Fuel load characterisation and quantification for the development of fuel models for *Pinus patula* in South Africa

By

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DECLARATION

I, the undersigned, hereby, declare that the work contained in this thesis is my own original work and that I have not previously in its entirety, or in any part, submitted it at any university for a degree.

Signature:

Date:

SUMMARY

The characteristics and total fuel load of the forest floor (FF) and harvest residue (HR) are needed to develop tools that can be used for fuel load management, fire risk analysis and fire behaviour prediction for *P. patula* grown in the summer rainfall area of South Africa (SA). Forest floor depth, mass and ash-free mass were measured and there was generally a greater range in depth under sawtimber (ST) stands than under pulpwood (PLP) stands. Forest floor loads, prior to ashing, ranged from 21 - 168 t ha^{-1} and 27 - 72 t ha^{-1}, for ST and PLP stands, respectively and loads increased linearly with stand age. Sawtimber and PLP stands were analysed together, which resulted in a significant correlation between depth and mass ($r^2 = 0.78$, $n = 31$). A loss on ignition procedure carried out on sub-samples of the FF improved the relationship between the FF depth and the ash-free mass for the different stands, and provided a more accurate model for the prediction of mass from depth. A multiple regression analysis revealed that age, altitude and mean annual precipitation (MAP) provided the best subset and accounted for 72% of the variation in the FF mass observed. The effect of increasing FF load and increasing moisture content on the fireline intensity (FLI) was examined using the fire behaviour prediction programme, BehavePlus.

Harvest residue was quantified and characterised in terms of fuel size classes, under current silvicultural regimes for ST and PLP, for the development of fuel models for this species over its planted range in SA. An investigation into the proportion (by mass) of the 1- (0.0 - 0.6 cm), 10- (0.6 – 2.5 cm), 100- (2.5 – 7.6 cm) and 1000-hr (> 7.6 cm diameter) fuel classes of the total HR mass indicated that there was a significant difference between the mass of the 1-, 10- and 1000-hr fuel classes of the two silvicultural regimes, and no significant difference for the 100-hr fuel class. Two fuel models for *P. patula* HR and two models for standing timber were developed using the new model (NEWMDL) programme of BEHAVE and tested in BehavePlus.

Nutrient concentrations were used with FF layer and HR size class load data to estimate the quantities of nutrients held in the fuel and to describe nutrient distributions in the fuel complex. Significant differences in the nutrient concentration of the FF layers and fuel components were observed which has important implications for fuel management. The concentration of N determined in this study, relative to that determined in other similar studies on *P. patula* was low. Forest floor loads were predicted and nutrient pools calculated for typical ST and PLP stands at both low and high altitude to provide insight into the nutrient distributions within the fuel complex.

OPSOMMING

Die karaktereienskappe en totale brandstoflading van die bosvloer (FF) en kaalkap oorskot (HR) word benodig om instrumente te ontwikkel wat gebruik kan word vir brandstoflading bestuur, brandgevaar ontleding en brandgedrag voorspelling vir *P. patula*, wat in die somer reënvalgebied van Suid-Afrika groei. Die bosvloer diepte, massa en asvrye massa is gemeet en daar was oor die algemeen ‘n groter variasie in diepte onder saaghout (ST) opstande as onder pulphout (PLP) opstande. Die bosvloerladings, voor verassing, het varieer van 21 – 168 t ha^{-1} en 27 – 72 t ha^{-1} vir ST en PLP opstande respektiwelik. Ladings het linieêr vermeerder met opstand ouderdom. Saaghout en PLP opstande is saam geanaliseer en het tot ‘n betekenisvolle korrelasie gelei tussen diepte en massa ($r^2 = 0.78$, n = 31). ‘n Verlies-tydens-ontbranding prosedure is uitgevoer op die FF monsters en het die verhouding tussen FF diepte en die asvrye massa van die verskillende opstande verbeter. Dit het ook gelei tot akkurater model vir die voorspelling van massa vanaf diepte. ‘n Veelvoudige regressie analise het aan die lig gebring dat ouderdom, hoogte en gemiddelde jaarlikse reënval (MAP) die beste sub-groep verskaf, en het 72% van die variasie in die FF massa verklaar. Ondersoek is ingestel op die effek van toenemende FF lading en toenemende voginhoud op die brandlyn intensiteit (FLI) deur die brandgedrag program, BehavePlus, toe te pas.

Die kaalkap oorskot is gekwantifiseer en gekarakteriseer volgens brandstof grootteklasse, onder die huidige boskultuurstelsels vir ST en PLP, vir die ontwikkeling van brandstofmodelle vir hierdie spesie oor die betrokke groeistreek in SA. ‘n Ondersoek in die verhouding (volgens massa) van die 1- (0.0 – 0.6 cm), 10- (0.6 – 2.5 cm), 100- (2.5 – 7.6 cm) en 1000-uur (> 7.6 cm deursnee) brandstofklasse van die totale HR massa het aangedui dat daar ‘n betekenisvolle verskil is tussen die massas van die 1-, 10- en 1000-uur brandstofklasse van die twee boskultuurstelsels, en geen betekenisvolle verskil vir die 100-uur brandstofklas nie. Twee brandstofmodelle is ontwikkel vir *P. patula* HR en twee modelle vir staande hout deur gebruik te maak van die nuwe model (NEWMDL) program van BEHAVE en getoets in BehavePlus.

Voedingstof konsentrasies is gebruik, tesame met die FF laag en HR klasgrootte ladingdata, om die voedingstof inhoud van die brandstof te skat en om die voedingstof verspreiding te beskryf in die brandstofkompleks. Betekenisvolle verskille is waargeneem in die voedingstof konsentrasies van die FF lae en brandstof komponente wat belangrike implikasies inhou vir brandstofbestuur. Die konsentrasie wat vir N in hierdie studie bepaal is, was laag relatief tot ander soortgelyke studies vir *P. patula*. Die bosvloer ladings is voorspel en voedingstofpoele bereken vir tipiese ST en PLP opstande vir beide lae en hoë hoogtes om insig te verkry, sodat insig verkry kon word in die voedingstof verspreidings binne die brandstofkompleks.

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LIST OF COMMONLY USED ABBREVIATIONS

ANOVA – Analysis of variance

CSA – Cross-sectional area

FF – Forest floor

FFs – Forest floors

FLI – Fireline intensity

HR – Harvest residue

hr – hour

LD – Forest floor depth

LMw – Weighed forest floor mass

Lmloi – Ash-free forest floor mass

MAP – Mean annual precipitation

PLP – Pulpwood

ROS - Rate of spread

SA – South Africa

SAV – Surface-to-area volume ratio

SD – Standard deviation

SE – Standard error

ST –Sawtimber

1. AIMS AND OBJECTIVES

Forest floors beneath *P. patula* plantations tend to be thick as needle production is high and decomposition occurs slowly due to inherent physiological and biological drivers present at growing sites. The factors that drive decomposition and that lead to a net accumulation of the FF are extremely complex and a host of factors have been correlated with litter production, decomposition and accumulation (Schutz, 1990). They can however be reduced to a few primary physiological and biological drivers that either directly affect these processes or influence other factors that indirectly affect them. The primary factors driving forest productivity are energy, water and nutrient supply (O'Connell and Sankaran, 1997). The rate of breakdown of the FF material is influenced by the physical and chemical nature of the litter, the aeration, temperature and moisture conditions of the FF and the kinds and numbers of the flora and fauna present (Pritchett and Fisher, 1987). These physiological and biological factors drive needle production, which affects litterfall and subsequent forest floor accumulation. Fast growth rates result in a high litter production rate that produces thick FFs consisting of needles, branches, twigs, bark, cones and strobili. Forest floor and HR loads realised from harvesting *P. patula* in South Africa (SA) have been reported as being amongst the highest in the world. The FF and additional residue from pruning, thinning and harvesting represent a fuel complex with a high fire potential (Goldammer, 1981). The factors affecting the build-up of the FF and HR load differ and, therefore, these two components of the fuel complex need to be separated and addressed separately. Fuel, consisting of a combination of the FF, prior to clearfelling, and the HR that is created as a result of clearfelling, also forms one of the most critical pools in the nutrient cycle of a plantation ecosystem. If these pools are depleted through mismanagement or as a result of natural occurrences such as wildfire, the results will not only affect the present stand, but also significantly influence the productivity of subsequent rotations. There is little quantitative data available pertaining to fuel loads on re-establishment sites in SA plantation forestry, and this limits effective fuel management, fuel load and fire behaviour prediction and the optimal attainment of management objectives. A method is required to allow management to quantify fuel loads in terms of available fuel, nutrient pools and estimate fire behaviour and risk and thus, allow for the effective implementation of the most suitable fuel management strategy for a particular site and quantify the impacts of a prescribed burn or wildfire on a particular site. The overall aim of this study was to quantify and characterise the fuel load in terms of fuel classes, across a range of rotation age pulpwood (PLP) and sawtimber (ST) sites for fuel management in SA and quantify nutrient pools in the fuel. To address the main aim efficiently, it was split into six objectives:

- To summarise, from existing studies, the effect of physiological and biological drivers of litter production, decomposition and resulting net accumulation;

- To quantify and predict the FF loads based on a number of these drivers and characterise them in terms of nutrient pools and fuel load properties across a range of sites;
- To quantify and characterise the fuel load, fuel size classes, using the line intersect sampling method;
- To summarise the effect of silvicultural regimes and harvesting techniques on fuel and fuel load properties and the fuel by individual fuel classes remaining on the site as well as scenarios of nutrient removal;
- To develop fuel models for *P. patula* fuel in SA;
- To lay the foundation for the development of a photo series as a practical guide to fuel assessment and management in SA.

2. LITERATURE REVIEW

Pinus patula is generally considered to be the biggest problem species in SA and southern Africa with regard to FF accumulation; nutrient lock-up and heavy HR loads after harvesting (Allan and Higgs, 2000; Allan *et al.*, 2001; Morris, 1986; Schutz, 1990). Much research has been conducted on litterfall, accumulation, and decomposition in *P. patula* plantations, as well as problems resulting from re-establishing sites previously planted to this species. Most of this work has been done in SA (Bosch, 1985; Carlson and Allan, 2001; Dames, 1996; Schutz, 1990) and in Swaziland (Evans, 1974, 1975; Germishuizen, 1979; Morris, 1986), although some studies have been done in Tanzania (Lundgren, 1978) and India (Singh, 1982). Little work has been done on characterising the fuel in terms of fuel load and nutrient pools and how this would affect, and be affected by, burning. In other countries, the characterisation of fuel loads has played an important part in the forest industry for several decades and is still considered to be an essential activity in managing productivity, and fire risk, in both natural and planted forests (Brown *et al.,* 1982, 1970, 1974; Burrows, 1980; Catchpole and Wheeler, 1992; De Ronde, 1988; Gove *et al.*, 2002; Hazard and Pickford, 1977; Howard, 1973, 1978, 1981; Johansen *et al.*, 1977; Johansen and McNab, 1977; O'Hehir and Leech, 1997; Ringvall and Ståhl, 1999; Roussopoulos and Johnson, 1973; Snell and Brown, 1980; Tolhurst, 2000; Trollope *et al*., 2004; van Wagner, 1968, 1982a; Valentine *et al.*, 2001; Warren and Olsen, 1964).

