</td>
<td>0.58</td>
<td>1.40</td>
<td>0.58</td>
<td>0.88</td>
</tr>
<tr>
<td>0.6 – 2.5 (10 hour)</td>
<td>3.20</td>
<td>1.13</td>
<td>0.52</td>
<td>0.88</td>
</tr>
<tr>
<td>2.5 – 7.5 (100 hour)</td>
<td>15.00</td>
<td>1.10</td>
<td>0.55</td>
<td>0.88</td>
</tr>
<tr>
<td>&gt; 7.5 (1000 hour)</td>
<td>178.80</td>
<td>1.00</td>
<td>0.50</td>
<td>0.88</td>
</tr>
</tbody>
</table>

The line-intersect method was applied for each plot in both trials. The length of each intersect was standardized by extending the line diagonally across each 30m x 30m plot (Figure 1.13).

Figure 3.13: Applying the line-intersect method.

Figure 3.14: Taking 1m$^2$ fuel samples to oven-dry.

Apart from the windrow-treatment plots, the line-intersections in all the plots were 42.5m long. In the windrow and inter-windrow plots, the intersect line was also extended as described above, but either the row or inter-row area was measured according to the treatment of the plot. These lines were thus shorter than 42.5m. The diameter of post-harvesting slash that were crossed by the extended lines were measured with callipers and recorded in different fuel classes for each plot. The thickness of the litter layer was measured every four metres, recorded and later averaged out.

In the mulched plots, the results of the line-intersect method were not valid as the mulching activity mixed the forest-floor material with the mulched post-harvesting slash. Although the line-intersect method was applied as well, four random samples of organic material, each a square
metre, were collected in every mulched plot and oven dried to determine the fuel mass. Figure 3.14 illustrates an area where organic material was collected.

The samples were bagged numbered in accordance to the trial and plot number they were gathered from and taken to the Institute of Commercial Forest Research (ICFR) in Pietermaritzburg. Here, they were floated to separate soil from the other components in the sample, and then oven dried to determine fuel load.

The oven-dry method as described by DeBano, Dunn and Conrad (1977) was used to determine fuel load. In accordance with the model described by DeBano, Dunn and Conrad (1977), samples were dried in an oven for at least three hours at a temperature of 70°C or until the sample did not lose more weight after further drying. Four samples were taken from each mulched plot and the average weight determined. By multiplying the average fuel load measured in the one-metre-square sample areas by 10 000, the fuel load in these plots was calculated in tonnes/ha. In this study, 24 samples from mulched plots were used to determine the dry mass of organic material and, thus, the fuel load in these plots. Fuel load results calculated in the trials is expressed in kg/m², as tonnes/ha would not have been a true representation of fuel load when considering the windrow treatment.

3.5.3 Fuel classification

Fuel was classified by applying the line-intersect method, where all 1-, 10-, 100- and 1000-hour fuels were distinguished by measuring diameter of individual pieces of fuel with callipers (see Table 3.2 above). Fuel-load and fuel-class distribution were calculated by making use of Equations 3.1 to 3.3 mentioned in Section 3.5.2.

3.5.4 Fuel moisture

Fuel moisture was measured using the ME2000 Fine Fuel Moisture meter. This meter is used by fire managers to determine fuel moisture before carrying out prescribed burnings. The instrument
provides a reading for a variety of organic materials and the appropriate selection has to be made before measuring fuel moisture. Material taken as samples from the inner measuring points of all plots was put in plastic bags before applying fire to the plots. The following day, this material was used to determine the fuel moisture. One bag of approximately 5kg including fuel from all fuel classes were collected from each plot in both trials.

As the 10-hour and 100-hour fuels were too coarse to process with the grinder supplied by the manufacturers of the ME2000 Fine Fuel Moisture meter, a coffee grinder and a rasp were used to produce sufficient material to sample (Wiltronics, 2009). Figures 3.15 shows the moisture meter as well as the coffee grinder and rasp.

![ME2000 Fine Fuel Moisture meter, used with coffee grinder and rasp to determine fuel moisture.](image)

**Figures 3.15:** ME2000 Fine Fuel Moisture meter, used with coffee grinder and rasp to determine fuel moisture.

DeBano, Dunn and Conrad’s (1977) oven-dry method for calculating fuel moisture was an alternative considered in these trials, but because of the impracticality and cost of collecting, transporting and oven drying numerous samples from each plot, this method was not used. By applying the results of oven-dried litter in **Equation 3.4** below, the moisture content of the fuel can be calculated:
3.5.5 Rate of spread (RoS)

According to Kennard (2008), the RoS of a fire is the horizontal distance that the flame zone moves per unit of time (metres per minute) and usually refers to the head-fire segment of the fire perimeter. As described by Gill and Knight (1991), poles were placed 10m apart at right angles to the advancing perimeter of the fire (Figure 3.16) and the time it took the head of the fire to cover the distance measured.

![Figure 3.16: Poles, calibrated in 0.5m sections, placed 10m apart, in a square.](image)

3.5.6 Flame height

Flame height was recorded by visual observation when flames were next to each of four metal poles, as indicated in Figure 3.16. The RoS of the fire was slow enough to allow one person to record flame height. These poles were calibrated in 0.5m sections. The average flame height was calculated for each plot.
3.5.7 Fire temperature

The temperature of the fire treatment was measured in each plot using of a FLIR Thermovision A20M camera (Figure 3.17).

![FLIR Thermovision A20M camera](image)

**Figure 3.17:** FLIR Thermovision A20M camera.

The Researcher 2000 software package was used to process the results obtained from camera measurements. This software package was developed by MOVIMED Custom Imaging Solutions Company for use with the FLIR Thermovision heat detection camera range. According to the manufacturer the FLIR Thermovision camera has the ability to record temperatures accurately over distances of up to 20m (FLIR, 2009). The camera was set up as close to the fire as possible but not exceeding a distance of 20m away from the fire. The camera was aimed at the centre of the fire area and recording was started once the fire approached the area until the head of the fire has passed the area. Recording times varied but on average lasted about five minutes at a time. Recorded data was downloaded on a laptop computer. The average and maximum temperatures of
each fire were recorded in degrees Centigrade. Figure 3.18 is an example of temperature results obtained from the broadcasting treatment in Plot 11 of the *P. patula* trial.

![Figure 3.18: Example of outputs of the FLIR Thermovision A20M camera in terms of maximum and average temperature for the broadcasting treatment in plot 11 of the *Pinus patula* trial](image)

### 3.6 FIRE APPLICATION TO PLOTS

The optimum time to execute the burning of the trials would have been during, or at the end of the winter months during high fire season (May to first spring rains), since it is during this period when destructive veldfires are experienced in the study area. However, due to strict company policies that prevent prescribed burning during this period and the above normal summer rainfall that followed the winter of 2009, burning could only take place in February the following year during the fire safe period.

Soil and organic matter were constantly too moist to burn as the water table was saturated and excess rain water did not drain fast. During the 2009 rainy season, the average rainfall on the Woodstock Plantation in the Lothair area was exceeded by 654mm. On the Driepan Plantation in the Iswepi area, the average rainfall was exceeded by 239mm (Figures 3.3 and 3.5).

Head-fire burning of each plot was undertaken and firing of the plots generally commenced on the leeward side of trials in an attempt to prevent excess smoke. Excessive smoke would have made it
difficult to measure and observe the fire in the fire treatments that followed. Only one plot was burnt at a time. The strip-ignition method was used and the fire front was allowed to burn into the plot as a head fire. This method was selected to simulate a natural fire scenario, where veldfires are usually wind-driven. The fire was also started on the edge of the 50m x 50m plots to allow the fire front to gain momentum by the time it reached the sampling points.

### 3.7 STATISTICAL ANALYSES

The STATISTICA version 9 software programme was used to analyse data. STATISTICA 9, a Web-based package, was released in 2009. It is a statistics and analytics software package providing data analysis, data management, statistics, data mining, and data visualization procedures. (Statsoft, 2009).

With the support of STATISTICA, a series of graphs signifying an analysis of variance (ANOVA) as well as regression were generated. In these graphs the level of significance, the p value, signifies an important finding that did not likely happen by chance. p<.05 means that there were less than 5 chances in 100 that the result would have happened randomly. The multiple coefficient of determination (R²) represents the proportion of variability on the criterion variable that can be explained by the combined set of two or more predictor variables. The p value is calculated by using the calculated F value, with the degrees of freedom indicated in brackets. With the aid of STATISTICA, Pearson correlation matrixes were compiled for both trials in order to compare, and thus comprehend, the margin of influence exerted by all independent variables on the dependent variables of flame height, RoS and fire temperature.

Tables and histogram graphs were generated with Microsoft Office 2010 to compare data gathered from the trials.
CHAPTER 4
RESULTS AND DISCUSSION

4.1 INTRODUCTION

Results reflected in this chapter aim to determine the effect of modified fuel loads on fire behaviour. Fire behaviour in different post-harvesting slash treatments were evaluated by comparing fuel load classes prior to burning and fire behaviour parameters during burning. At the same time the effects of independent environmental variables on fire behaviour parameters were also investigated. These results are presented and discussed in this chapter.

4.2 MEASUREMENTS PRIOR TO BURNING

The results in this section represent the total fuel load as measured in respective classes across the different post harvesting slash treatments. Fuel-load composition is an important variable to record for the prediction of fire behaviour as fine fuels (one-hour fuels) lose moisture faster than fuels of coarser classes with subsequent effects on fire behaviour. A higher fuel load will also provide fuel for a more intense fire (Teie, 2005).

4.2.1 Fuel load and classes – Pinus patula

Table 4.1 displays the fuel load of the different fuel classes in slash treatments of the P. patula trial, and identifies litter and total slash loads. As the litter layer in the mulched plots was mixed with the slash layer, it could not be measured separately and has therefore not been indicated. Average- and standard-deviation calculations exclude results from mulched plots. Figures 4.1 and 4.2 provide a graphical comparison of this information. In all tables and graphs chopper-roll
Table 4.1: Fuel load per fuel class (P. patula).