A review of the literature has revealed numerous studies documenting the negative effects of wildfire and burning on the long-term sustainability of plantations (Germishuizen, 1979; Morris, 1986, Norris, 1993). Other studies have found no negative long-term effects of fuel burning on the growth and nutrient content of a site (De Ronde, 1988, 1992a; McKee, 1982). The effects of fire on site fertility are difficult to determine, but are highly dependent on the fire intensity and period of fire exposure (fire residence time) (Bird, 2001; De Ronde, 1990; Geldenhuys *et al*., 2004). Some sites are very sensitive to fire, both prescribed burning and wildfire with associated nutrient loss. However, there are less sensitive sites where burning may be a viable option. Prescribed burning is an important tool for fuel management and in reducing wildfire risk. It is one of the cheapest means of reducing the fuel load and, is also considered to be environmentally acceptable if it is carried out in a 'controlled' manner, given certain conditions. Practical recommendations are needed for sites where burning can be practised in a responsible manner and for those sites where it should be avoided. On the latter, alternative fuel management strategies need to be implemented. In order to provide these recommendations and guidelines, more information is required on the effect of the fuel load on fire behaviour and the effect of different intensity fires on the nutrient pools of the site.

2.1 FOREST FLOOR

2.1.1 Forest floor loads

Schutz (1990) noted that FF loads under *P. patula* in the Mpumalanga escarpment (MPUE) region of SA are amongst the heaviest in the world. Litter accumulates at high altitude as a result of the imbalance between the rate of litter production, inputs, and rate of decomposition or output of nutrients experienced on these sites (Dames, 1996), resulting in the immobilisation of nutrients and reduced productivity, often through the advent of catastrophic wildfires. **Photograph 2.1** shows a 24 cm deep FF layer in the MPUE region.

Photograph 2.1: Heavy forest floor accumulation (24 cm) under a *P. patula* ST stand, Sabie, 2003.

2.1.2 Forest floor classification

In *P. patula* plantations, live needles remain on the branches for approximately 24 months, with definite seasonal trends (Morris, 1986; Dames, 1996), and become incorporated into the FF. Forest floor horizons are stratified into L, F and H layers (Fisher and Binkley, 1987; Schutz, 1990). The upper layer is the L, or litter layer, which consists of, unaltered dead plant and animal remains. The second layer is the F, or fermentation layer consisting of partly decomposed organic materials. These materials are sufficiently well preserved to allow for identification as to their origin. The third layer is the H or humus layer, which lies directly beneath the F layer and comprises largely of well-decomposed, amorphous organic matter

(Barney *et al.*, 1981; Schutz, 1990). The H layer is often not recognised because it has a friable crumb structure and contains considerable mineral materials (Pritchett and Fisher, 1987). These three layers are not always discernable under *P. patula* in SA. The presence or absence of these layers also differs in PLP and ST stands, with the layers more discernible in the thicker FFs, and appears to be greatly influenced by factors such as region, lithology, altitude and several other factors that will be discussed in detail in this chapter. It is often extremely difficult to separate the decomposed H layer from the mineral soil. During the collection of FF samples, this results in contamination with a high percentage of mineral soil, resulting in predicted fuel loads being higher than in reality. For this reason, FF loads in this study have been expressed on an 'ash-free' mass basis in an attempt to provide greater accuracy in predicting FF loads. **Figure 2.1** shows the structure of the FF as classified in this study and summarises the most important characteristics of each layer.

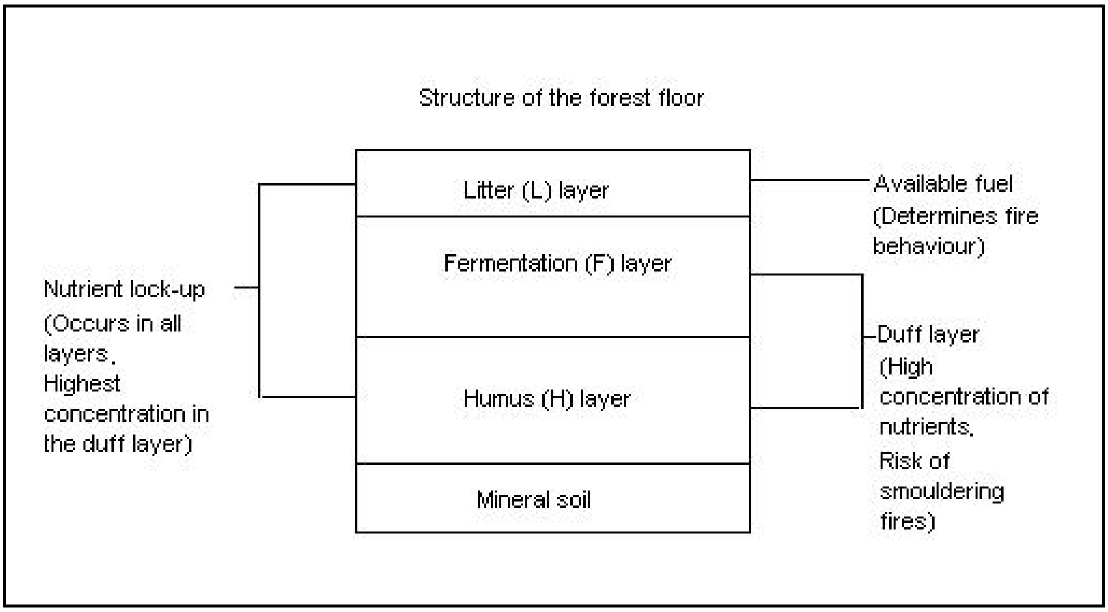

Figure 2.1: Structure (by layer) of the forest floor.

Accumulation at high altitude often results in the formation of a 'mor' layer. A 'mor' layer occurs when the rate of decomposition is low, and it is characterised by a clear distinction between the soil and the FF (**Photograph 2.1**). The 'mor' layer can be easily separated from the soil and can be further subdivided into layers or horizons (Attiwill and Leeper, 1987). This layer is often very distinct, but at other times it may be less so, and in these cases it may be better defined as a 'mull'. A 'mull' layer occurs when there is no clear distinction between the FF and the soil. In this study the distinction was generally clear except when the soil was wet or in stands where there was less accumulation. According to the definition of a 'mor', which results from a low decomposition rate, sites that show no distinct boundary between the litter and the soil might indicate areas where the decomposition rate is normal. Two different types of 'mor' layers have been identified beneath pine plantations in SA. 'Humimor' layers have a very thin L and F layer and a very thick H layer. This type of ‘mor’ is more typical of the southern Cape plantations. ‘Fibrimor’ layers have thicker L and F layers and almost no H layer. The boundary between the L and F layer is also sometimes unclear and the F layer changes gradually into the H layer forming a layer that is also known as the FH layer. This type of ‘mor’ layer better describes the conditions found beneath *P. patula* plantations (De Ronde, 2003). **Figure 2.2** shows examples of a ‘Humimor’ and a ’Fibrimor’ layer, the latter of which are found in this study.

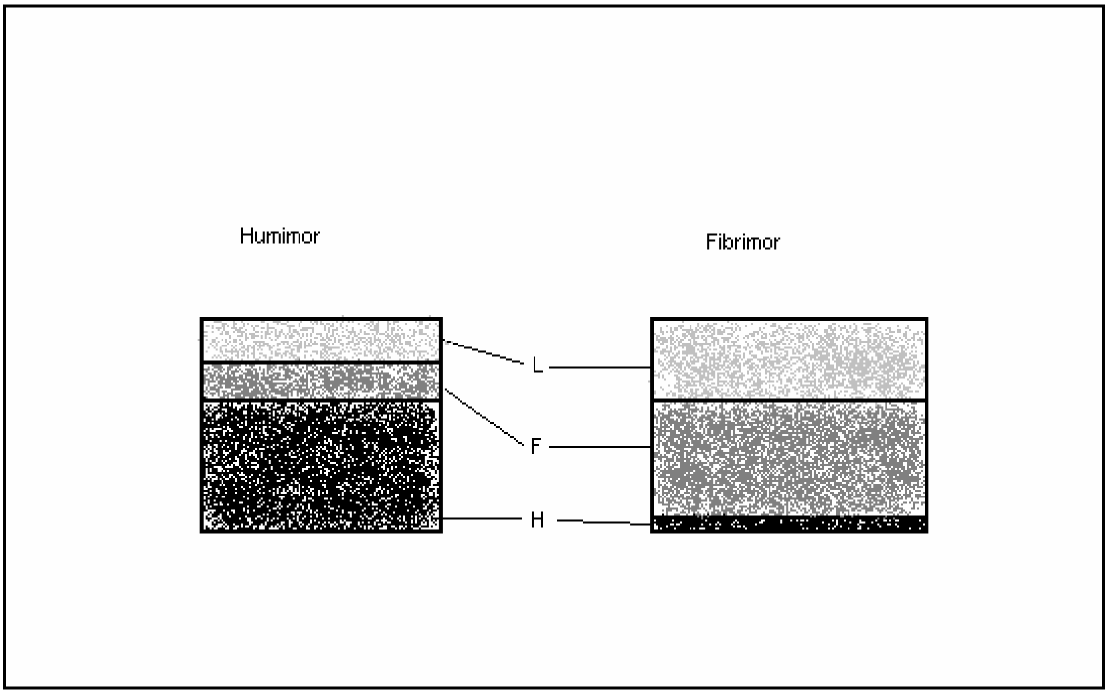

Figure 2.2: Different types of ‘mor’ layers that exist in SA pine plantations showing the relative thickness of the different layers (De Ronde, 2003, pers. comm.[1]).

2.1.3 Positive and negative aspects of the forest floor

Litter should be viewed as a valuable feature of forest ecosystems as it is responsible for the regulation of most of the functional processes occurring in the system, such as the release and return to the soil of nutrients metabolised by microorganisms. It should be managed properly as it can have long-term impacts on the productivity of the site (Carlson and Allan, 2001). Positive aspects of the FF include its role in nutrient retention and supply. Valuable nutrients are stored therein and it can be used to enhance the moisture content of sites, protect soils from erosion and frost, and in the long term, make soils more resilient to site degradation. Litter also provides energy and nutrients for a host of heterotrophic organisms (Allan *et al.*, 2001; Dames, 1996; Little *et al.*, 1996; Schutz, 1990). Forest floor layers also assist in keeping weed growth to a minimum in mature stands. The presence of litter in

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[1] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

unburned stands may prevent the germination and growth weeds (van den Berg and Little, 2003). Prescribed burning reduces FF loads but often stimulates weed growth (especially for those species relying on the by-products of fire to break dormancy), which are then free to grow unhindered beneath the canopy or on a re-establishment site, often resulting in greater fire danger than existed before such an operation was carried out (Little *et al.*, 1996; Potgieter, 2003). A list of weed species recorded after under-canopy prescribed burning in a ST stand in the Mpumalanga Highveld region is given in **Table 2.1**.

Table 2.1: List of weeds recorded after prescribed burning in ST stands in the Mpumalanga Highveld region (Van den Beg and Little, 2003).