<table>
<thead>
<tr>
<th>Treatment &amp; Repetition</th>
<th>Plot</th>
<th>1h kg/m²</th>
<th>10h kg/m²</th>
<th>100h kg/m²</th>
<th>1000h kg/m²</th>
<th>Slash kg/m²</th>
<th>Litter kg/m²</th>
<th>Total fuel kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch 1</td>
<td>1</td>
<td>0.45</td>
<td>1.32</td>
<td>0.77</td>
<td>1.55</td>
<td>4.09</td>
<td>0.00</td>
<td>4.09/4.37*</td>
</tr>
<tr>
<td>Mulch 2</td>
<td>2</td>
<td>0.44</td>
<td>1.18</td>
<td>0.79</td>
<td>1.29</td>
<td>3.7</td>
<td>0.00</td>
<td>3.70/5.77*</td>
</tr>
<tr>
<td>Mulch 3</td>
<td>15</td>
<td>0.4</td>
<td>1.33</td>
<td>0.62</td>
<td>1.55</td>
<td>3.91</td>
<td>0.00</td>
<td>3.91/5.39*</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>0.43(0.03)</td>
<td>1.28(0.08)</td>
<td>0.73(0.09)</td>
<td>1.46(0.15)</td>
<td>3.90(0.02)</td>
<td>0.00</td>
<td>5.18(0.72)</td>
</tr>
<tr>
<td>C-Roll 1</td>
<td>3</td>
<td>0.54</td>
<td>2.01</td>
<td>1.69</td>
<td>0.78</td>
<td>5.01</td>
<td>4.03</td>
<td>9.04</td>
</tr>
<tr>
<td>C-Roll 2</td>
<td>8</td>
<td>0.6</td>
<td>2.12</td>
<td>1.75</td>
<td>2.33</td>
<td>6.79</td>
<td>4.52</td>
<td>11.31</td>
</tr>
<tr>
<td>C-Roll 3</td>
<td>10</td>
<td>0.57</td>
<td>1.96</td>
<td>0.9</td>
<td>1.81</td>
<td>5.24</td>
<td>4.03</td>
<td>9.27</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>0.57(0.03)</td>
<td>2.03(0.08)</td>
<td>1.45(0.47)</td>
<td>1.64(1.24)</td>
<td>5.68(0.97)</td>
<td>4.19(0.28)</td>
<td>9.87(1.25)</td>
</tr>
<tr>
<td>Inter-windrow 1</td>
<td>4</td>
<td>0.89</td>
<td>2.78</td>
<td>0.25</td>
<td>0.87</td>
<td>4.79</td>
<td>3.33</td>
<td>8.12</td>
</tr>
<tr>
<td>Inter-windrow 2</td>
<td>12</td>
<td>1.04</td>
<td>3.57</td>
<td>0.29</td>
<td>0.99</td>
<td>5.88</td>
<td>3.4</td>
<td>9.28</td>
</tr>
<tr>
<td>Inter-windrow 3</td>
<td>14</td>
<td>1.29</td>
<td>2.6</td>
<td>0.51</td>
<td>3.08</td>
<td>7.49</td>
<td>2.77</td>
<td>10.26</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>1.07(0.20)</td>
<td>2.98(0.52)</td>
<td>0.35(0.14)</td>
<td>1.65(1.24)</td>
<td>6.05(1.36)</td>
<td>3.17(0.35)</td>
<td>9.22(1.07)</td>
</tr>
<tr>
<td>Windrows 1</td>
<td>5</td>
<td>0.48</td>
<td>3.27</td>
<td>4.11</td>
<td>5.24</td>
<td>13.11</td>
<td>5.22</td>
<td>18.33</td>
</tr>
<tr>
<td>Windrows 2</td>
<td>9</td>
<td>0.66</td>
<td>3.74</td>
<td>0.93</td>
<td>4.85</td>
<td>10.19</td>
<td>4.8</td>
<td>14.99</td>
</tr>
<tr>
<td>Windrows 3</td>
<td>13</td>
<td>0.8</td>
<td>4.11</td>
<td>3.33</td>
<td>4.78</td>
<td>13.01</td>
<td>5.15</td>
<td>18.16</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>0.65(0.16)</td>
<td>3.71(0.42)</td>
<td>2.79(1.66)</td>
<td>4.90(0.25)</td>
<td>12.10(1.33)</td>
<td>5.06(0.23)</td>
<td>17.16(1.88)</td>
</tr>
<tr>
<td>Broadcast 1</td>
<td>6</td>
<td>0.55</td>
<td>2.3</td>
<td>2.82</td>
<td>3.36</td>
<td>9.03</td>
<td>4.52</td>
<td>13.55</td>
</tr>
<tr>
<td>Broadcast 2</td>
<td>7</td>
<td>0.53</td>
<td>2.14</td>
<td>1.52</td>
<td>3.88</td>
<td>8.08</td>
<td>3.75</td>
<td>11.82</td>
</tr>
<tr>
<td>Broadcast 3</td>
<td>11</td>
<td>0.54</td>
<td>2.69</td>
<td>3.1</td>
<td>2.85</td>
<td>9.17</td>
<td>5.01</td>
<td>14.18</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>0.54(0.01)</td>
<td>2.38(0.25)</td>
<td>2.48(0.84)</td>
<td>3.36(0.52)</td>
<td>8.76(0.59)</td>
<td>4.43(0.64)</td>
<td>13.18(1.22)</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.71</td>
<td>2.77</td>
<td>1.77</td>
<td>2.9</td>
<td>8.15</td>
<td>4.21</td>
<td>10.92**</td>
</tr>
<tr>
<td>Std. deviation</td>
<td></td>
<td>0.25</td>
<td>0.73</td>
<td>1.29</td>
<td>1.59</td>
<td>2.88</td>
<td>1.88</td>
<td>4.31**</td>
</tr>
</tbody>
</table>

* Oven-dried mass, **Standard deviation and average calculated using oven-dried mass

Figure 4.1: Total fuel load per treatment for P. patula (including post-harvesting slash and litter layer).
Figure 4.2: Summary of fuel classes in the *P. patula* trial.
In Table 4.1, the slash refers to organic material generated during the harvesting of the trees. Litter refers to the ‘duff’ layer, which consists of organic material generated through the process of needle/leaf, bark and branch shedding while trees grow. The slash is classified as 1-hour, 10-hour, 100-hour and 1000-hour fuel classes. Measurements of fuel classes obtained from the mulched plots were problematic because the line-intersect method used to determine these fuel loads has not been developed to measure a mixed/mulched organic layer. A more accurate measure are the oven-dried mass of the total fuel load indicated with an asterisk (*) in Table 4.1.

The data indicate that the highest overall fuel load in the trial was generated in the windrow treatment and the lowest fuel load in the mulch treatment. Although most of the slash had been removed from the inter-windrow treatment, it still carried a higher fuel load than the mulched treatment and its fuel load closely matched that of the chopper-roll treatment. It can therefore be assumed that the chopper-roll treatment has been effective in reducing fuel load in the *P. patula* trial. The inter-windrow treatment had the highest one-hour fuel-load component and the second highest 10-hour fuel load, but lacked 100-hour and 1000-hour fuels which had been removed to stack on the windrows. The windrow and broadcast treatments had the highest 100-hour and 1000-hour fuel loads. It could therefore be expected that fire behaviour in the different treatments would differ because of different fuel class distribution.

The chopper-roll treatment in the *P. patula* trial resulted in a 3.31 kg/m² lighter fuel load than in the broadcast treatment, a 7.29 kg/m² lighter fuel load than in the windrow treatment and a 0.65 kg/m² heavier fuel load than the inter-windrow treatment. During the chopper-roll treatments, post-harvesting slash was compacted and broken into smaller pieces. As the chopper-roll action enlarged the surface area of fuels and brought it in close contact with mineral soil and soil moisture, an accelerated mineralisation was expected. This was confirmed by Hakkila (1984) and Rolando, *et al.* (2008), who found that chopper-rolling contributes towards faster mineralisation of post-harvesting slash.
4.2.2 Fuel load and classes – *Eucalyptus macarthurii*

Table 4.2, Figure 4.3 and Figure 4.4 represent the same information for the *E. macarthurii* trial as were measured in the *P. patula* trial.

**Table 4.2:** Fuel load per fuel class (*E. macarthurii*)

<table>
<thead>
<tr>
<th>Treatment &amp; Repetition</th>
<th>Plot</th>
<th>1h kg/m²</th>
<th>10h kg/m²</th>
<th>100h kg/m²</th>
<th>1000h kg/m²</th>
<th>Slash kg/m²</th>
<th>Litter kg/m²</th>
<th>Total fuel kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch 1</td>
<td>3</td>
<td>3.86</td>
<td>4.35</td>
<td>0.8</td>
<td>9.92</td>
<td>0.00</td>
<td>7.95/3.94*</td>
<td></td>
</tr>
<tr>
<td>Mulch 2</td>
<td>5</td>
<td>5.77</td>
<td>5.42</td>
<td>1.01</td>
<td>12.2</td>
<td>0.00</td>
<td>14.19/4.37*</td>
<td></td>
</tr>
<tr>
<td>Mulch 3</td>
<td>7</td>
<td>5.4</td>
<td>5.18</td>
<td>0.76</td>
<td>13.17</td>
<td>0.00</td>
<td>12.38/4.11*</td>
<td></td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td>5.01(1.01)</td>
<td>4.98(0.56)</td>
<td>0.86(0.13)</td>
<td>0.91(0.46)</td>
<td>11.76(1.67)</td>
<td>0.00</td>
<td>4.14(0.22)</td>
<td></td>
</tr>
<tr>
<td>C-Roll 1</td>
<td>9</td>
<td>4.33</td>
<td>8.18</td>
<td>2.27</td>
<td>15.23</td>
<td>1.23</td>
<td>16.46</td>
<td></td>
</tr>
<tr>
<td>C-Roll 2</td>
<td>11</td>
<td>3.8</td>
<td>7.49</td>
<td>1.93</td>
<td>14.13</td>
<td>1.3</td>
<td>15.43</td>
<td></td>
</tr>
<tr>
<td>C-Roll 3</td>
<td>13</td>
<td>3.67</td>
<td>7.05</td>
<td>2.4</td>
<td>14.47</td>
<td>1.23</td>
<td>15.7</td>
<td></td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td>3.90(0.35)</td>
<td>7.57(0.57)</td>
<td>2.20(0.24)</td>
<td>0.91(0.46)</td>
<td>14.61(0.56)</td>
<td>1.25(0.04)</td>
<td>15.86(0.53)</td>
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</tr>
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<td>2</td>
<td>4.15</td>
<td>3.75</td>
<td>0.62</td>
<td>0.67</td>
<td>9.2</td>
<td>0.95</td>
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</tr>
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<td>4.3</td>
<td>3.81</td>
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<td>0</td>
<td>8.59</td>
<td>0.95</td>
<td>9.54</td>
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<tr>
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<td>2.12</td>
<td>9.82</td>
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<td>10.84</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
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<td>0.93(1.08)</td>
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<td>4.57</td>
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<td>20.72</td>
<td>1.65</td>
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<tr>
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<td>3.36</td>
<td>3.96</td>
<td>11.3</td>
<td>1.14</td>
<td>19.76</td>
<td>1.72</td>
<td>21.48</td>
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<tr>
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<td>4.37(0.36)</td>
<td>7.70(5.28)</td>
<td>1.56(0.76)</td>
<td>17.12(5.42)</td>
<td>1.70(0.04)</td>
<td>18.82(5.40)</td>
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</tr>
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<td>2.42</td>
<td>2.85</td>
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<td>1.37</td>
<td>7.9</td>
<td>0.74</td>
<td>8.64</td>
</tr>
<tr>
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<td>2.47</td>
<td>3.05</td>
<td>1.47</td>
<td>0.91</td>
<td>7.9</td>
<td>1.02</td>
<td>8.92</td>
</tr>
<tr>
<td>Broadcast 3</td>
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<td>2.95</td>
<td>3.15</td>
<td>1.18</td>
<td>1.37</td>
<td>8.64</td>
<td>1.16</td>
<td>9.8</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
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<td>3.02(0.15)</td>
<td>1.30(0.15)</td>
<td>1.22(0.27)</td>
<td>8.15(0.43)</td>
<td>0.97(0.21)</td>
<td>9.12(0.61)</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>3.58</td>
<td>4.62</td>
<td>2.92</td>
<td>1.16</td>
<td>12.27</td>
<td>1.22</td>
<td>11.62**</td>
<td></td>
</tr>
<tr>
<td>Std. deviation</td>
<td>0.68</td>
<td>1.88</td>
<td>3.71</td>
<td>0.67</td>
<td>4.54</td>
<td>0.32</td>
<td>5.75**</td>
<td></td>
</tr>
</tbody>
</table>