Woody	Herbaceous broadleaves	Grasses	Other species
Pine regeneration	*Bidens pilosa*	grass sp.	sedge sp.
Acacia mearnsii	*Conyza sumatrensis*		*Senecio* sp.
Phytolacca octandra	*Senecio polyanthemoides*		*Diospyros lycioides*
Solanum mauritianum			*Hypochoeris radicata*
			Cheilanthes viridis
			Pygmaeothamnus sp.
			Rhus dentate

Van den Berg and Little (2003) found that the highest percentage weed cover, density and biomass occurred on sites that had received a high intensity prescribed burn, followed by medium, low and no-burn treatments. Woody weeds accounted for 37% of the vegetation, of which 65 % was pine regeneration, contributing 60 plants m^{-2} for the high-burn treatment. The percentage cover of herbaceous broadleaves and grasses was low in comparison. The highest biomass was recorded in the high-burn treatment with a mean mass of 1017 kg ha^{-1} (van den Berg and Little, 2003).

The FF can become a threat to productivity when it accumulates and nutrients become immobilised. This process of immobilisation and accumulation is a feature of cool, high-altitude sites in southern Africa (Dames, 1996; Morris, 1986; Schutz, 1990). The amount of nutrients that become immobilised in the FF greatly affects the long-term sustainability and productivity of a plantation (Madgwick *et al.*, 1977; Santana *et al.*, 2000). Thick FF layers are potentially harmful for a number of other reasons. Penetration of water to underlying soil is reduced, nutrients are tied up in the FF in a form, which may be unavailable for use by trees, and the release of organic acids accelerates podsolisation in coarse-textured soils (Schutz *et al.*, 1983). Not only does FF build-up result in immobilisation of nutrients during the rotation, but thick FF layers combined with HR form heavy fuel mats and hamper access and silvicultural activities in successive rotations and the development of a fuel load, which increases fire risk (Allan *et al.*, 2001; Schutz *et al.*, 1983). The most extensive threat to the long-term productivity of plantations is the excessive immobilisation of nutrients in the FF. The release of nutrients through mineralisation processes from organic material has important implications for management. Morris (1986) associated a decline in ten-year-old; second rotation *P. patula* stands in Swaziland to the increased immobilisation of nitrogen (N), phosphorous (P) and possibly calcium (Ca) in the FF. Nutrient concentrations between first and second rotation PLP stands did not differ significantly but calcium (Ca), magnesium (Mg) and potassium (K) concentrations were found to be lower on second rotation sites (Morris, 1986). This trend will continue with successive rotations leading to nutrient deficiencies, unless measures are taken that result in the release of ‘locked-up’ nutrients back into the soil. Large amounts of nutrients accumulate in the FF (particularly N) and these amounts become much larger than the available nutrients in the topsoil as the FF accumulates (particularly in the case of P and Ca). Dames (1996) recorded large reserves of N (1442 kg ha^{-1}) and P (103 kg ha^{-1}) in the FF and Schutz (1990) recorded 1045 to 2994 kg ha^{-1} of N. Comparisons are shown in **Table 2.2**. Phosphorous, calcium (Ca), sodium (Na), sulphur (S) and manganese (Mn) are retained in the FF whereas N, K, Mg and zinc (Zn) are not retained as strongly with K being the least retained (Morris, 1986; Schutz, 1990).

2.1.4 Nutrient pools and cycling in the forest floor

Ecologically sustainable forest management requires an understanding of the effect of forest operations on the supply of resources that drive growth (du Toit and Scholes, 2002). Biogeochemical nutrient cycling is dominated by litter production and decomposition (O’Connel and Sankaran, 1997) which are driven by incoming radiation (light), the carbon dioxide concentration of the atmosphere, temperature and soil water, nutrient availability and the presence of decomposer organisms (Fisher and Binkley, 2000). Sustainable silviculture also requires the retention of nutrients for successive rotations, and patterns of nutrient release through immobilisation and mineralisation processes have important management implications (Bird and Scholes, 2002a). The FF forms one of the most critical nutrient pools in the forest ecosystem and the key to maintaining the productivity of plantations is through the proper management of these pools.

Table 2.2: Estimated nutrient content (kg ha^{-1}) of the forest floor under first rotation *P. patula* stands.

Age (yrs)	Altitude (m)	N	P	K	Ca	Mg	Author
		kg ha^{-1}					
10	all	498	27	30	72	34	Morris (1986)
17	1150	557	30	34	81	38	
17	1450	1036	55	63	150	71	
5-30 (18)*	950-1771 (1224)*	1442	103				Dames (1996)
29-47 (38)*	912-1984 (1380)*	1045-2994	130-381	82-218	229-272		Schutz (1990)

* - Mean

Nutrient cycling in forest ecosystems is often represented diagrammatically as pools and fluxes indicating inputs, storage pools and outputs (input-output budget) (Fisher and Binkley, 2000; Binkley, 1986). Nutrients enter the nutrient cycle via two main pathways: Firstly, atmospheric inputs which include: those dissolved in rainfall, dry deposition, occult deposition and orographic deposition and secondly, through the weathering of primary rock minerals. Other inputs into the system include inputs of elements in solutions, biological inputs, nitrogen fixation, and direct foliar absorption of nitrogen (du Toit and Scholes, 2002; Ranger and Turpault, 1999). A third, less significant pathway is often followed through the manual addition of nutrients into the system at planting or at some other point during the rotation. The total input of nutrients from these sources over a rotation is significant but a direct estimate of inputs from specific sources is difficult to achieve.

Nutrients are removed from the system by two main pathways: firstly, by losses associated with deep drainage during the rotation and during the regeneration phase, and secondly through losses associated with biomass removals such as harvesting. Other outputs from the system include outputs of elements in solutions, N-gaseous losses due to denitrification and volatilisation due to high intensity fires, erosion losses and losses from the soil via decomposition and leaching (Gresham, 1982; Morris, 1986; Ranger and Turpault, 1999). Nutrients are also being continuously recycled within the system. Re-translocation of nutrients takes place in the crown between new growth and senescent foliage and nutrients released through the decomposition of litterfall are taken up into the tree through the roots. The rate of nutrient cycling is indirectly influenced by the nutrient content of the litter as this, impacts directly on microbial activity, which is a primary driver of decomposition. Accumulation depends on an imbalance of ecosystem processes and the absence of disturbances such as fire or harvesting operations (Hendrikson, 1987 cited by Carlson and Allan, 2001; Norris, 1993). The nature of the FF and the biota of this layer and the underlying soil are of critical importance in decomposition and nutrient cycling (Spain, 1975). This is because a substantial proportion of the organic matter and certain plant nutrient elements contained within the forest system may reside therein for varying amounts of time.

Nutrient uptake by a stand is influenced by several factors, which include the stand density, the growth rate, climate, soil properties and the efficiency of the nutrient uptake processes of the tree (Carlson and Allan, 2001). When trees are harvested and removed, or when high intensity prescribed burning is applied to reduce excessive fuel loads or a wildfire burns through a stand, the nutrient status of the site is altered, perhaps even permanently if the disturbance is large enough, a good example being unchecked wildfires (De Ronde, 1992b; Hough, 1981). The effects of fire on site fertility are highly dependent on the fire intensity and period of fire exposure (fire residence time) (Bird, 2001; De Ronde, 1990, 1992a; Geldenhuys *et al*., 2004). Repeated low-intensity fires result in the acceleration of nutrient cycling within the system, wheras high intensity fires oxidise large quantities of nutrients such as nitrogen (Fisher and Binkley, 2000). Allan *et al*. (2001) found that burning tended to make more cations available on the exchange complex of the soil due to the high cation content of the ash. De Ronde (1992b) reported that N levels between burned and unburned areas were significantly different but some values increased while others decreased on a burnt site in Nyalazi and Dukuduku State forests. These differences in the N responses to fire are difficult to explain are related to soil type. Soils with a high clay percentage are less susceptible to N loss than sandy soils (De Ronde, 1990). Disturbances, such as harvesting and burning act as primary drivers and cause acceleration of the transfer of nutrients from forests to the atmosphere and streams through a number of processes (Adams and Attiwill, 1991). Harvesting and re-establishment practices result in an export of nutrients from the system in the form of logs and through smoke losses associated with fuel burning, increased leaching and erosion (Morris, 1986). Prescribed, low-intensity burns are an important method of fuel load reduction and site preparation. More information is required as to the immediate ‘downstream’ effects of different fire intensities on a site as well as on the long-term site stability and sustainability. Before this can be achieved, nutrient pools in FFs and HR need to be quantified and understood. A number of local studies have measured the nutrient content of the various layers of the FFs formed beneath *P. patula* stands. Nutrient concentrations of the FF layers from a number of studies conducted in southern Africa are provided in **Table 2.3**.

Table 2.3: The mean and standard deviation of the nutrient concentrations (%) of the forest floor.

	N	P	Ca	Mg	K	Na	Author
	(%)						
mean	1.14	0.05	0.07	0.05	0.06	0.01	Carlson and Allan (2001)
SD[1]	0.15	0.01	0.04	0.02	0.03	0.00	
L Layer	1.29	0.07	0.32	0.15	0.10	not determined	Morris (1986)
F Layer	1.32	0.07	0.15	0.08	0.07		
mean	1.28	0.16	0.28	0.08	0.10	0.06	Schutz (1990)
SD[1]	0.16	0.14	0.22	0.05	0.05	0.01	
mean	1.64	0.08	not determined				Dames (1996)

[1] SD = standard deviation.

The N concentrations are all relatively similar but there are large variations in all the studies with regard to P, Ca, Mg, K and Na. The nutrient concentration values provided by Morris (1986) translate into relatively large nutrient pools, particularly with respect to N. Values are given for a layer of mean thickness and for the maximum thickness recorded by Schutz (1990) in **Table 2.2**. The estimated nutrient content (kg ha^{-1}) in the FF under first rotation *P. patula* stands at different ages for high and low altitudes (Morris, 1986) is also given in **Table 2.2**.

2.1.5 Factors affecting litter production and forest floor decomposition

Resource availability determines a number of primary physiological and biological drivers of litter production and decomposition (Dames, 1996; Morris, 1982; Olson, 1963; Schutz, 1990). The primary factors driving forest productivity are energy, water and nutrient supply (O'Connell and Sankaran, 1997). The rate of breakdown of the FF material is influenced by the physical and chemical nature of the litter, the aeration, temperature and moisture conditions of the FF and the kinds and numbers of the flora and fauna present (Pritchett and Fisher, 1987). Post *et al.* (1985) report that the amount of N stored in the soil is related to climate through biotic processes associated with the productivity of the vegetation and decomposition of organic matter. Decomposition rates are primarily driven by biological factors that affect the microbial population present on the site. Other factores such as fire, acid rain and management practices may affect the composition of the microbial population. Breakdown of FF layers is largely dependant on the soil and FF micro flora and fauna. Where there is a limited amount of or lack of these organisms, accumulation of the lower FF layers (F and H) results (De Ronde, 1988). Schutz (1990) grouped the factors affecting FF decomposition into three broad classes: i) site factors, ii) stand factors and iii) litter properties (substrate quality) however these are all "surrogates" for the afore-mentioned primary drivers.

Within the FF, decomposition takes place through the action of bacteria, fungi and a variety of macro-, meso- and microfauna. The rate of the breakdown of organic matter by soil microbes depends on several factors including: the chemical quality of the material (litter quality), the availability of energy sources to fuel the microbes, the activities of meso- and microfauna, and environmental conditions (Fisher and Binkley, 2000). Changes in microbial activity are linked to biological factors such as temperature, moisture, the quality of the litter and acidic conditions in FF layers of high altitude stands (Dames, 1996; Morris, 1993). Carey *et al.* (1982) ascribe the decomposition of organic matter to (1) microclimate of the FF, (2) the soil on which the FF develops and (3) the physical and chemical composition of the litter. Dames (1996) noted that litter in high altitude stands of varying ages (5 to 30 years) decomposed slower than low altitude stands of the same age, but that decomposition was not significantly correlated with either stand age or altitude.

The role of species in affecting FF depth is clearly evident. Forest floor layers under stands of *P. patula* are more variable and of a greater thickness than those found under other commercially planted species in the same area. Undecomposed FF layers, 15 cm or thicker were found on almost a quarter of sites sampled by Schutz (1990) under *P. patula* ST in the MPUE region. Forest floor depths for *P. patula* recorded in some other SA studies range from 10 to 121 cm (Dames 1996; Schutz, 1990). Average depths for other species planted on similar sites were 3 to 13 cm under *P. taeda* and 3 to 14 cm under *P. elliottii* (Schutz, 1990).

2.1.5.1 Stand age and management

The litter production rate for *P. patula* plantations increases rapidly with age to canopy closure, which, for *P. patula* is 4 to 5 years, where after it decreases. Forest floor accumulation also increases to canopy closure, where after it continues to increase, but at a slower rate or remains relatively constant (Bray and Gorman, 1964; Morris, 1986; Poynton, 1980). Morris (1993) found that the FF mass approached equilibrium of 40 t ha^{-1} after age 10 years for *P. patula* when planted at lower (1150 m a.s.l.) altitudes. The FF mass of high altitude stands however, accumulated steadily up to 34 years of age. This was confirmed by Dames (1996) who found the decrease in litter production to start at 10 years for low altitude (below 1200 m a.s.l.) sites and at 15 years for high altitude (above 1200 m a.s.l.) sites, and recorded an annual litter production rate of between 3.64 and 5.89 t ha^{-1} yr^{-1}, respectively. Litter production patterns in ST stands can be altered by silvicultural practices such as thinning. Compartments are thinned at around 5 to 8 years and again at 15 to 18 years, which will have an effect on litter production and could contribute to this decline. Morris (1992) noted that litter production increased up to 10 years in *P. patula* stands grown for PLP, and thereafter remained constant.

Studies by Lundgren (1978) show a fairly rapid increase in the mass of the FF up to 25 t ha^{-1} at 10 years followed by a more gradual increase up to 40 t ha^{-1} at 30 years. Equilibrium between litter fall and decomposition was recorded after 20 years in *P. echinata* stands in the eastern USA by Johansen *et al*. (1977). An average total litterfall rate after canopy closure for *P. elliottii* in the south eastern United States of 4.5 t ha^{-1} yr^{-1} was recorded by Gholz *et al*. (1985). The authors also noted an increase in litterfall with stand age to canopy closure at 15-16 years, with a decline in older stands. Gresham (1982) recorded a total annual litterfall rate of 7.8 t ha^{-1} yr^{-1} for *P. taeda* in coastal South Carolina in the United States. This then suggests that if pruning, thinning and clearfelling regimes were altered, it would have a significant influence on the depth of the FF. Schutz *et al*. (1983) found that stand density appeared to have no significant influence on FF depth or on the development of thick layers under *P. patula* in high altitude stands in Mpumalanga (MPU). This is due to the fact that crown biomass is equivalent over all stand densities once canopy closure has taken place. Forest floor depth was found to be uniform under closely spaced stands but more variable in widely spaced stands, being thickest around the base of trees.

2.1.5.2 Temperature

Within a given latitude, altitude can be considered as a surrogate for temperature, with biological processes being inhibited by lower temperatures (Schutz, 1990). Net accumulation of litter in *P. patula* is strongly correlated with altitude (temperature) and there are a number of factors that vary with elevation that can be linked to slower decomposition at high altitudes. High altitude sites experience cooler temperatures, mist and an increase in rainfall amount and frequency (Dames, 1996). Temperature decreases by approximately 0.6°C per 100 m increase in altitude (Lundgren, 1978). Greater FF accumulation at higher altitudes is a result of the slower decomposition that takes place on these sites (Morris, 1986). Forest floor decomposition is strongly positively correlated to temperature. Microorganisms are sensitive to low temperature and therefore, microbial activity is reduced at high altitudes. Increased temperatures stimulate microbial growth, provided that there is sufficient moisture. The activity of microorganisms responsible for FF decomposition is therefore, strongly dependent on favourable environmental conditions (Dames, 1996).

Greater accumulation results from differences in decomposition rates rather than a difference in the litterfall rate (Dames, 1996; Morris, 1993). Morris (1986) found that the FF mass increases by 0.4 t ha^{-1} yr^{-1} at 1150 m a.s.l and by 5.8 t ha^{-1} yr^{-1} at 1450 m a.s.l for *P. patula* stands aged between 10 to 30 years. Average litterfall rates for exotic plantations have been reported at 6.4 t ha^{-1} yr^{-1} (Morris, 1986). All masses given refer to the oven-dry mass in tons per hectare. Dames (1996) reported litterfall rates of between 2 and 8 t ha^{-1} yr^{-1} for both low and high altitude *P. patula* stands between the ages of 5 to 30 years in the Mpumalanga Escarpment region. These masses are given as the loss on ignition masses in tons per hectare. Loss on ignition mass includes only the organic fraction of the FF and excludes the mineral fraction. Net FF accumulation tends to increase with an increase in site productivity (Brown and See, 1981; Shanks and Olson, 1961). Site index influences microorganism activity and ultimately, FF breakdown. Morris (1986) concluded that there is a significant correlation between site index and altitude (temperature) with site index decreasing with elevation and that litter production is highest in stands with a high site index for *P. patula* PLP in the Usutu forest in Swaziland. Schutz (1990) however found that there was an inverse relationship between site index and FF depth for three different pine species growing in the MPUE region.

2.1.5.3 Moisture availability

Rainfall influences decomposition by maintaining the moisture content of the FF at a particular level, which sustains microbial activity. Rainfall also affects the activity of microorganisms by influencing the aeration and temperature of the FF. Higher rainfall reduces the aeration of the FF and by doing so, inhibits biological processes from taking place. The amount of rainfall reaching the FF is influenced by the amount of interception that occurs, which, in turn, is influenced by the leaf area index (LAI) of the stand. In pines the LAI, and thus the interception, is relatively high. The number of rainfall events rather than the total amount of rainfall is better correlated with decomposition. This indicates that regular moderate rainfall is more favourable than a small number of heavy rainfall events with longer dry periods in between, which may lead to temporary FF dryness (Post *et al.*, 1985, 1996; Vanlauwe, 1995).

2.1.5.4 Substrate quality

The quality of the litter that forms the FF influences the patterns of nutrient release from this layer. The quality of the litter is detrermined by the amount of readily available substrate and the C:N ratio. Readiliy available substrates such as starch will decompose faster than less available substrates such as lignin (Attiwill and Leeper, 1987; Nambiar and Brown, 1997). This means that even litter from some N-fixing species, such as acacias, will decompose slowly due to the high lignin content of the litter material (Nambiar and Bromn, 1997). The slow decomposition of litter has been correlated with a high C:N ratio and immobilisation of N occurring in litter with C:N ratios of > 30:1 Dames (1996). High quality litter (low carbon C:N ratio) results in the rapid decomposition and N release, whereas low quality litter (high C:N ratio) leads to N becoming locked-up followed by slow release (Bird and Scholes, 2002a). The L layer has a higher C:N ratio than the F and H layers derived from it (Dames (1996). As litter decomposes, easily decomposed material disappears and N is immobilised in microbial biomass and decay products. This leaves behind more recalcitrant material with slower decomposition rates and lower C:N ratios. Dames (1996) reported that the N and P concentrations increase and that the C:N ratio decreases with stand age which indicates that litter quality improves. The decrease in the C:N ratio is slowed by those factors that slow the decay rate, namely high lignin: N ratios, cool temperatures and poor soil aeration due to high moisture levels (Post *et al.*, 1985).

2.1.5.5 Needle production

Litter production is dependent on needle production, crown biomass and the availability of growth resources (Dickinson *et al.*, 1974 cited by Dames, 1996). It is also determined by the longevity of the needles, which is dependent on species and on climatic factors and events such as drought. Needles are produced during the growing season and older, senescent needles die and are dropped to the FF where they decompose and form humus (De Ronde, 1988). Litter production rates may vary according to site (Pritchett, 1979; Singh, 1982). Litter production also varies in relation to latitude, litter production decreases with increasing distance from the equator (Bray and Gorman, 1964). However, extremely thick FF layers have been recorded in high-altitude *P. patula* stands in the Mpumalanga Escarpment area of SA (Schutz, 1982, 1990). This is due mostly to policies of fire exclusion in the management of fuel generated from clearfelling and shorter rotation crops, which leads to the development of thick FF layers in older plantations at higher altitudes. The rate of development of the FF in coniferous forests has been shown to increase with the litter production rate up until the point of canopy closure. The rate of accumulation slows after canopy closure but continues to increase slowly over the whole rotation (Morris, 1986). In a balanced system decomposition equals the rate of litter production (De Ronde, 1988). Bray and Gorman (1964) have reported that the rate of FF accumulation reaches a steady state at canopy closure and remains constant thereafter.

2.1.6 Net effect of production and decomposition

The amount and character of the FF depends largely on the decomposition rate of the organic debris (Pritchett and Fisher, 1987). Litter generally accumulates where environments are cool, wet and where there has been little mixing by soil fauna (Fisher and Binkley, 2000). Accumulation on the FF is largely a function of the annual amount of litter fall minus the annual rate of decomposition. Although many environmental factors determine the rate of decomposition, the rate of litterfall is remarkably uniform among tree species growing under similar soil and climatic conditions (Johansen *et al.*, 1977; Pritchett and Fisher, 1987). If the seasonality of litterfall is out of phase with the seasonality of decomposition, litter may accumulate at a certain time of the year (De Ronde, 1988). Forest floor accumulation is influenced not only by the annual rate of decomposition but also by the age of the floor or the elapsed time since the last fire or other disturbance (Pritchett and Fisher, 1987). *P. patula* as a species has a heavy crown and has been shown to produce some of the heaviest FF loads for this species anywhere in the world as indicated in **Table 2.4** below.

2.1.7 Predicting forest floor loading

A good prediction of FF depth can be determined by combining a number of site and stand factors, the most important being: available resources, temperature, moisture and substrate quality. These can be represented by easily obtainable or measurable “surrogates” such as site index, altitude and age (Dames, 1996; Morris, 1986; Schutz, 1990). These factors are “surrogates” for the primary physiological and biological drivers of litter production and decomposition. Site index is a “surrogate” for growth resource availability. Models for FF load prediction are useful for determining where FF accumulation is, or has the potential to become a problem, and highlighting those stands where litter management should be implemented. Stands with FF loads below 70 t ha^{-1} at clearfelling age are still manageable for economic re-establishment. Once the FF load exceeds this level, it should be reduced before the stand is re-established (De Ronde, 1984). Forest floor mass increases with stand age, however, the range in mass also increases with age. This suggests that other factors play a role in determining the rate of accumulation. Temperature (altitude, slope position), available moisture (rainfall, site index, mean annual increment, basal area) and stand age are all determinants of FF mass and therefore, all have to be taken into account when developing models to predict litter mass. Because of the complex nature of the factors affecting FF depth, it is difficult to extrapolate these models over large areas. Morris (1993) examined altitude, slope position, site index, stand age, basal area and height as predictors of FF mass and found that age and altitude (temperature) provided the best correlation. Information regarding the FF is absolutely necessary in evaluating the effects of fire, either wildfire or prescribed burning. Improvements in fire behaviour prediction and fire management have resulted in the need for more information regarding the FF as a fuel component (Barney *et al*., 1981).