* Oven-dried mass **Standard deviation and average calculated using oven-dried mass

![Figure 4.3: Total fuel load per treatment for *E. macarthurii* (including post-harvesting slash and litter layer).](image-url)
Figure 4.4: Summary of fuel classes in the *E.macarthuri* trial.
Figure 4.3 and Table 4.2 indicate that the highest overall fuel load in the trial was generated in the windrow treatments and the lowest fuel load in the mulch treatments. It can also be seen that there was not a significant difference between the total fuel load in inter-windrow and broadcast treatments, as the fuel load in the broadcast plots was only 0.94 kg/m² more. Broadcasting therefore seems to be an effective treatment in *E. macarthurii* at this site.

The windrow, chopper-roll and broadcast treatments had the highest one-hour fuel load but the chopper-roll treatment accounted for the highest 10-hour fuel load. The windrow treatment carried the highest 100-hour and 1000-hour fuel loads. Chopper-rolling therefore was not an effective fuel-load-reduction treatment in this trial as it carried a 6.74 kg/m² heavier fuel load than the broadcast treatment and a 3kg/m² lighter fuel load than in the windrow treatment (Figure 4.4). This result is supported by others (Norris, 1994; da Costa, 2006; Glutz, Wilibald and Harrison, 2006), who found that chopper-rolling in *Eucalyptus* compartments was less effective than in softwood compartments.

### 4.2.3 Comparison between *P. patula* and *E. macarthurii* fuels

Figure 4.5 compares different fuel classes as well as post-harvesting slash and litter layers of the broadcast treatment in both trials. As fuel within this treatment has not been manipulated, it gives an indication of the distribution of fuel classes and total fuel load. The *E. macarthurii* trial contained a higher percentage 1h and 10h fuels than the *P. patula* trial and therefore contributed to more intense fire behaviour in the *E. macarthurii* trial.

Distribution of the fuel classes across all treatments within the two trials are compared in Figure 4.6. These results indicate similar fuel class distributions in both trials after treatment if compared to Figure 4.5.
The vertical distribution of fuels within the trials is displayed in Figure 4.7. It indicates that the mulch, inter-windrow and broadcast treatments in the *E. macarthurii* trial had a smaller fuel-bed depth if compared to the *P. patula* trial. Mulched plots in both trials had a lower fuel-bed depth and fuel load than all the other treatments, with the exception of the inter-windrow treatment where slash was removed. Fuel within the mulched areas was therefore restricted to a thinner vertical layer compared to fuels in other treatments.
Figure 4.7: Average fuel bed depth for different treatments.

Figure 4.8 indicates that the average fuel load and the depth of the litter layer across treatments in the *P. patula* trial were higher when compared with those of the *E. macarthurii* trial. This might have implications for aspects such as higher percentage fuel moisture and less intense fire behaviour in the *P. patula* trial. According Chandler, *et. al.* (1983), fuel absorbs moisture from the soil. The proximity if the forest litter layer to the soil will therefore influence the moisture content of the fuels. Moist fuels burn less intense than dry fuels (Teie, 2005).

Figure 4.8: Average fuel load and depth for litter layer across treatments for the two trials.
A period of eight months and nine months respectively passed between the harvesting of the *P. patula* and *E. macarthurii* trials and fire application. Fuel management of all the plots in the *E. macarthurii* trial took place within a month of clear felling, so manipulated post-harvesting slash had a mineralisation period of between seven and eight months before fire application. In the *P. patula* trial, this mineralisation period only lasted between six and seven months, with chopper-rolling and mulching operations taking place just four months prior to the fire application. Fuel loads were measured four months after harvesting in the *P. patula* trial and five months after harvesting in the *E. macarthurii* trial. Fuel loads for chopper-rolling and mulching in the *P. patula* trial were measured once the treatments had been completed.

Fuel loads on the inter-windrow plots and the windrow plots were spatially manipulated and those on the other treatments were not. It can therefore be concluded that the only other factor responsible for the differences in oven dried fuel load between broadcasting, mulching and chopper-rolling treatments was the tempo of post harvesting slash mineralisation.

### 4.3 MEASUREMENTS DURING BURNING

In this section results obtained during the burning treatment of the two trials represent the Fire Danger Index, fuel moisture variables as well as the dependant fire behaviour variables: RoS, flame height and fire temperature. Independent variables are discussed first, after which dependent variables are examined. A series of graphs illustrating an analysis of variance (ANOVA) within both trials are presented in Figures 4.11 – 4.22.

#### 4.3.1 Fire Danger Index (FDI)

A challenging factor to overcome on the day of the fire treatment was to ensure that burning was carried out under relatively similar weather conditions. Air temperature and wind speed varied throughout the day and, in some cases, had a noticeable effect on the FDI. On both sites, the FDI
remained within the 10-point deviation margin considered acceptable during the burning operation (Section 3.5.3). *Pinus patula* plots were burned on 2 February 2010 and the *E. macarthurii* plots on 3 February 2010. Weather conditions were very stable on 2 February, where the difference between the highest and lowest FDI measured was eight points (Figure 4.9). On 3 February 2010, the weather was less stable and the difference between the highest and lowest FDI measurements was 15 points (Figure 4.10). In general terms, the factor influencing FDI the most is variation in wind conditions (Dyer, *et al.*, 2001; Teie, 2005). Gusts of wind measured on the day of fire application, explain the high level of variation in FDI recorded for the *E. macarthurii* trial.

![Figure 4.9](image)

**Figure 4.9:** FDI during burning of the *P. patula* plots (2 February 2010).

![Figure 4.10](image)

**Figure 4.10:** FDI during burning of the *E. macarthurii* plots (3 February 2010).
4.3.2 Fuel moisture and relative humidity (RH)

The *P. patula* trial contained significantly thicker fuels, had a thicker litter layer and a higher litter-fuel load than the *E. macarthurii* trial. The fuel load in the latter trial consisted mostly of fine, woody material and leaves, with a big surface-to-volume ratio (Tables 4.1 and 4.2). According to Dyer, *et al.* (2001), fuels with a big surface-to-volume ratio, as in the case of *E. macarthurii*, lose moisture fast and will burn more intensely when exposed to drier and warmer weather.

Dead fuels with low fuel moisture will absorb moisture from the atmosphere if the relative humidity (RH) is high (de Ronde, 1996a; Fernández and Botelho, 2003). On the day that the *P. patula* trial was burned, the average RH was 21.67%; for the *E. macarthurii* trial, it was 47.4%.

The fuel in the *E. macarthurii* trial was therefore exposed to a higher moisture content and could potentially absorb more moisture from the atmosphere than fuels in the *P. patula* trial.

The variations in fuel moisture for different fuel load treatments for both trials are displayed in Figures 4.11 and 4.12.

In both trials, mulched plots had higher moisture content than all the other treatments. However, fuel moisture was higher in the *P. patula* trial than in the *E. macarthurii* trial and could have had a significant effect on fire behaviour. A more compact and deeper mulch layer, with a higher potential to retain moisture, probably caused a higher fuel-moisture content in the *P. patula* trial. The average moisture content of fuel in the *P. patula* trial was 22.45%; in the *E. macarthurii* trial, it was 8.91%. It could therefore be expected that fire behaviour would be more intense in the *E. macarthurii* trial.
Figure 4.11: Fuel-moisture percentage for different treatments in *P. patula*.

Figure 4.12: Fuel-moisture percentage for different treatments in *E. macarturii*. 
4.3.3 Fuel treatments and fire-behaviour variables

The variation in fire behaviour variables across the various post-harvesting slash treatments of the *P. patula* and *E. macarthurii* trials was conducted by an analysis of variance (ANOVA) and presented in Figures 4.13 – 4.22). Significant differences between the fire-behaviour variables (p ≤ 0.05) are indicated in red and are presented in tabular format at the bottom of graphs. Tables 4.3 and 4.4 are summaries of the data of dependent fire-behaviour variables measured in both trials during the burning of the different treatments, as well as the independent variables FDI and fuel moisture.