Table 2.4: Forest floor mass (t ha^{-1}) recorded under a range of fast growing pine plantations (Morris, 1995).

Species	Country	Age (yrs)	Mass (t ha^{-1})	Author
P. patula	SA	Mature	102	Von Christen (1964)
P. patula	SA	Mature	320	Schutz (1982)
P. patula	SA	44	217	Schutz *et al.* (1983)
P. patula	India	12-34	21-70	Singh (1982)
P. patula	Tanzania	10-30	25-35	Lundgren (1978)
P. patula	Swaziland	12-14	44 (1st rotation)	Morris (1986)
			60 (2nd rotation)	
P. radiata	Australia	30-40	16-28	Florence and Lamb (1974)
P. radiata	Australia	12	17	Forrest and Ovington (1970)
P. radiata	Australia	12	23	Williams (1976)
P. radiata	South Africa	37	7	Versfeld (1981)
"Southern"	U.S.A.	4-11	5-6	Nemeth (1973)
P. elliottii	U.S.A.	34	41	Gohlz and Fisher (1982)
P. elliottii	Australia	14-19	13-20	Maggs (1988)
P. sylvestris	Britain	23-35	13-110	Ovington (1962)
P. caribaea	Nigeria	10	4	Enjunjobi and Onweluzo (1979)

2.2 Harvest residue

Harvest residue is seen as an additional source of raw material, nutrients, energy, a fire hazard, habitat for pests and diseases, a control of soil erosion and an inhibitor to re-establishment (Timson, 1980; Welch, 1978). Harvest residue that results from clearfelling can augment already thick FF layers, particularly if a fire exclusion policy is implemented. The portion of the fuel that can be burnt during a prescribed burn will differ considerably depending on the management decision taken. The ratio of fine to large fuel differs greatly depending on the silvicultural regime being followed. The impact of HR on nutrient availability and future silvicultural and harvesting activities requires consideration in the development of management strategies (Bird and Scholes, 2002a). An understanding of the nature and amount of HR left on a site is important in the management of prescribed burning operations and seedling mortality associated with re-establishment into high HR loads. A nutrient analysis of the HR components provides further insight into the impacts of management practices on sustainability (Carlson and Allan, 2001; Welch, 1978).

2.2.1 Effect of silvicultural regime on harvest residue loading

The volume of HR varies greatly by product, species and dbh, and different silvicultural management regimes can have profound effects on tree biomass at clearfelling (Carlson and Allan 2001; Kiil, 1965; Welch, 1978). Factors affecting HR loading include species choice, rotation length, initial stocking and the timing and intensity of pruning and thinning operations. Other factors such as fertiliser application, site preparation and weed control have an indirect effect by reducing factors that limit growth.

Photograph 2.2 and **Photograph 2.3** show a comparison of the appearance and distribution of a PLP and a ST compartments fuel load. The fuel generated from the PLP regime is made up of a greater proportion of smaller branches and is much deeper. The ST fuel contains a higher proportion of larger branches and the fuel load is therefore much more compact. The fuel loads of the PLP and ST compartments were 74.6 and 68.5 t ha^{-1} respectively.

Photograph 2.2: Pulpwood harvest residue, KwaZulu-Natal Midlands.

Photograph 2.3: Sawtimber harvest residue, KwaZulu-Natal Midlands.

2.2.2 Aboveground biomass of *P. patula*

Harvest residue is produced from three parts of the tree: i) the crown, which is made up of foliage and branches, ii) tops, and iii) defective and broken stems. The ratio of these three parts is affected by several factors which include site and stand factors as well as those brought about by different management scenarios (**Photograph 2.2** and **Photograph 2.3**). Stands produced for PLP or ST exhibit noticeably different ratios of the three parts of the tree and this has a large influence on the fuel load of the site. The proportion of the different fuels present on the site significantly influences fire intensity and behaviour. The total amount of HR that remains on the site after harvesting is the sum of the residue prior to harvesting (FF, pruning and thinning residue, in the case of a ST regime) and the HR, which is produced from clearfelling operations, which contains a much greater proportion of branches, tops and broken and defective stems. It is important to consider the spatial variation and the ratios of the different biomass components that are left after a clearfelling operation, in order to estimate the total fuel load (litter plus HR). Once the fuel load and fuel load ratios are known, the total nutrient content of the fuel complex can be calculated, giving insight into nutrient pools within the fuel. Knowledge of the fuel quantity and characteristics are extremely important for management for a number of reasons, namely: fire risk and behaviour assessment, site preparation and re-establishment issues and nutrient management issues, for harvesting system and re-establishment impact assessment, as it will impact on the amount of nutrients remaining on, or being exported from the site (Carlson and Allan, 2001;

Miller *et al.,* 1985). Biomass estimates are also essential for fuel load and fire modelling as the amount; make-up and spatial distribution of the fuel largely determine fire behaviour on the site. Factors such as species, dbh, stand condition; stand density and accuracy of the cruise data affect the biomass per tree. This figure can vary substantially within individual stands and therefore affects the accuracy of predictions (Snell and Brown, 1980).

Ratios of the volume of material left on the site, to the volume of products removed are required by source of material and product (Welch, 1978). Stems often break during the felling process, particularly if felling takes place downhill on steep terrain. Broken stems and stems with defects are much more difficult to predict than the weights of crowns and tops. Lees (1969) found that the diameter at the point of break (dpb) was related to the dbh and that the volume of timber above the dpb was approximately 14%-21% of the total stem volume (with the mean being around 14%) for *P. radiata* grown in New Zealand. This value is comparable with that of Snell and Brown (1980) who estimated the percentage of broken stems remaining on the site to be 15% of the cruised utilisable volume in Pacific north-west old-growth stands in the USA. Birk (1993) found that up to 27% (360 t ha^{-1}) of the total aboveground biomass, of a number of 21 year-old *P. radiata* stands in New Zealand, was made up of branches and unmerchantable stemwood. Bosch (1985) found that the proportion of branches in a mature *P. patula* ST stand accounted for 14% of the total aboveground biomass. Studies on *P. patula* in southern Africa have shown that about 71 to 81% of the biomass is removed from the site for ST and PLP respectively. These figures as well as some other studies on different pine species in other parts of the world are listed in**Table 2.5**. Stemwood generally forms the greatest portion (63%) and, of the residue left on the site, the secondary branches contribute the greatest to the overall mass, followed by smaller branches (Carlson and Allan, 2001). These figures compare well with those determined by Lees (1969) who recorded that the volume of sawlogs removed from a site averaged 72% of the total stem volume for *P. radiata* in New Zealand. Lundgren (1978) determined that for *P. patula* in Tanzania, the stem (including the wood and bark) makes up 63% of the stand biomass in mature, 22 year-old stands.

Table 2.5: Biomass removed from the site compared with that remaining, under current harvesting practices, for *P. patula* and *P. radiata*.

Species	Area	Biomass removed (%)	Biomass remaining (%)	Author
P. patula	Mpumalanga	71	29	Carlson and Allan (2001)
P. patula	Swaziland	83	17	Germishuizen (1979)
P. radiata	New Zealand	81	19	Birk (1993)

A summary of comparisons of the total above ground dry biomass (t ha^{-1}) components for an individual tree in a number of different studies involving *P. patula* conducted in southern Africa and internationally is given in **Table 2.6**.

Table 2.6: Total above ground dry biomass (t ha^{-1}) components for various studies conducted on *P. patula*.

Age (yrs)	Total Biomass (t ha^{-1})	Stem Wood (t ha^{-1})	Stem Bark (t ha^{-1})	Branches (t ha^{-1})	Cones (t ha^{-1})	Needle Mass (t ha^{-1})	Litter (t ha^{-1})	Author
				Live				
29	161.5	102.99 (63.8%)	14.50 (9.0%)	24.49 (15.2%)	1.9	7.54 (4.7%)	54.1	Carlson *et al*. (2001)
5	310.2	125.0	6.9	21.0	-	14.3	143.0	Dames (1996)
19	266.4	184.6	14.0	18.4	-	7.2	-	Morris (1995)
21	247.6	175.1	14.7	15.0	-	3.8	-	
21-34	164.9	128.5	8.2	14.3	-	4.7	-	Bosch (1985)
17-19	268.0	215.9 (80%)	14.4 (5.3%)	11.6 (4.3%)	-	5.7 (2.1%)	-	Germishuizen (1979)
25	192.2	168.6		19.9	0.5	3.1	18.8	Singh (1982)
34	381.3	324.7		39.0	6.7	10.9	23.2	
15		0.6	0.1	0.1		0.1		Du Plooy (1978)

2.2.3 Nutrient pools and cycling in the biomass

An analysis of the nutrients contained in different biomass components and the rate of uptake provide important information for understanding nutrient cycles and the impact of management practices on the site. The needle material is the most nutrient rich portion of the biomass and for most nutrients, the concentration in the biomass component decreases in the following order: needles > secondary branches > stem bark > main branches > dead branches > stemwood (Carlson and Allan, 2001). Birk (1993) found that both N and P were evenly distributed between the stem and the crown components for 21 year-old *P. radiata* in New Zealand. Under current harvesting practices for pine in SA, only the stemwood and bark are removed from the site, leaving the needles, secondary branches, main branches and dead branches on the site. Nutrients can remain in these components for varying lengths of time depending on the fuel management policies followed. Burning constitutes a rapid release or ‘flush’ of nutrients back into the system with some associated loss.

The mass of nutrients (kg ha^{-1}) contained in the biomass of a number pine species from southern Africa and around the world are given in **Table 2.7** along with the total biomass present on the site (t ha^{-1}). This table indicates that the macronutrient pools determined in the biomass for *P. patula* are higher than for any other species. The mass of N in the biomass of *P. patula* is considerably higher than that of other species although this is linked to the higher total biomass values.

Table 2.8 provides a comparison of the concentration (%) values of nutrients present in the live and dead branches of *P. patula* and *P. nigra*. The nutrient content remains fairly constant between live and dead branches for all nutrients except K, which has a much higher concentration in the live branches, indicating the leacing of this nutrient from dead branches. Knowing the amount of nutrients that are contained in the live and dead branches, which make up the HR is important for making the appropriate fuel management decision as this could ultimately determine the quantity of nutrients available for the following rotation. Although these values are much lower than those found in the FF, they still make a significant contribution to the total nutrient pool contained within the biomass.

Table 2.7: Biomass and selected nutrient pools of a range of pine forests (Morris, 1986).