**Table 4.3:** Fire-behaviour variables (*P. patula*).

<table>
<thead>
<tr>
<th>Treatment &amp; Repetition</th>
<th>Plot</th>
<th>Max. flame height (m)</th>
<th>Avg. flame height (m)</th>
<th>RoS (cm/min)</th>
<th>Fuel moisture (%)</th>
<th>Max. fire temp. (°C)</th>
<th>Avg. fire temp. (°C)</th>
<th>FDI</th>
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<tr>
<td>Mulch 1</td>
<td>1</td>
<td>0.5</td>
<td>0.16</td>
<td>7.8</td>
<td>45.45</td>
<td>649.7</td>
<td>427.5</td>
<td>37</td>
</tr>
<tr>
<td>Mulch 2</td>
<td>2</td>
<td>0.5</td>
<td>0.23</td>
<td>10.5</td>
<td>49.58</td>
<td>600.4</td>
<td>425.7</td>
<td>39</td>
</tr>
<tr>
<td>Mulch 3</td>
<td>15</td>
<td>0.3</td>
<td>0.21</td>
<td>6.9</td>
<td>41.7</td>
<td>569.5</td>
<td>448.4</td>
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<td>606.53(40.45)</td>
<td>433.87(12.62)</td>
<td>38.33(1.15)</td>
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<td>C-Roll 1</td>
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<td>1.4</td>
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<td>14.1</td>
<td>797.4</td>
<td>602.8</td>
<td>35</td>
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<td>878.2</td>
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<td>16.78(4.91)</td>
<td>837.37(40.41)</td>
<td>688.43(76.45)</td>
<td>37.67(3.06)</td>
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<td>19.76(4.72)</td>
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<td>10.92(1.67)</td>
<td>877.83(243.30)</td>
<td>730.20(164.40)</td>
<td>40.00(3.00)</td>
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<td>1.7</td>
<td>0.91</td>
<td>37.5</td>
<td>27.55</td>
<td>957.1</td>
<td>699.9</td>
<td>39</td>
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<td>46.1</td>
<td>11.4</td>
<td>715.8</td>
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<td>40</td>
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<td>1.73(0.71)</td>
<td>50.10(15.01)</td>
<td>19.23(8.09)</td>
<td>885.97(148.03)</td>
<td>688.43(85.08)</td>
<td>39.67(0.58)</td>
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<td>35.84</td>
<td>22.45</td>
<td>775.84</td>
<td>603.68</td>
<td>39.07</td>
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<tr>
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<td>22.81</td>
<td>13.13</td>
<td>162.61</td>
<td>152.89</td>
<td>2.09</td>
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</table>

* Data did not record
Individual fire-behaviour variables measured are important as they may influence suppression of veldfires. Flame height gives an indication of the spotting potential of the fire, as well as the possibility of crown fires. RoS will have an effect on the time available to fire fighters to complete suppression activities and fire temperature influences the pre-heating and ignition of fuels ahead of the fire. The different fuel load treatments for the *P. patula* trial, as listed in Table 4.3 will be discussed briefly with reference to fire behaviour variables measured during the burning operation.

**Mulch treatment:** - The lowest average flame height was measured in the mulch treatment and was significantly lower (p ≤ 0.05) than flame lengths of the broadcast and windrow treatments (Figure 4.13). This was expected as the fuel load, fuel-bed depth and fuel-moisture content of the mulched material also differed significantly from these two treatments. In Figure 4.14, a similar pattern could be observed for maximum flame heights.

As indicated in Figure 4.15, the RoS in the mulch treatment was significantly slower (p ≤ 0.05) than in all other treatments with the exception of the inter-windrow treatment. The fuel-moisture content of 45.53% in this treatment was more than twice as high as that of the other treatments and this, combined with a low fuel-bed depth, explains the slow RoS. It must be noted that the absence of a strong wind had a negative influence on the RoS in all treatments.

There were no significant differences among any of the treatments with regard to average and maximum temperatures of fire. The lowest temperatures, however, were recorded in the mulch treatment. This was probably because of the high fuel-moisture content and the compact nature of the fuel load (Figures 4.16 and 4.17).

**Chopper-roll treatment:** - The average flame height in the chopper-roll treatment was significantly lower (p ≤ 0.05) than that of the windrow treatment (Figure 4.13) and this was also true for
maximum flame height (Figure 4.14). This result was surprising as the fuel-bed depth was 12.84cm lower than in the broadcasting treatment. However, fuel moisture was 2.44% less. RoS within this treatment was significantly higher than with the mulch treatment, but was lower than with the broadcast and windrow treatments and higher than with the inter-windrow treatment. The factor possibly responsible for the slower spread rate in this treatment is a lower fuel-bed depth with more compact fuel, as well as a lower fuel load than with the broadcast and windrow treatments. This is confirmed by Teie (2005) and Chandler, et. al. (1983), who states that a lower vertical distribution of fuel as well as more compacted fuels cause less intense fires.

The third lowest average temperature was recorded in the chopper-roll treatment. Maximum temperatures recorded in the different treatments are not reliable indicators of the fire behaviour experienced as fuel distribution was often distorted as a result of obstacles like stump and rocks that prevented proper treatment of slash.

*Inter-windrow treatment:* - The average flame height in the inter-row treatment was only significantly lower (p ≤ 0.05) than that of the windrow treatment and this was also true for maximum flame height. The fuel bed depth in this treatment was only 8.5cm and fuel moisture 3% higher than in the chopper-roll treatment and 0.5% higher than in the broadcast treatment. Although not statistically significant, this possibly explains the low average and maximum flame lengths measured in this treatment. RoS in this treatment was significantly lower (p ≤ 0.05) than in the broadcast and windrow treatments possibly because a lower flame lengths and fuel bed depth. The second lowest average and maximum temperatures were recorded in this treatment but it was not significantly lower than that of other treatments. The low temperature probably resulted because of the low fuel load, high fuel moisture percentage as well as the compact nature of fuels (Figures 4.16 and 4.17).
Windrow treatment: - Average flame height in the windrow treatment was significantly higher (p ≤ 0.05) than in all other treatments. This can be explained because of the high fuel load and fuel bed depth in windrows. The only exception was that there was not a significant difference in maximum flame height between the broadcast and windrow treatments – possibly because post-harvesting slash were still high in some areas in the broadcast area.

The fastest RoS was measured in this treatment and was significantly faster (p ≤ 0.05) than in the mulch and inter-windrow treatments. A high fuel load and vertical fuel distribution, possibly explains the high RoS.

The highest average and maximum fire temperatures were recorded in this treatment and are probably because of the high fuel load and fuel bed depth of fuels in this treatment. The temperature differences were not significant, possibly because of the stable weather conditions on the day of fire application (Figures 4.16 and 4.17).

Broadcast treatment: - Comparisons with other treatments revealed that there was also a significant difference between average flame length (p ≤ 0.05) in the broadcast treatment and the mulching treatment (Figure 4.13). A similar pattern, although not significant, could be observed for maximum flame height in the different treatments in Figure 4.14. The exception was that there was not a significant different between the broadcast and windrow treatments’ maximum flame heights – possibly because post-harvesting slash were still high in some areas in the broadcast area. RoS in the broadcast treatment followed the same trend as in the windrow treatment. The higher fuel bed depth with less compacted fuel possible caused the faster RoS.

The second highest fire temperature – equal to that of the chopper-roll treatment - was recorded in this treatment, but temperature differences were not significant higher compared to that in other treatments. This is possibly because of a higher fuel moister percentage and not the higher fuel bed depth when compared to the chopper-roll treatment (Figures 4.16 and 4.17).
Current effect: $F(4, 10) = 17.957$, $p = .00015$, $R^2 = 0.877792$

Average flame heights for different treatments in *P. patula*.

**Figure 4.13:**

Current effect: $F(4, 10) = 12.869$, $p = .00059$, $R^2 = 1.000000$

Maximum flame heights for different treatments in *P. patula*.

**Figure 4.14:**
Current effect: $F(4, 10)=16.082$, $p=0.00023$, $R^2=0.811651$

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrow</th>
<th>Windrow</th>
<th>Broadcast</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>C-roll</td>
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<td></td>
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<td>Inter-windrows</td>
<td>0.769</td>
<td>0.153</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windrows</td>
<td>*0.000</td>
<td>0.058</td>
<td>*0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>*0.003</td>
<td>0.621</td>
<td>*0.017</td>
<td>0.441</td>
<td></td>
</tr>
<tr>
<td>Avg. RoS (cm/min)</td>
<td>8.40</td>
<td>38.5</td>
<td>17.83</td>
<td>64.37</td>
<td>50.10</td>
</tr>
</tbody>
</table>

* $p < 0.05$

**Figure 4.15:** RoS for different treatments in *P. patula*.

Current effect: $F(4, 9)=3.3978$, $p=0.05894$, $R^2=0.42456$

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrow</th>
<th>Windrow</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-roll</td>
<td>0.133</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-windrows</td>
<td>0.888</td>
<td>0.437</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windrows</td>
<td>0.114</td>
<td>0.994</td>
<td>0.342</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>0.133</td>
<td>1.000</td>
<td>0.437</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>Avg. fire temp (°C)</td>
<td>433.87</td>
<td>688.43</td>
<td>519.63</td>
<td>730.20</td>
<td>688.43</td>
</tr>
</tbody>
</table>

* $p < 0.05$

**Figure 4.16:** Average fire temperatures (°C) for different treatments in *P. patula*. 62
Current effect: F(4, 10)=2.8624, p=.08081, R²=0.53379

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrow</th>
<th>Windrow</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-roll</td>
<td>0.272</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-windrows</td>
<td>0.971</td>
<td>0.559</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windrows</td>
<td>0.160</td>
<td>0.995</td>
<td>0.365</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>0.143</td>
<td>0.990</td>
<td>0.332</td>
<td>01.000</td>
<td>01.000</td>
</tr>
<tr>
<td>Max. fire temp (°C)</td>
<td>606.3</td>
<td>873.37</td>
<td>671.50</td>
<td>877.83</td>
<td>885.97</td>
</tr>
</tbody>
</table>

*p ≤ 0.05

**Figure 4.17:** Maximum fire temperatures (°C) for different treatments in *P. patula.*

The different fuel load treatments for the *E. macarthurii* trial as listed in Table 4.4 will be discussed briefly with reference to fire behaviour variables measured during the burning operation.
Table 4.4: Fire behaviour variables (*E. macarthurii*).