Species	Age (yrs)	Country	Biomass (t ha^{-1})	N	P	K	Ca	Mg	Author
				(kg ha^{-1})					
P. patula	10	Tanzania	299	1057	96	506	622	194	1
P. patula	19	Swaziland	238	331	18	165	223	94	2
P. patula	20	Tanzania	535	1672	153	828	955	289	1
P. patula	25	India	192	967	158	234	966	119	3
P. patula	30	Tanzania	780	2315	212	1161	1279	397	1
P. radiata	12	New Zealand	166	346	31	295	176	74	4
P. radiata	15	Australia	162	370	43	297	220	84	5
P. radiata	26	New Zealand	222	221	28	224	130		6
P. radiata	29	New Zealand	425	434	66	464	333	102	7
P. caribaea	10	Nigeria	185	509	25	328	249	102	8
P. caribaea	6	Brazil	66	197	33	46	78	25	9
P. taeda	10	USA	28	85	10	49	33	10	10
P. taeda	15	USA	63	140	16	82	62	17	10
P. taeda	20	USA	90	174	19	99	91	24	10
P. nigra	20	Scotland	88	209	28	139	111	35	11
P. nigra	40	Scotland	180	321	43	202	217	59	11
P. nigra	60	Scotland	240	374	48	232	252	74	11
P. nigra	80	Scotland	295	404	51	250	325	84	11

1-Lundgren (1978); 2-Germishuizen (1979); 3-Singh (1982); 4-Will (1964); 5-Stewart *et al.,* (1981); 6-Orman and Will (1960); 7-Webber and Madgwick (1983); 8-Egunjobi and Bada (1979); 9-Chijioke (1980); 10-Switzer and Nelson (1972); 11-Mill *et al.,* (1980).

Table 2.8: Concentrations (%) of oven-dry weight, of N, P, K, Ca and Mg in live and dead branches.

Species		Element					Author
		N	P	K	Ca	Mg	
		Dead branches					
P. nigra		0.20	0.02	0.05	0.29	0.06	Miller *et al.* (1985)
P. patula		0.13	0.00	0.01	0.09	0.02	Germishuizen (1979)
P. patula	mean	0.18	0.02	0.01	0.14	0.04	Morris (1986; 1992)
	std	0.07	0.01	0.00	0.04	0.01	
		Live branches					
P. nigra		0.22-0.34	0.03	0.17-0.20	0.3-0.37	0.06-0.06	Miller *et al.* (1985)
P. patula	mean	0.05	0.02	0.28	0.05	0.34	Dames (1996)
	std						
P. patula	mean	0.28	0.04	0.25	0.14	0.07	Morris (1986; 1992)
	std	0.05	0.02	0.09	0.05	0.03	
P. patula		0.30	0.02	0.18	0.17	0.06	Germishuizen (1979)

2.2.4 Nutrient budgets

The continued productivity of a plantation over successive rotations requires that nutrient losses be balanced by inputs (Morris, 1986). Forest floor and HR accumulation result in immobilisation of nutrients, and therefore no returns to the soil. The FF contains large reserves of nutrients, particularly N and P. The retention of nutrients for successive rotations is an important aspect of sustainable silviculture (Bird and Scholes, 2002a). Knowledge of the nutrient content of fuel components is essential for the consideration of different management options that can result in the removal of nutrients from the site (Hendrickson, 1987). Nutrients are lost from the system through harvesting, wildfire and re-establishment practices such as burning (Adams and Attiwill, 1991). High intensity prescribed under-canopy burning is seldom experienced, but HR burning after clear felling provides medium to high intensity fires with a longer residence time (De Ronde, 2004, pers. comm.[2]). Removal in logs and loss through high intensity prescribed burning or wildfires after clear felling are important pathways of nutrient output from the site. Harvest logs account for the largest removal of K off a site (Morris, 1986). If nutrients are not replaced, be it through fertilisation or natural deposition, they will become limiting to long-term growth. It is important to determine the amount of nutrients that are lost from a site through management practices in order to improve or at least maintain the current levels of site productivity in SA. Knowledge of nutrient losses from prescribed burns of different intensities would allow for burns with minimal adverse impact on ecosystem nutrient status to be implemented (Feller, 1988).

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[2] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

Nutrient losses depend to some extent on FF depth and the resulting depth of the burn and N loss was found to be directly proportional to FF consumption (Little and Ohmann, 1988).

Fahey *et al*. (1991) report that in conventional tree-length harvesting, the majority of the HR, if it is not burnt, is broadcast and left on the site where it contributes to the nutrition of the next rotation. These nutrients are either leached off the site, or become available for uptake by the next rotation or are retained in the logging residue. Harvesting has been shown to increase the rate of mineralisation taking place in the FF. The process of mineralisation transforms considerable amounts of organic-N to more mobile forms (Adams and Attiwill, 1991). Morris (1986, 1992) reported a range of potential annual nutrient export (kg ha^{-1}) in harvest logs from *P. patula* sites in Swaziland. These losses, although significant, are relatively small when compared with the amount of nutrients taken up by a stand during the rotation.

Fire causes a loss of nutrients to the atmosphere through five processes: oxidation of compounds to gaseous form, vaporisation of compounds that were solid at normal temperatures, convection of ash particles in fire generated winds, leaching of ions in solution out of the soil and accelerated erosion following a fire (Feller, 1988; Fisher and Binkley 2000). Ash contains large quantities of highly soluble nutrients but losses through leaching following clearfelling are small compared to log removal and burning losses (Morris, 1986). Ash remaining on a site after burning contains large quantities of highly soluble nutrients, which are easily leached from the site. Germishuizen (1979) recorded an erosion loss of 16 t ha^{-1} in one rainy season on a recently clearfelled site in Swaziland. Burning of fuel prior to re-establishing a clearfelled area is still a common practice in many plantations (Morris, 1986; Norris, 1992, Potgieter, 2003; personal observation, 2003). Nutrient loss depends on the amount of fuel burnt, i.e. the fuel load, fuel type, on the nature and moisture content of the fuel and on climatic conditions (Attiwill and Leeper, 1987; Fahey *et al*., 1991). Fires result in a reduction in ecosystem biomass, a potential loss of nutrients through various processes and increases in the availability of N and P (De Ronde, 1992a; 1992b). Large quantities of N and P are lost from a site by burning (up to 100% of N is lost from burnt fuels depending on the intensity of the fire). Fire may also increase the concentrations of soluble Ca, Mg and K in soil and then these nutrients become susceptible to leaching (Dyck *et al*., 1981). In particular, P availability has been shown to increase temporarilay after fire (De Ronde, 1992a; Fisher and Binkley, 2000). Feller (1988) found that nutrient losses (g/m^2) decreased in the order: N>Ca>S>K>Mg>P>Na, for different species studied in Canada. Particulate matter losses are smallest for low intensity fires and losses can be minimised by minimising FF and HR fuel consumption during burning (Fahey *et al*., 1991, Morris, 1986). Uptake and mineralisation of N has also found to be increased through burning (Adams and Attiwill, 1991). Nutrient losses increase with an increase in the mass of material consumed. This is attributed to the greater fire intensity and fuel consumption that occurs with increased fuel loads (Little and Ohmann, 1988; Fisher and Binkley, 2000). The ability to predict nutrient loss from burning allows managers to implement a prescribed burn that has minimal negative impacts on the nutrient status of the site (Fahey *et al*., 1991; Feller, 1988). A range of atmospheric losses resulting from burning of fuel after clearfelling for a number of species, listed by Morris (1986), is presented in **Table 2.9**.

2.2.5 Fuel

The effects and management of fuel have received much attention in plantation forestry. Fuel is defined as a complex consisting of a combination of litter (leaves, bark, twigs, and reproductive organs) and HR (branches and whole stems) (Attiwill and Leeper, 1987; Brown, 1974). It is important for fire, as a habitat for insects, carbon storage and as a potential source of energy (Nalder *et al*., 1997). Positive aspects of fuel include its role in nutrient retention and supply and it therefore acts as a major source of nutrients to the stand (Carlson and Allan, 2001; Morris, 1982). Quantities of nutrients retained in the fuel can constitute a significant proportion of the total accumulation in organic material above the soil surface (Little *et al*., 1996; Singh, 1982). It is the recycling of the nutrients contained in the fuel that is a key to maintaining the long-term productivity of plantation ecosystems (Gresham, 1982; Schutz, 1990).

Table 2.9: Nutrient export in harvest logs and nutrients taken up by a stand over the rotation for *P. patula*, and atmospheric losses resulting from fuel burning after clearfelling for various species (kg ha^{-1}) (Morris, 1986).

N	P	K	Ca	Mg
10.2-15.1$^{(1)}$	0.5-2.8$^{(1)}$	4.1-9.4$^{(1)}$	6.5-9.2$^{(1)}$	2.2-3.9$^{(1)}$
331-2315$^{(2)}$	18-212$^{(2)}$	165-1161$^{(2)}$	223-1279$^{(2)}$	94-397$^{(2)}$
106-220$^{(3)}$	6-10$^{(3)}$	5-21$^{(3)}$	100-123$^{(3)}$	13-37$^{(3)}$

1 – Nutrient export in *P. patula* harvest logs
2 – Nutrients taken up by *P. patula* over the rotation
3 – Nutrient loss due to burning different species fuel after clearfelling

Fuel, created by harvesting and thinning operations, constitutes a serious fire risk and causes problems during re-establishment. It negatively affects the growth of seedlings by changing the microclimate and providing a habitat for insect pests (Albini and Brown, 1978; Allan, 1999; Allan and Higgs, 2000; Allan *et al.*, 2001; Carlson and Allan, 2001). The presence of fuel, particularly in the case of *P. patula*, is regarded as a hindrance to re-establishment as it affects planting and other follow-up silvicultural activities by increasing the labour required and making access to the stand extremely difficult (Allan *et al*., 2001). It also represents a fuel complex that greatly enhances the risk and intensity of runaway wildfires occurring on a clearfelled site and spreading to neighbouring compartments.

Knowledge of the distribution, amount and size characteristics of fuel is applicable to fuel load estimation for fuel burning operations and for fire danger prediction (Brown, 1970, 1974; Carlson and Allan, 2001). Should a hot fire occur, burning can result in the loss of nutrients, particularly N, through oxidation and volatilisation. Burning also leads to leaching, erosion losses and the alteration of soil chemical properties (Allan *et al.*, 2001; Attiwill and Leeper, 1987; Germishuizen, 1979; Morris, 1986). Such losses are difficult to determine since they depend on numerous factors, which include the amount of fuel burnt, spatial variation, fuel load and weather conditions (Attiwill and Leeper, 1987).

2.2.6 Negative effects of high fuel loads

There is evidence available from a number of studies to both support, and dispute, the negative effect of heavy fuel loads on seedling survival. High fuel loads do not provide a favourable microclimate (increased temperatures at ground level due to low heat exchange lead to seedling stress and increased susceptibility to insect attack) for the survival and growth of young trees planted in summer (Allan *et al*., 1997; Allan *et al*., 2001). A recent study by Rolando and Little (2004) reported significantly higher temperatures at ground level within planting pits than under surrounding slash. High slash loads create a heat sink within planting pits and reduce heat exchange. The fuel load-microclimate interaction is a complex one. Increased temperature and low heat exchange lead to seedlings becoming stressed and more susceptible to fungal and insect attack. In areas that generally have high wind (such as Zululand), heat exchange and increased ground temperatures are not a problem but seedlings are more susceptible to sand blasting (Little *et al*., 1996).