<table>
<thead>
<tr>
<th>Treatment &amp; Repetition</th>
<th>Plot</th>
<th>Max. flame height (m)</th>
<th>Avg. flame height (m)</th>
<th>RoS (cm/min)</th>
<th>Fuel moisture (%)</th>
<th>Max. Fire temp. (°C)</th>
<th>Avg. Fire temp. (°C)</th>
<th>FDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch 1</td>
<td>3</td>
<td>0.7</td>
<td>0.5</td>
<td>52.2</td>
<td>10.83</td>
<td>788.1</td>
<td>651.6</td>
<td>39</td>
</tr>
<tr>
<td>Mulch 2</td>
<td>5</td>
<td>0.85</td>
<td>0.56</td>
<td>75.8</td>
<td>12.1</td>
<td>802.7</td>
<td>647.1</td>
<td>48</td>
</tr>
<tr>
<td>Mulch 3</td>
<td>7</td>
<td>0.45</td>
<td>0.25</td>
<td>23</td>
<td>10.25</td>
<td>745.8</td>
<td>533</td>
<td>40</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>0.67(0.20)</td>
<td>0.44(0.16)</td>
<td>50.33(26.45)</td>
<td>11.06(0.95)</td>
<td>778.87(29.55)</td>
<td>610.57(67.21)</td>
<td>42.33(4.93)</td>
</tr>
<tr>
<td>C-Roll 1</td>
<td>9</td>
<td>1.5</td>
<td>1.13</td>
<td>109.1</td>
<td>6.98</td>
<td>874</td>
<td>683</td>
<td>48</td>
</tr>
<tr>
<td>C-Roll 2</td>
<td>11</td>
<td>4</td>
<td>1.98</td>
<td>77.9</td>
<td>7.13</td>
<td>868.7</td>
<td>747.8</td>
<td>51</td>
</tr>
<tr>
<td>C-Roll 3</td>
<td>13</td>
<td>3</td>
<td>1.58</td>
<td>70.59</td>
<td>9.18</td>
<td>851</td>
<td>757</td>
<td>49</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>2.83(1.26)</td>
<td>1.56(0.43)</td>
<td>85.86(20.45)</td>
<td>7.76(1.23)</td>
<td>864.57(12.04)</td>
<td>729.27(40.33)</td>
<td>49.33(1.53)</td>
</tr>
<tr>
<td>Inter-windrow 1</td>
<td>2</td>
<td>1.2</td>
<td>0.46</td>
<td>18</td>
<td>10.75</td>
<td>687.2</td>
<td>627.5</td>
<td>43</td>
</tr>
<tr>
<td>Inter-windrow 2</td>
<td>4</td>
<td>0.75</td>
<td>0.5</td>
<td>44</td>
<td>6.25</td>
<td>687.7</td>
<td>585.6</td>
<td>49</td>
</tr>
<tr>
<td>Inter-windrow 3</td>
<td>15</td>
<td>1.1</td>
<td>0.6</td>
<td>46.2</td>
<td>6.83</td>
<td>650.6</td>
<td>417.2</td>
<td>53</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>1.02(0.24)</td>
<td>0.52(0.07)</td>
<td>36.07(15.68)</td>
<td>7.94(2.45)</td>
<td>675.17(21.28)</td>
<td>543.43(111.31)</td>
<td>48.33(5.03)</td>
</tr>
<tr>
<td>Windrows 1</td>
<td>1</td>
<td>4.5</td>
<td>2.45</td>
<td>61.2</td>
<td>10.43</td>
<td>832.1</td>
<td>632.9</td>
<td>43</td>
</tr>
<tr>
<td>Windrows 2</td>
<td>6</td>
<td>4.6</td>
<td>2.45</td>
<td>60</td>
<td>9.93</td>
<td>865.8</td>
<td>764</td>
<td>48</td>
</tr>
<tr>
<td>Windrows 3</td>
<td>8</td>
<td>3.3</td>
<td>2.05</td>
<td>57</td>
<td>9.35</td>
<td>964.5</td>
<td>831.2</td>
<td>38</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>4.13(0.72)</td>
<td>2.32(0.23)</td>
<td>59.40(2.16)</td>
<td>9.90(0.54)</td>
<td>887.47(68.81)</td>
<td>742.70(100.85)</td>
<td>43.00(5.00)</td>
</tr>
<tr>
<td>Broadcast 1</td>
<td>10</td>
<td>5.5</td>
<td>2.45</td>
<td>130</td>
<td>6.88</td>
<td>909.3</td>
<td>748</td>
<td>51</td>
</tr>
<tr>
<td>Broadcast 2</td>
<td>12</td>
<td>1.8</td>
<td>0.58</td>
<td>46.1</td>
<td>7.93</td>
<td>845.6</td>
<td>456.6</td>
<td>48</td>
</tr>
<tr>
<td>Broadcast 3</td>
<td>14</td>
<td>1.6</td>
<td>1.38</td>
<td>52.2</td>
<td>8.9</td>
<td>900.7</td>
<td>748.4</td>
<td>47</td>
</tr>
<tr>
<td>Mean (Std. dev)</td>
<td></td>
<td>2.97(2.20)</td>
<td>1.47(0.94)</td>
<td>76.10(46.78)</td>
<td>7.90(1.01)</td>
<td>885.20(34.56)</td>
<td>651.00(168.36)</td>
<td>48.67(2.08)</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2.32</td>
<td>1.26</td>
<td>61.55</td>
<td>8.91</td>
<td>818.25</td>
<td>655.39</td>
<td>46.33</td>
</tr>
<tr>
<td>Std. deviation</td>
<td></td>
<td>1.67</td>
<td>0.83</td>
<td>29.11</td>
<td>1.81</td>
<td>90.68</td>
<td>118.63</td>
<td>4.62</td>
</tr>
</tbody>
</table>

Mulch treatment: - The lowest average and maximum flame heights were measured in the mulch treatment and were significantly lower (p ≤ 0.05) than the flame lengths of the windrow treatment (Figures 4.18 and 4.19). This is probably as a result of the significant differences in the fuel load, fuel-bed depth and fuel moisture of the mulched material from this treatment.

In spite of the higher fuel-moisture percentage in this treatment, the RoS did not differ significantly from that measured in other treatments. However, the broadcast treatment did have a faster RoS than the inter-windrow treatment. This might be accounted for by the higher deviation in the FDI conditions, including wind speed. Lower fuel-bed depth and flame heights in the mulch treatment area possibly caused the slower RoS in this treatment.
There were no significant differences among treatments with regard to average fire temperature (Figure 4.21). The second lowest average temperature was measured in this treatment. This was probably because of the high fuel moisture and the compact nature of the fuel load. Figure 4.22 indicates that the maximum temperature recorded in the mulch treatment was significantly higher (p ≤ 0.05) than that of the inter-windrow treatment, but, at the same time, significantly lower than the broadcast and windrow treatments. This was to be expected as fuel-bed depth and fuel load were lower and fuel moisture higher in comparison with those of the latter treatment. As mentioned before, maximum temperatures recorded are not reliable indicators of fire behaviour as external factors may influence them (Chandler, et.al., 1983; Dennison, et.al., 2006).

*Chopper-roll treatment:* - Statistically, there were no significant differences in the average and maximum flame heights of the chopper-roll treatment when compared with the other treatments. Average flame height was, however, comparable with that of the broadcast treatment. This is a surprising result, as the fuel-bed depth was 31cm lower than in that treatment. However, fuel moisture was only 0.14% less in the chopper-roll treatment. In this case, neither fuel moisture nor fuel-bed depth had a significant influence on flame height. This is possibly because the chopper-roll treatment did not break down post-harvesting slash properly.

Rate of Spread was the highest in the chopper-roll and broadcast treatments, although not significantly different from other treatments (Figure 4.20). The higher fuel-bed depth in the chopper-roll treatment possibly caused the higher flame lengths. This confirms that chopper-rolling is not an effective treatment in *Eucalyptus* slash (da Costa, 2006). The second highest average and maximum temperatures were recorded in this treatment, but the maximum temperature was only significantly higher (p ≤ 0.05) than that recorded in the inter-windrow treatment (Figures 4.21 and 4.22).
Inter-windrow treatment: - Statistically, there were no significant differences in the average and maximum flame heights in the inter-windrow treatment compared with the other treatments. Flame lengths in this treatment also compared well with flame lengths in the mulched area, although average and maximum flame lengths were slightly higher in the inter-windrow treatment. Fuel-bed depth was only 5.57 cm compared with the 4.7 cm of the mulch treatment. Fuel moisture, however, was 3.12% lower than that of the mulch and, although not statistically significant, this explains the higher average and maximum flame lengths measured in the inter-windrow treatment. The lowest RoS was recorded in this treatment, but was not significantly lower than that of other treatments (Figure 4.20). Lower fuel-bed depth and flame heights in the inter-windrow treatment possibly caused the slower RoS.

While not statistically significant, it is interesting to note that the average temperature in the inter-windrow treatment was the lowest of all treatments. Average temperature was recorded as being 199.3°C lower than that of the windrow treatment, although only 67.1°C lower than that of the mulch treatment. Maximum temperatures recorded were significantly lower than those of the windrow, chopper-roll and broadcast treatments. The fuel-bed depth of the inter-windrow treatment was 0.9 cm higher than that of the chopper-roll treatment and fuel load was 6 kg/m² higher than in the mulch treatment. It was expected that temperatures would have been higher than in the latter case, but fuel moisture was 3.14% lower and the fuel more compacted (Figures 4.21 and 4.22).

Windrow treatment: - Average and maximum flame heights measured in the windrow treatment were the highest in the trial. However, these flame heights were only significantly higher (p ≤ 0.05) in the mulch treatment, with the average flame height also significantly higher (p ≤ 0.05) in the inter-windrow treatment. This can be explained by the high fuel load and fuel-bed depth in windrows.
The RoS measured in this treatment contradicted expectations that it would be the highest in the trial. In fact, it did not differ significantly from the RoS in other treatments, only being the third fastest RoS recorded. The slower RoS could be because the windrows were stacked at a 90-degree angle in relation to the wind experienced during the burn. The wind could not bend the flames parallel to the direction of the windrows and thus pre-heat fuels to cause a fast RoS.

Average and maximum temperatures recorded in this treatment were higher than those of all other treatments. However, only maximum temperatures were significantly higher ($p \leq 0.05$) than those recorded in the mulch and inter-windrow treatments. This result can be explained by the higher fuel load and fuel-bed depth measured in this treatment in comparison with all other treatments (Figures 4.21 and 4.22).

**Broadcast treatment:** Comparisons with other treatments revealed that there were no significant differences between average and maximum flame lengths in the broadcast treatment (Figure 4.18 and 4.19). Rate of Spread was highest in the broadcast treatment. This was possibly caused by continuity in the fuels and a deeper fuel-bed depth than in the other treatments, apart from the windrow treatment (Figure 4.20). Although statistically not significant, the average temperature recorded in this treatment was only 40.4°C higher than that of the mulched treatment and 91.7°C lower than that of the windrow treatment. Maximum temperatures recorded were significantly higher than those of the mulch and inter-windrow treatments (Figures 4.21 and 4.22). These results were surprising: much higher flame lengths, RoS and fire temperatures had been expected as in the case of the *P. patula* trial. It is suspected that the plots where this treatment was carried out had a very low fuel load as a result of the harvesting method which had been used, as well as the position of roads in the compartment. Both these factors can cause uneven distribution of post harvesting slash because of felling patterns as well as vehicle movement along the road. This is confirmed by the low fuel load (1.06kg/m² less than in the inter-windrow treatment) and low fuel-bed depth (only 5.1cm higher than in the inter-windrow treatment).
Current effect: \( F(4, 10) = 8.1041, \ p = .00351, \ R^2 = 0.7642 \)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrows</th>
<th>Windrows</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-roll</td>
<td>0.094</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-windrows</td>
<td>0.999</td>
<td>0.130</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>0.005</em> Windrows</td>
<td>0.364</td>
<td><em>0.007</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>0.135</td>
<td>0.999</td>
<td>0.184</td>
<td>0.267</td>
<td></td>
</tr>
<tr>
<td>Avg. flame height (m)</td>
<td>0.44</td>
<td>1.56</td>
<td>0.52</td>
<td>2.32</td>
<td>1.47</td>
</tr>
</tbody>
</table>

* \( p < 0.05 \)

**Figure 4.18**: Average flame heights for different treatments in *E. macarthurii*.

Current effect: \( F(4, 10) = 4.4840, \ p = .02474, \ R^2 = 0.6420 \)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrows</th>
<th>Windrows</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-roll</td>
<td>0.241</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-windrows</td>
<td>0.996</td>
<td>0.387</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>0.032</em> Windrows</td>
<td>0.673</td>
<td>0.056</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>0.199</td>
<td>1.000</td>
<td>0.326</td>
<td>0.749</td>
<td></td>
</tr>
<tr>
<td>Max. flame height (m)</td>
<td>0.67</td>
<td>2.83</td>
<td>1.02</td>
<td>4.13</td>
<td>2.97</td>
</tr>
</tbody>
</table>

* \( p < 0.05 \)

**Figure 4.19**: Maximum flame heights for different treatments in *E. macarthurii*. 
Figure 4.20: RoS for different treatments in *E. macarthurii.*

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrow</th>
<th>Windrow</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch C-roll</td>
<td>0.512</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-windrows</td>
<td>0.962</td>
<td>0.226</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windrows</td>
<td>0.993</td>
<td>0.744</td>
<td>0.817</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>0.761</td>
<td>0.990</td>
<td>0.405</td>
<td>0.935</td>
<td></td>
</tr>
<tr>
<td>Avg. RoS (cm/min)</td>
<td>50.33</td>
<td>85.86</td>
<td>36.07</td>
<td>59.4</td>
<td>76.1</td>
</tr>
</tbody>
</table>

*p ≤ 0.05

Figure 4.21: Average fire temperatures (°C) for different treatments in *E. macarthurii.*

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrow</th>
<th>Windrow</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch C-roll</td>
<td>0.663</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-windrows</td>
<td>0.934</td>
<td>0.280</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windrows</td>
<td>0.576</td>
<td>1.000</td>
<td>0.226</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>0.989</td>
<td>0.892</td>
<td>0.734</td>
<td>0.826</td>
<td></td>
</tr>
<tr>
<td>Avg. fire temp (°C)</td>
<td>610.57</td>
<td>729.27</td>
<td>543.43</td>
<td>742.70</td>
<td>651.00</td>
</tr>
</tbody>
</table>

*p ≤ 0.05
Current effect: $F(4, 10) = 16.947$, $p = .00019$, $R^2 = 0.8714$

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mulch</th>
<th>C-roll</th>
<th>Inter-windrow</th>
<th>Windrow</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td>0.119</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-roll</td>
<td></td>
<td>0.049</td>
<td>*0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-windrows</td>
<td>*0.049</td>
<td>*0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windrows</td>
<td>*0.039</td>
<td>0.945</td>
<td>*0.000</td>
<td></td>
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<tr>
<td>Broadcast</td>
<td>*0.043</td>
<td>0.961</td>
<td>*0.001</td>
<td>1.000</td>
<td>885.20</td>
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<td>Max. fire temp (°C)</td>
<td>778.87</td>
<td>864.57</td>
<td>675.17</td>
<td>887.47</td>
<td>885.20</td>
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</tbody>
</table>

*p ≤ 0.05

Figure 4.22: Maximum fire temperatures (°C) for different treatments in *E. macarthurii*.

### 4.3.4 Comparisons of the fire-behaviour variables in the two trials

In the *P. patula* trial, there was a bigger difference between the flame heights of the different post harvesting slash treatments than in the *E. macarthurii* trial. When comparing flame height across trials, average (1.49m) and maximum (2.60m) flame heights for the *P. patula* trial were higher compared with average (1.26m) and maximum (2.33m) flame heights in the *E. macarthurii* trial. This is probably because the average fuel load in the *P. patula* trial was 4.6 kg/m² higher than in the *E. macarthurii* trial (Tables 4.1 and 4.2). Average and maximum flame heights in the mulching and chopper-roll treatments of the *E. macarthurii* trial were higher than those of the *P. patula* trial- possibly because the *E. macarthurii* trial contained more 1h and 10 fuels than the *P. patula* trial (Figures 4.5 and 4.6). In all the other treatments, flame heights were higher in the *P. patula* trial. Higher fuel moisture in the *P. patula* mulched treatment than in the *E. macarthurii* mulch treatment (Figures 4.11 and 4.12) trial and because the chopper-roll treatment in the
*P. patula* trial was more effective than in the *E. macarthurii* trial. The latter is supported by Chandler, *et al.* (1983), who state that compact fuels consumed by fire result in less intense fire behaviour.

The average RoS in the *E. macarthurii* trial was 36.9m/h as opposed to 21.5m/h in the *P. patula* trial. RoS in all the *E. macarthurii* treatments, with the exception of the windrow treatment, was faster than that in the *P. patula* treatments. The lower fuel moisture, as well as the higher average FDI (7.2 points) in the *E. macarthurii* trial, can be seen as contributing factors to a higher RoS. A high fine-fuel percentage, with a big surface-to-volume ratio in the *E. macarthurii* trial, possibly also increased the RoS.

When there is an increased flame height, the fire temperature and the RoS of fires also increase. This is significant as the probability of spot fires also increase under these conditions (Teie, 2005). This proved true in the *P. patula* trial. RoS was the fastest in the windrow treatment, followed in order of speed by the broadcast, chopper-roll, inter-windrow and mulch treatments. However, this was not the case in the *E. macarthurii* trial. Although the temperature and flame height were the highest in the windrow treatment, it had the third fastest RoS. A possible explanation is that the wind blew at a 90-degree angle in relation to the windrows and therefore could not spread the fire parallel to the rows. RoS was the fastest in the chopper-roll treatment, followed in order of speed by the broadcast, windrow, mulch and inter-windrow treatments.

In the *P. patula* trial, the highest average temperatures were measured in the windrow treatment, followed in order of temperature intensity by the broadcast, chopper-roll, inter-windrow and mulch treatments. In the *E. macarthurii* trial, the windrow treatment had the highest average temperature, followed in order of temperature intensity by chopper-roll, broadcast, mulch and inter-windrow treatments.

When compared with the broadcasting and windrow treatments, chopper-rolling seemed to be an effective treatment in the *P. patula* trial, as the compacted fuel bed produced a much lower
average flame height and RoS (Figures 4.13 and 4.15). If the results of average flame height and RoS in the *E. macarthurii* trial are compared, it can be seen that broadcasting was more effective than the chopper-roll and windrow treatments (Figures 4.18 and 4.20).

In terms of fire suppression, it is important to compare maximum flame heights in the different treatments because incidences of maximum flame height and flare-ups are the most likely to cause spot fires (de Ronde, 1996b). Differences in maximum flame height within different treatments in both trials are depicted in Figures 4.14 and 4.19. In the *P. patula* trial, the windrow and broadcast treatments produced the highest flame heights and the mulch and inter-windrow treatments the lowest. In the *E. macarthurii* trial, flame heights in the chopper-roll and windrow treatments were the highest. This confirmed that chopper-rolling was not as effective as a treatment in the *E. macarthurii* trial as in the *P. patula*.

After comparing fire parameters measured during the burning treatment of both trials, fuel modification techniques were ranked in terms of its desirable effect on fire parameters (Table 4.5). This was done by allocating a value of ‘1’ to the most desirable effect of the parameter and ‘5’ to the least desirable effect. These numerical values were then added across all parameters and ranked to indicate the most effective fuel load treatment method with regards to fire behaviour. In the *P. patula* trial mulching was the most effective treatment followed by inter-windrow (removing of slash), chopper-roll, broadcast and the windrow treatment. In the *E. macarthurii* trial the same results were obtained with the exception of the broadcast treatment being more effective than the chopper-roll treatment. Although the results displayed in Table 4.5 can still be refined, it may serve as decision making tool to select the most effective fuel load modification method in post-harvesting slash.
Table 4.5: Numerical ranking comparing effectiveness of slash treatments with regards to fire behaviour parameters.

<table>
<thead>
<tr>
<th></th>
<th>Avg. flame height</th>
<th>Max. flame height</th>
<th>RoS</th>
<th>Avg. fire temp.</th>
<th>Max. fire temp.</th>
<th>Total</th>
<th>Ranking</th>
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<td>Chopper roll</td>
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<td>3.5</td>
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4.4 INFLUENCE OF ENVIRONMENTAL VARIABLES ON FIRE BEHAVIOUR PARAMETERS

Identification of environmental variables that influenced fire behaviour most provides a better understanding of how successful the different slash treatments were as it gives an indication of which variables had a significant influence on fire behaviour. Fuel characteristics were altered in different ways by the various post-harvesting slash treatments. The altered status of fuels – for example, size and shape, elevation, fuel load and compaction – meant that weather variables also affected fuels differently, indirectly changing the fire behaviour.