Although this is often the case, there is also evidence to suggest that the microclimate surrounding the seedling is in fact enhanced in the presence of fuel. High fuel loads tend to reduce soil temperatures and exposure to high air temperatures and wind, resulting in lower evaporation rates. Another factor influencing the initial tree survival and growth in fuel is the quality of pitting and planting operations, which is directly affected by the quantity of fuel present (Allan *et al*., 2001). The poor survival of seedlings encountered when they are planted into areas of high fuel loads therefore, has more to do with the quality of the planting pits themselves, than with the microclimate effects created by the fuel. Survival in fuel may be reduced by as much as 25% when compared to survival in areas where no fuel is present. Fuel may also be used as a breeding ground for *Hylastes angustatus* (Allan, 1997; Allan and Higgs, 2000; Allan *et al.*, 2001). Higher mortality rates experienced in areas with high fuel loads have generally been attributed to fungal and insect attack. A reduction in the quantity or physical height of the fuel was found to decrease the negative effect of fuel on survival (Allan and Higgs, 2000; Allan *et al*., 2001). Survival and growth can be improved by removing or crushing the fuel prior to establishment (Allan, 1999). Allan *et al.* (2001) found that seedling survival was lower in a burn (‘cool’ burn) treatment than for a chopper-rolled treatment, which, in turn was less than a broadcast treatment, which, had the best survival. Allan and Carlson (1998) however found that poor survival and early growth of seedlings was evident when seedlings were planted following a severe wildfire and dry weather conditions prior to planting. Norris *et al*. (1995) found that in the first year of growth, trees growing on burnt plots initially performed better than those growing on plots where the fuel had been broadcast, although the difference was minimal. Superior growth was attributed to the rapid release of nutrients from burning but as the fuel on the broadcast plot decomposed the trend reversed, with the benefits derived from retaining fuel becoming influential. In a second fuel management experiment, Norris *et al.* (1995) recorded little difference in height between trees growing in different fuel treatment plots. Although burning results in a nutrient 'flush', a "hot" burn may also result in the loss of a large proportion of the nutrients present in the fuel, the effects of which may only become noticeable much later in the rotation or even only in the next rotation.

2.2.7 Harvest residue as fuel

The ability to predict fire behaviour is important in silviculture, however, very little has been done in this field in plantation forestry in SA. Fire behaviour prediction for use in prescribed burning has been important in the U.S.A, Canada and Australia for a number of years (De Ronde, 1988). Fuel loads can be predicted in terms of fuel characteristics to determine the risk, behaviour and intensity of prescribed burns and wildfire. Hot prescribed burns and wildfires after harvesting result from high fuel loads and may lead to a fire spreading to neighbouring compartments. The organic matter content, bulk density and moisture content of the fuel components determine the temperatures attained during a burning operation (Catchpole and Wheeler, 1992). Fire behaviour depends largely on the physical properties of the fuel components, with the type, amount and condition of the fuel present on a site being critical to fire management (Teie, 2003). Knowledge of the volume and surface area of the fuel load is required for fire research and management operations (Brown, 1971). This information is also applicable to fuel load estimation for prescribed burning operations (Carlson and Allan, 2001).

2.2.8 Factors affecting fire behaviour

Fire behaviour is defined as the manner in which fuel ignites, flames develop and fire spreads and exhibits other phenomena (Luke and McArthur, 1977). There are three primary factors that affect fire behaviour, namely: fuel, weather and topography. The only factor that can be manipulated in any way is the fuel and it is therefore important to manage fuel in order to reduce the risk of uncontrolled fires (Tolhurst, 2000). Fire behaviour depends to a large extent on the physical properties of individual and collective fuel components. The amount of fuel, and its structure and arrangement are the most important factors affecting fire behaviour (Luke and McArthur, 1977). Fuel loads are highly variable within and between sites and species with regard to type and condition. The intensity and duration of a fire is related to the characteristics of the fuels and fuel moisture (Barney *et al.*, 1981). Fuel parameters, along with topographic and readily available, up-to-date weather information are a prerequisite for fire behaviour prediction and knowledge of the volume and surface area of a fuel complex is important from a management perspective. By measuring the depth of the fuel present on a site and then converting this measurement into a fuel load an accurate prediction of fire behaviour can be generated. However, it is not only the amount of fuel present that affects fire behaviour but also the height and packing of the fuel. Fuel depth is more important to the rate of spread (ROS) and flame height than the fuel load alone. Fuel load is important in determining the amount of heat generated by a fire and knowledge of the structure of the fuel provides further insight into the ROS and flame height of the fire (Tolhurst, 2000).

Knowledge of the kind, volume and surface area of a fuel complex is essential for effective fire management. Knowing the size of fuel materials present is important because fine fuel is critical to fire behaviour (Brown, 1970; Roussopoulos and Johnson, 1973). Fuels can be divided into three levels according to where they occur: ground, surface or crown fuels. Each fuel level impacts on the ease of ignition and the combustibility of the fuels. Surface fuels, consisting of grass; litter and fuel up to 2 meters in height are usually where fires start and are responsible for the spread of the fire and for carrying the fire to aerial fuels (Teie, 2003).

2.2.8.1 Fuel size and shape

Fuel size has a great influence on fire risk and behaviour and therefore, information regarding loading of live and dead material by size class is very important for effective management. Assuming all other factors such as sufficient oxygen are in place, the ease of ignition depends on the fuel thickness or diameter (Luke and McArthur, 1977). The size of the fuel load components is related to fire duration and amount of heating of the FF (Kiil, 1965; McNab *et al.*, 1978). The surface area to volume (SAV) relationship is the ratio of the surface area of fuel components to their volumes. The finer the fuel, the higher its ratio, the more quickly it will release its moisture and less heat will be required to ignite it. Large fuels such as logs have a low ratio and release moisture slowly; more heat is therefore required to ignite such fuels and to sustain combustion. Small diameter fuels ignite and burn readily, while heavier fuels require more heat to ignite and thereafter burn more slowly and often incompletely. Heavier fuels cannot be ignited unless fine fuels are present (Luke and McArthur, 1977).

The size and shape of fuels also determines how much spotting will occur and over what distances. Spotting results from fire brands being lifted by convected heat and then carried downwind into new fuels (Teie, 2003). Small fuels have a short spotting range as they burn out quickly. Shape is also an important factor and flat fuels are able to remain airborne for longer periods and can therefore spot over greater distances. Fine fuel is defined as that part of the fuel complex that burns in the flaming zone at the fire and determines how fast the fire will spread and what the height of the flames will be. It may be live (< 2 mm diameter) or dead (< 6 mm diameter) and consists of needles, bark and small branches. Fine fuel hazard can be effectively estimated by the direct measurement of the fuel quantity or by measuring or estimating the depth of the litter layer.

2.2.8.2 Fuel load

Fuel load is the dry weight of a fuel in a given area, expressed as mass per unit area (usually t ha^{-1}) (Luke and McArthur, 1977). The quantity of fuel present on a given site is influenced by a number of site and stand characteristics as well as the management practices implemented on the site. Silvicultural regimes and harvesting operations all greatly influence the size and distribution of the fuel load across a site. Total fuel loading may be extremely high but not all of the fuel present on the site may be able to support a fire, for example, large diameter logs. It is the fuel that is most readily subjected to burning that is the most important for fire management. These are live 1-hr fuels and dead 1-, 10-, and 100-hr fuels (Teie, 2003). Fuel classes that are used in fire behaviour prediction programmes are shown in **Photograph 2.4**.

2.2.8.3 Fuel depth and level of compaction

Fuel depth is a measure of the vertical extent of fuel in the zone that is actively involved in the spreading flame front. Teie (2003) defines it as the average height of surface fuel that is available for combustion. Fuel depth is critical for fire behaviour prediction as it determines the bulk density of the fuel for given fuel loads. Fuel orientation refers to the horizontal or vertical orientation of the fuel and is another important property to consider in fire behaviour. Fuel generally consists of horizontally orientated fuels, which slowly increase in depth as the load increases (Teie, 2003). Harvesting systems also influence fuel depth because the amount of compaction and breakage depend on how the trees were felled and how they were removed. Settling of HR with age has an important influence on fuel depth (Albini and Brown, 1978).

Photograph 2.4: Hour fuel classes used in the study. From left to right: 1000-, 100-, 10-, 1-hour fuels (Bark, cones and needles also shown).

Compactness can be defined as the spacing between fuel particles. It is the compactness of the fuel complex that influences the ease with which it will burn. Compact fuels burn more slowly than loosely packed fuels as there is less surface area exposed to the flames and there is also less oxygen available to sustain combustion. Most fuels are loosely packed and oxygen is free to circulate (Luke and McArthur, 1977). Compact fuels also tend to have higher moisture content than loosely packed fuels, which dry more easily (Teie, 2003). During harvesting there are a number of operations, such as felling and extraction, that affect the fuel load both vertically and horizontally. Management treatments such as chopper-rolling, stacking and windrowing further influence the spatial distribution of the fuel across the site. The horizontal continuity of the fuel impacts on the ROS of a fire. Continuous fuel complexes provide available fuels that allow the fire to spread horizontally through surface fuels and vertical to crown fuels (Teie, 2003).

2.2.8.4 Fuel moisture content

Fuel moisture content (%) is the amount of water present at a given time in a fuel, and it is expressed as a percent of the dry weight of the fuel (Teie, 2003). The moisture content of the fuel varies considerably with changes in daily and seasonal weather conditions, rain or dew, the humidity in the air, moisture content of the soil, and aspect and is lost from fuels through the process of evaporation (Luke and McArthur, 1977). Fuel moisture content influences the potential for ignition, intensity and the effect of fire duration on the depth of the burn. A fuel complex generally consists of both dead and live fuels at any one time and therefore may have large differences in moisture content over short distances. Live fuels can be divided into herbaceous (grasses and perennial plants) and woody fuels (needles, twigs and small branches). The moisture content of the 1-hr and 10-hr fuels is highly variable over the course of a single day. The moisture content of the 100- and 1000-hr fuel only varies on a weekly or monthly basis (Teie, 2003). This relationship is demonstrated in **Figure 2.3**. The moisture content of the fuel complex determines what portion of the fuel actually ignites and sustains combustion at the fire front. The depth of burn depends on the amount of heat available to vaporise free moisture, rather than fire duration (Little and Ohmann, 1988).

There is a constant exchange of moisture between the dead fuels making up the fuel complex and the atmosphere. There are several factors regulating the rate at which this exchange takes place. Atmospheric moisture is the dominant cause of variations in the moisture content of dead fuels. The moisture content of the atmosphere is highly variable and changes from one hour to the next and also from one site to another. The difference in moisture content between the fuels and the atmosphere determines if the fuel will absorb or release moisture and at what rate this will take place. Wind speed also influences the rate of exchange, high wind speed leads to the rapid drying out of fuels. Fine fuels exchange moisture with the atmosphere much more rapidly than large fuels. The compactness of the fuel complex affects the drying rate, tightly packed fuels result in decreased air movement through the complex with a corresponding decrease in the rate of exchange. Several other factors such as the time of year, time of day, percentage cloud cover, shading, aspect, slope, solar radiation and altitude indirectly affect the moisture content of dead fuels. All of these factors vary both within the site and between sites. All of these factors essentially affect one major driver of fuel moisture content and that is the balance between the evaporative demand in the atmosphere and the fuel moisture content.