4.4.1 Pearson correlation matrix of trial variables

Pearson correlation matrixes were compiled for both trials in order to investigate the interrelations between all variables recorded in the study (Tables 4.6 and 4.7). Within these tables the correlation coefficient (R) represents the correlation between a set of two variables. Correlations show both direction (positive or negative) and strength (how positive or negative). Only significant correlations have been indicated in the tables. These were marked to indicate the weight of p values as follows: *p ≤ 0.05; **p ≤ 0.03; ***p ≤ 0.001. Non-significant correlations
were omitted from the tables. It must be noted that the three dependant variables of fire behaviour had a positive correlation with one another and an increase in any of these variables had a similar effect on the other variables. A series of scatter-plot graphs (Figures 4.23–4.34) are referred to, in order to illustrate the significance of the correlations between the range of variables in both trials.
### Table 4.6: Pearson correlation matrix of *P. patula* trial variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>1h fuels (kg/m²)</th>
<th>10h fuels (kg/m²)</th>
<th>100h fuels (kg/m²)</th>
<th>1000h fuels (kg/m²)</th>
<th>Fuel bed depth (cm)</th>
<th>Fuel load (kg/m²)</th>
<th>Max. flame height (m)</th>
<th>Avg. flame height (m)</th>
<th>RoS (cm/min)</th>
<th>Fuel moisture (%)</th>
<th>Max. fire temp. (°C)</th>
<th>Avg. fire temp. (°C)</th>
<th>FDI</th>
<th>Air temp. (°C)</th>
<th>RH</th>
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<td>*<strong>0.780</strong></td>
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<tr>
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<tr>
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<td><strong>-0.561</strong></td>
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<td><strong>-0.556</strong></td>
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Marked correlations are significant at p < 0.05; N = 11 (R values)

*p < 0.05; **p < 0.03; ***p < 0.01

### Table 4.7: Pearson correlation matrix of *E. macarthurii* trial variables

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<th>Variables</th>
<th>1h fuels (kg/m²)</th>
<th>10h fuels (kg/m²)</th>
<th>100h fuels (kg/m²)</th>
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Marked correlations are significant at p < 0.05; N = 12 (R values)

*p < 0.05; **p < 0.03; ***p < 0.01
4.4.1.1 *P. patula* trial

Correlations for the *P. patula* trial are discussed in terms the dependant variables recorded (Table 4.6).

*Average and maximum flame heights:* A positive correlation exists between average and maximum flame heights to 10-hour, 100-hour and 1000-hour fuels, fuel-bed depth and fuel load. However, a negative correlation exists with an increase in fuel moisture. In the *P. patula* trial, the 1-hour fuels represented 8.7%, 10-hour fuels 34.2%, 100-hour fuels 21.7% and 1000-hour fuels 35.6% of the post-harvesting slash. Fine fuels ignite the fastest of all fuel classes and preheat the thicker fuel classes (Chandler, *et. al.*, 1983; Teie, 2005). The diameter of the 10-hour fuels ranged between 6mm and 25mm and ignited easily. Ten-hour fuels accounted for a third of the slash and would have had a positive correlation with flame height (Figure 4.6).

Figure 4.23 indicates a positive correlation between fuel-bed depth and flame height. An increase in the vertical distribution of fuels allows more oxygen for the combustion process, resulting in greater flame heights (Chandler, *et. al.*, 1983; Teie, 2005).

According to de Ronde, *et. al.* (1990), a higher fuel load, especially in woody fuels, facilitates a longer fire-residence time, resulting in a higher fire temperature with stronger heat convection and, thus, a positive correlation with flame height. This statement is reflected in Figure 4.24.

Fuels with higher fuel moisture take longer to preheat and need more heat to ignite (Chandler, *et. al.*, 1983; Teie, 2005). This was confirmed in this trial and fuel moisture had a negative correlation with flame height, as is indicated in Figure 4.25.
Figure 4.23: Correlation between average flame height and fuel-bed depth for \textit{P. patula} 
\(r = 0.906; \ p < 0.01\).

Figure 4.24: Correlation between average flame height and fuel loads for \textit{P. patula} 
\(r = 0.863; \ p < 0.01\).
RoS: - A positive correlation exists between RoS and 10-hour, 100-hour and 1000-hour fuels, fuel-bed depth, air temperature and fuel load. However, a negative RoS correlation exists with an increase in fuel moisture. Fuel ignites once it has been preheated (Ahlgren, 1974; Barrett, 1982; Teie, 2005). Therefore, the faster fuels preheat, the faster fire spreads. Fuel-bed depth, fuel load and fuel moisture had a significant influence on fire behaviour and their correlation with RoS is demonstrated in Figures 4.26 – 4.28 respectively. A higher air temperature also contributes to preheating fuels and will indirectly increase RoS (Chandler, et. al., 1983; Cheney, et. al., 1993).
Figure 4.26: Correlation between RoS and fuel bed depth for *P. patula* ($r = 0.863$; $p < 0.01$).

Figure 4.27: Correlation between RoS and fuel load for *P. patula* ($r = 0.834$; $p < 0.01$).
Figure 4.28: Correlation between RoS and fuel moisture for *P. patula* (r = −0.728; p < 0.01).

**Average and maximum fire temperature:** A positive correlation exists between average and maximum fire temperature and 100-hour and 1000-hour fuels, fuel-bed depth, air temperature and fuel load. However, a negative correlation exists with an increase in fuel moisture. The diameters of the 100-hour and 1000-hour fuel classes range upwards from 26mm and are regarded as coarse fuels (Teie, 2005). These fuels represented 57% of the total fuel load in the *P. patula* trial and would have had a longer combustion period than the thinner fuels. These fuels could therefore be expected to generate more heat than the fine fuels that were consumed at a fast rate by the fire (Barrett, 1982; Cheney, Gould, *et al.*, 2001; Post-harvest care, 1999).

Figures 4.29–4.31 confirm a significant positive correlation between fuel-bed depth and fuel load with fire temperature, as well as a negative correlation between fuel moisture and fire temperature.
Figure 4.29: Correlation between average temperature and fuel-bed depth for *P. patula* 
\( r = 0.575; p < 0.05 \).

Figure 4.30: Correlation between average temperature and fuel load for *P. patula* 
\( r = 0.705; p < 0.01 \).
Figure 4.31: Correlation between average temperature and fuel moisture for *P. patula*  
(r = –0.553; p < 0.05).

The one-hour fuels had no significant influence on any dependent variable. Although mulching changed the size of thicker fuels, it also compacted fuels and in the process reduced surface area exposed to pre-heating. The average RH on the day of burning for the *P. patula* trial was only 22% and therefore it can be expected that it did not have a significant influence on the one-hour fuels. Although wind is the weather variable which influences fire behaviour the most (Teie, 2005), on the day of burning, the average wind speed was very light at 5.3 km/h. This is regarded as being ideal for a safe slash burn. It is clear, however, that total fuel load, fuel-bed depth and fuel moisture had a significant influence on fire behaviour. Fuel moisture influences the flammability of fuels the most (Chandler, *et al.* 1983) and, as indicated in Figure 4.11, moisture retention in mulched fuels was significantly higher compared with other treatments. At the same time, mulching also changed the fuel-bed depth
and it can be assumed that it indirectly decreased the fuel load through accelerated decomposition.

4.4.1.2 E. macarthurii trial

Correlations for the E. macarthurii trial are discussed in terms the dependant variables recorded (Table 4.7).

Average and maximum flame height: - A positive correlation exists between average and maximum flame heights to 1-hour fuels, 10-hour fuels, 100-hour fuels and fuel-bed depth.

In the E. macarthurii trial, the 1-hour fuels represented 29.2%, 10-hour fuels 37.6%, 100-hour fuels 23.8% and 1000-hour fuels 9.4% of the post-harvesting slash. According to Chandler, et. al. (1983) and Teie (2005), fine fuels ignite fast and represented 66.8% of the post-harvesting slash in this trial (Figure 4.6). This was confirmed by the positive correlation of fine fuels to flame height in this trial.

An increase in the vertical distribution of fuels allows more oxygen for the combustion process, resulting in greater flame heights (Teie, 2005). Figure 4.32 indicates a positive correlation between fuel-bed depth and flame height.

RoS: - Ten-hour, 100-hour and 1000-hour fuels, fuel-bed depth, total fuel load and air temperature had a positive correlation with RoS and fuel moisture a negative correlation, but none of these correlations were statistically significant. The average wind speed during the burning operation was also lower than in the P. patula trial and therefore would have had a negative influence of RoS.
Average and maximum fire temperature: Hundred-hour fuels, fuel-bed depth and fuel load had a positive correlation with average and maximum fire temperature.

The diameters of the 100-hour fuel class range from 26 to 75mm and are regarded as a coarse fuel (Teie, 2005). Fuel moisture in the 100-hour fuels was probably lower than in the other fuel classes and could explain why this fuel class is the only one with a significant influence on the average fire temperature. This fuel would have been preheated by the finer fuel classes and generated more heat during combustion, as it would have had a longer fire-resident period (Barrett, 1982; Cheney, Gould, et al., 2001; Post-harvest care, 1999).

Figures 4.33 and 4.34 confirm a significant positive correlation between fuel-bed depth and fuel load with fire temperature. The low fuel moisture was of less significant influence than in the *P. patula* trial.
Figure 4.33: Correlation between average temperature and fuel-bed depth for *E. macarthurii* 
(\(r = 0.569; p < 0.05\)).

Figure 4.34: Correlation between average temperature and fuel load for *E. macarthurii* 
(\(r = 0.588; p < 0.05\)).
It was interesting to note that maximum temperature did not correlate positively with fuel load, but was correlated positively with one-hour fuels. A possible explanation for this could be the high percentage of fine woody fuels in this trial, with complete combustion and a longer fire-resident time compared with one-hour fuels in the *P. patula* trial. The specific gravity of *E. macarthurii* is 0.88 g/cm³ and that of *P. patula* is 0.54 g/cm³ (Table 3.2), which explains the higher fire-resident time in the former species (Banks, 1954).

The average RH on the day of burning the *E. macarthurii* was 47% and therefore would have influenced the 1-hour and 10-hour fuels. Table 4.7 indicates a significant negative correlation between air temperature and FDI with regard to fuel moisture. This confirms the findings of Teie (2005) and Gould, *et al.*, (2001). As mentioned above, these fuels represented 66.83% of the total fuel load and could have been expected to have had a more significant influence on fire behaviour with a lower RH.

A high fuel-moisture content in fine fuels will have an effect on the way fuels will ignite (Ahlgren, 1974; Barrett, 1982; Chandler, *et al.*, 1983; Cheney, Gould, *et al.*, 2001; Post-harvest care, 1999; Teie, 2005) and will cause a much slower RoS, flame height and fire temperature. The fuel moisture in 100-hour and 1000-hour would not have been influenced during a single day and would therefore probably have had a lower fuel-moisture percentage compared with the 1-hour and 10-hour fuels.

As in the case of the *P. patula* trial the wind had no significant influence on fire behaviour in the *E. macarthurii* trial, where the average wind speed was very light at 4.4 km/h. The fuel factors that had the most significant effect on fire behaviour were total fuel load and fuel-bed depth. As indicated in Figure 4.12, moisture retention in mulched fuels was significantly higher compared with other treatments. At the same time, mulching also changed the fuel-bed depth and indirectly decreased the fuel load through accelerated decomposition.
4.5 IMPLICATIONS FOR FIRE MANAGEMENT IN PLANTATIONS

The results of these trials should serve as guideline to forest managers to select the most effective slash-treatment method, as methods that cost less or hold less risk of runaway fires are often preferred. In both trials the windrow and inter-windrow treatments can be regarded as one treatment since windrowing cannot be done without creating an inter-row. However, utilizing post-harvesting slash as biofuels can be compared to the inter-windrow treatment. Results of the fire application to these trials, however, indicated that fire behaviour was the worst the windrow treatment. Flame height, RoS and fire temperature were the highest in this treatment. These results were confirmed by Rietz and Smith (2009) who found that fire damage in a three year old stand of *E. grandis* in the KZN Midlands was more severe in areas where post-harvesting slash was managed by windrowing when compared to broadcast and residue removal. They also found that tree growth in the areas where residue was removed was significantly less compared to that in broadcast and windrow areas.

In a Decision Analysis System (DAS) study conducted by Lindsley (2006) in the Kwambonambi area of KwaZulu Natal (KZN), a comparison of site preparation methods (mulching, windrowing, coppice reduction and burning), prior to re-establishment of a compartment, was compiled to determine which method/s would be most appropriate. Variables considered during the analysis included survival of new plants, ease of management, cost and fire risk. Lindsley (2006) found that plant survival was the most important factor considered by forest managers, followed by cost, fire risk and ease of management. He concluded that regardless of the importance of site sustainability and plant survival, burning was still the site-preparation method preferred by managers in KZN, followed by mulching. Burning post-harvesting slash on the sandy soils of KZN has a negative effect on both site sustainability as well as plant survival, but serves as a cheap fuel load manipulation method to reduce the risk of runaway fires (Lindsley, 2006). If foresters
still prefer burning as a method of slash management, the results of the trials described in this dissertation should assist them to decide upon a method that will reduce the risk of runaway fires and possibly maintain site sustainability and improve plant survival.

Benefits of retaining slash should be considered before using fire as the preferred slash-management method. Klockow, et. al. (2013) found that nutrients are concentrated in post-harvesting slash (leaves, twigs, bark, cambium and roots of trees) which are mostly volatised, leached or windblown in the case of burning (Du Toit, et. al. (2004). The soil of a forest ecosystem is one of its principal components and it may be that the short-term protection afforded by fuel-reduction burning could cause a long-term loss of productivity (Hall, 1986; Fernández and Botelho, 2003). Frandsen and Ryan (1986) found that soil in mulched areas that burned during wild fires was not degraded to the same extent as in other slash treatments, as the soil contained more moisture. Iles and Dosmann (1999) found that mineral soil covered by organic mulches was 6 °C cooler, contained 13% more moisture and had a higher pH when compared to their broadcast control. The results obtained by these authors support the results obtained in the study areas. Organic material in the mulched areas contained 26% more moisture in the *P. patula* trial and 4% more moisture in the *E. macarthurii* trial in comparison with the broadcasted plots. Benefits of retaining slash should therefore be considered before using fire as preferred slash management methods.

Fire behaviour measured in mulched plots indicated that it is an effective slash management method to reduce fire risk. According to Norris, (1994) better soil moisture results if slash is retained after post-harvesting operations. Burger and Pritchett (1984), states that an increased organic surface layer will improve various aspects of nutrient cycling as well as soil tilth. Where mechanized post-harvesting, site preparation and planting are used an increased organic surface layer will also act as a buffer against soil compaction (Rietz, and Smith, 2010; Glitzenstein, *et al.*, 2006).
According to Hacker (2005), decomposition rates are impacted by soil moisture, temperature, and other micro-site and microbial characteristics. In both trials it was found that the constant hot, humid conditions prior to applying fire to the treatment plots accelerated the decomposition of organic material. The tempo of decomposition also varied between treatments. There were signs of accelerated decomposition of organic material in mulched plots, which contained 60% less organic material in the *P. patula* trial and 50% less in the *E. macarthurii* trial when compared with the fuel loads of the broadcast treatments. At the time of burning only 75% of the original amount of fuel remained in the chopper-roll plots of the *P. patula* trial. This indicated that chopper-rolling was an effective treatment in the *P. patula* trial. If the scheduling of mulching is therefore planned correctly it could be effective to mitigate veldfire behaviour during the fire season.

Regrowth of herbaceous plants and annual grasses took place in both trials during the elapsed time between treatment and burning, but it was observed that plant regrowth was considerably less in the mulched areas. This observation corresponds with results obtained by Norris (1994). Mulching is also promoted as a slash-treatment method that suppresses weed growth (Forestry Solutions, 2011). It was noted that there was significantly more regrowth within the *E. macarthurii* trial than in the *P. patula* trial. This could possibly be as a result of the thicker litter layer in the latter trial.

The *E. macarthurii* trial contained 27% more 1-hour and 10-hour fuels than the *P. patula* trial and fuels therefore lost moisture faster. Fire managers should keep this in mind because fire behaviour parameters in fuels with a low fuel moisture percentage will be higher.

Although not measured, it was observed in both trials that consumption of mulched slash by the fire was less than slash in other treatments. Frandsen and Ryan (1986) found that combustion of the mulched organic material was not as complete as in the case of windrow treatments. This was confirmed by Glitzenstein, *et al.* (2006) who found that fire consumed
up to 50% organic material in a mulch trial conducted in post-harvesting slash, compared to 80% and upwards of slash in untreated plots. Smoke monitoring data in the same plots indicated a 60% reduction in smoke particulate production from mulched areas. They concluded that mechanical chipping appears to be a useful method for limiting fire-hazard and smoke production in long-unburned fuels.

Areas with moist soil will not only reduce fuel temperatures but release moisture to the litter layer causing it to burn and smoulder for a longer period. Heat output is low when the litter layer moisture content is high and only minimal soil heating results (Frandsen, 1989). Although temperatures (500 - 600° C) from smouldering organic matter are lower than that of flaming material (1000 - 1500° C), the longer duration of smouldering and the close proximity of organic matter to the soil may also result in greater heating of the soil, unless it is so moist that it restricts heat flow to the mineral soil (Frandsen and Ryan, 1986). Forest fuels that are mulched will have a high amount of smouldering in case of fire and therefore a long residence time that might damage soil if the soil is not moist enough.

Preferred slash-management methods therefore have to be assessed carefully to obtain maximum benefits.
CHAPTER 5
CONCLUSION

The objectives set out for this study have been achieved by addressing the effect of different methods of slash management and modified fuel classes on the fire-behaviour parameters within *P. patula* and *E. macarthurii* stands. Fire-behaviour variables fluctuated across post-harvesting slash treatments in terms of RoS, average and maximum fire temperatures and flame lengths. These also differ between *P. patula* and *E. macarthurii* stands. Fuel characteristics also varied across post-harvesting slash treatments in terms of fuel-class distribution, fuel-bed depth and fuel load and are different in *P. patula* and *E. macarthurii* stands. Fire behaviour variables measured within the *E.macarthurii* trial indicate that this species poses a greater fire hazard than *P. patula* in terms of RoS and fire temperature. It was evident that fire-behaviour conditions became more dangerous with a higher FDI, fuel load and fuel-bed depth and less dangerous with an increased fuel moisture content.

In the *P. patula* trial mulching of post-harvesting slash, followed by the inter-windrow was the most effective treatments to reduce all fire-behaviour parameters and windrowing the worst. In the *E. macarthurii* trial the inter-windrow post-harvesting slash treatment, followed by mulching was the most effective treatments to reduce all fire-behaviour parameters and windrowing the worst.

A higher average FDI in the *E. macarthurii* trial caused fire behaviour in this trial to be less predictable. The *E. macarthurii* trial contained more 1-h and 10-h fuels than the *P. patula* trial, resulting in faster exchange of fuel moisture with the atmosphere. Disregarding a higher RH in the *E. macarthurii* trial on the day of burning, average fuel moisture was lower than that in the *P. patula* trial, thus retention of fuel moisture in the *P. patula* trial was higher than that of the *E. macarthurii* trial. Other observations within the trials included lower fuel loads, less weed growth and less consumption of the fuel by fire in mulched plots.
Fuel characteristics (fuel moisture, fuel size and shape, fuel load and fuel-bed depth) were directly or indirectly influenced by the different methods of slash treatment and had a significant influence on fire behaviour. Preferred treatment methods of post-harvesting slash should therefore not only be considered in terms of cost and direct and indirect influence on fire behaviour, but also in terms of other factors such as weed suppression, post-harvesting slash decomposition and nutrient mineralisation brought about by specific slash-management treatments.

Sustainability of growing sites in commercial forestry remains a concern and more studies should be carried out to determine the long-term effect of different methods of slash management on these sites. At the same time, treatment cost and fire risk should be considered.

Should the trial be repeated, it will be important to select a period with uniform weather conditions for more accurate measurements. Studies in slash management should consider the direct and indirect effects of slash treatments, cost effectiveness of such treatments and the environmental impact, as well as the effect on sustainability of growing sites. Although the three replications used in this study were statistically significant, it is recommended that five replications be considered in order to validate the quality of results obtained.

It would have been ideal to attempt the burning of the trials under unfavourable weather conditions, as it is under these circumstances (dry, hot and windy) that damaging fires are experienced in forestry areas. In a winter burn, weather conditions are normally more homogenous for longer periods. A repeat of this study should be embarked upon under these circumstances, in a fire-risk situation that is more realistic.

This study contributes towards existing knowledge in terms of fire behaviour within different slash management treatments. The outcome of this study highlighted important implications for fire management in plantations. It therefore has the potential to contribute towards a
decision support system that will assist fire managers to select the optimum method of effective post-harvesting slash management while taking into consideration the conditions under which the specific plantation operates.


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**Personal communications**

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<tr>
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