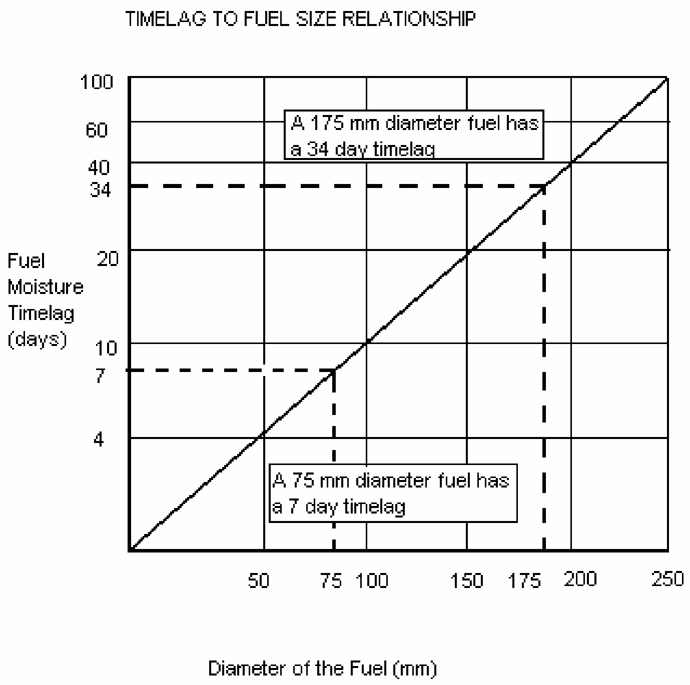

Figure 2.3: Relationship between the diameter of the fuel and its fuel moisture timelag Fuel moisture timelag is defined as the time it takes a fuel of a certain size to gain (or lose) moisture when the environment around it changes. (Teie, 2003).

When vegetation dies it shrinks, but it does not lose its basic cell structure and it is therefore capable of soaking up free water from rainfall. Fine fuels reach the limit of their water holding capacity within a few minutes. Larger diameter fuels seldom reach a condition of complete saturation. The cell walls of plants are hygroscopic and they are therefore able to take in water from the atmosphere through the process of adsorption. Most dead fuels reach their fibre saturation point when the moisture content is 30-35% of dry weight (Luke and McArthur, 1977). Dead fuel moisture is the moisture content of dead fuels at a given time and it is influenced primarily by the humidity of the surrounding air. Dead fuel time-lag is the time it takes for the moisture content of dead fuels and the surrounding air to equalise. The 1-, 10-, 100-, and 1000-hr fuel classes are derived from this definition, the larger the fuel, the smaller the SAV ratio and the longer the time-lag. Needles are considered a 1-hr fuel and have timelags that are less than or equal to an hour. This means that it takes about one hour of exposure to significantly increase or decrease the moisture content in dead needles. The fuel moisture of a fine fuel (less than 0. 6 cm diameter) will vary by the hour whereas those of coarse fuels (greater than 2. 5 cm diameter) will only vary over the course of an entire day. The 1-hr fuels are the most critical for ignition and spread and it is the moisture content of this fuel class that is the most important when predicting fire risk and behaviour. The moisture content of the 1-hr fuels can simply be determined by measuring changes in the relative humidity of the atmosphere (Teie, 2003). This relationship is shown in **Figure 2.4**.

One of the major factors to consider when predicting fire risk and behaviour is the fuel load that could be burnt under given weather conditions. This fuel load is made up primarily of the dead surface fuels less than 7.6 cm in diameter and live fuels less and 0.6 cm in diameter. The size of the fuel affects how it will respond to various forms of moisture (such as rain, dew and relative humidity) and also how quickly dead fuel will lose moisture. The 1-, 10-, 100-, and 1000-hr fuels fall into the following size class categories shown in **Table 2.10**.

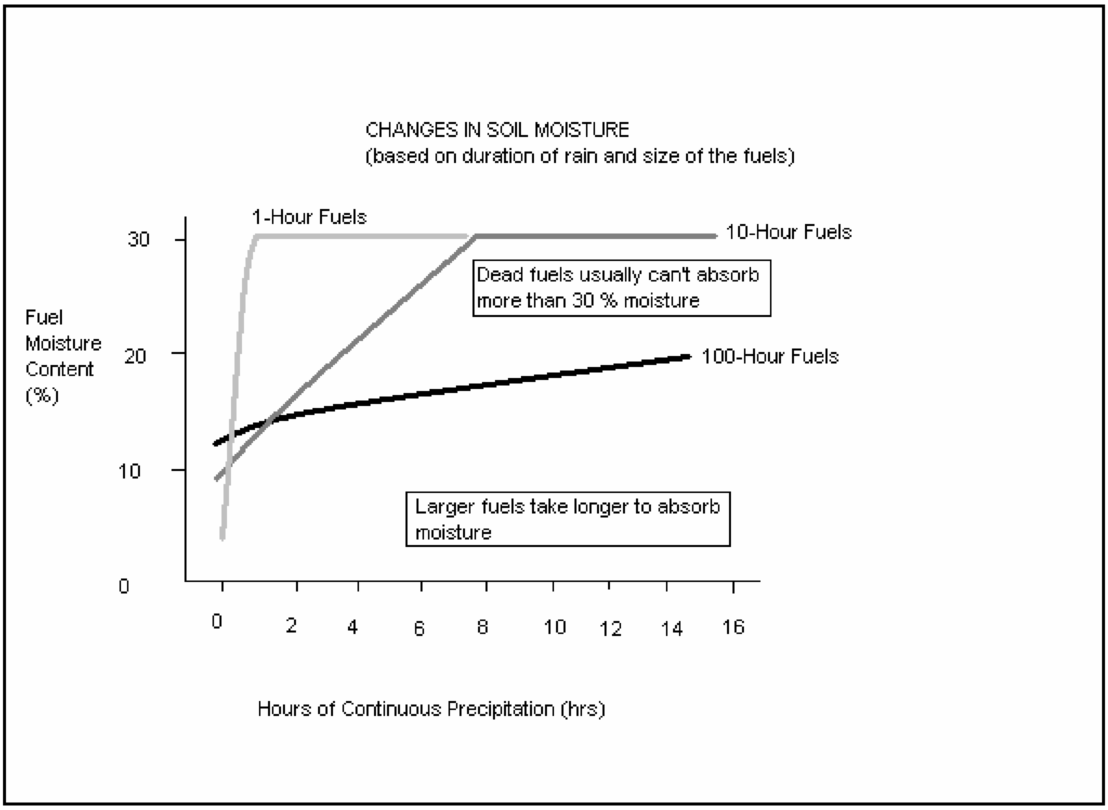

Figure 2.4: Relationship between the fuel class, period of constant precipitation and moisture content of the fuel (Teie, 2003).

2.2.8.5 Fire behaviour prediction models

In order to manage fire risk it is critical to be able to predict how a fire will behave under various conditions and several computer programmes, such as BEHAVE, BehavePlus and FARSITE, have been developed for this purpose (Andrews, 1986; Burgan and Rothermel, 1984; Teie, 2003; www.fire.org). These programmes reguire, among other things, an estimate of the quantity of HR by fuel class, fuel depth and level of compaction and moisture content. BehavePlus uses these variables in conjunction with site-specific input data to predict fire behaviour for a point in time and space. BehavePlus works on the actual available fuel that is in a 1-hr, 10- or 100-hr state of combustion and the 1-hr fuel load is the most important fuel component as it is responsible for driving the fire. (Andrews, 1986). Fuel models cannot be developed using BehavePlus so custom fuel models were developed using the NEWMDL programme of the fuel subsystem of BEHAVE and the models were run using BehavePlus (Burgan and Rothermel, 1984; www.fire.org).

Interactions between fuel model, topography and environmental parameters and the mathematical fire spread model are so numerous that attempting to present all the possible results is unreasonable (Burgan and Rothermel, 1984). The mathematical fire spread model provides a means to estimate the rate at which a fire will spread through a uniform fuel array that may contain fuel particles of mixed sizes. The model demonstrates that the ROS of the fire is a ratio of the heat received by the potential fuel ahead of the fire, to the heat required to ignite this fuel (Burgan and Rothermel, 1984).

The basic fire spread model is given in **Equation A**.

Equation A: The basic fire spread model (Rothermel 1972).

$$R = \frac{I_r \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$$

Where: R = the forward rate of spread of the flaming front

I_r = the reaction intensity – a measure of the energy release rate per unit area of fire front

ξ = the propagating flux ratio - a measure of the proportion of the reaction intensity that heats adjacent fuel particles to ignition

φ_w = a dimensionless multiplier that accounts for the effect of wind in increasing the propagating flux ratio

φ_s = a dimensionless multiplier that accounts for the effect of slope in increasing the propagating flux ratio

ρ_b = a measure of the amount of fuel per cubic foot of fuel bed

ε = a measure of the propagation of a fuel particle that is heated to ignition temperature at the time flaming combustion starts

Q_{ig} = a measure of the amount of heat required to ignite 1 kilogram of fuel

2.2.9 Fuel management

Effective forest management requires that the treatment of fuel be an integral part thereof (Howard, 1978). Maintaining an acceptable fire hazard level is expensive and requires skilful management. Forest managers require an inexpensive, simple, and objective method of appraising potential fire behaviour to aid in fuel management decisions. Knowledge of potential constraints on re-establishment and fire intensity and behaviour can help determine alternative fuel management options to burning and costs of specific regimes (Albini and Brown, 1978). A major problem associated with fuel management and research is the amount of variation of the fuel load between and within a site due to pruning and thinning operations, and as a result of clearfelling operations (Dames, 1996).

The rate at which the fuel decomposes needs to be considered when implementing a management option. If the fuel decomposes to an acceptable level within a sufficiently short space of time, it may be an unnecessary expense to reduce it further. In some cases, no additional management operations are required and the fuel is simply left where it falls and the site is then re-established through the fuel. Management options for fuel include broadcasting, burning, windrowing or chopper-rolling using mechanical means. All of these options are expensive and have certain limitations under various conditions and have the potential to either positively or negatively affect long-term site productivity (Allan and Higgs, 2000; Allan *et al.*, 2001). Burning accumulated fuel by means of a prescribed burn can reduce the danger of uncontrolled wildfires, although there is always some risk associated with prescribed burning as it has the potential to get out of control, resulting in a wildfire. There are still arguments against prescribed burning, whether it is under-canopy or post-harvest, since the effects of fire on many factors is extremely complex and difficult to manage in practice (Attiwill and Leeper, 1987). Burning reduces the dry mass of fuel considerably relative to practices such as broadcasting. Morris (1986) recorded a fuel mass of 127 t ha^{-1} on a site that had not received a fuel burn treatment, and a mass of 40 t ha^{-1} on a site that had received a fuel burn. The difference in the two fuel loads constitutes a large fuel complex with the potential for very intense, hot wildfires.

Table 2.10: The relationship between dead fuel class, characteristics, and the associated approximate timelag for the fuel to reach equilibrium with atmospheric moisture.

Hour Fuel*	Fuel Diameter Size Class (cm)	Fuel Examples
1	0-0.6	Needles
10	0.6-2.5	Fine branches and twigs
100	2.5-7.6	Secondary branches and tops
1000	> 7.6	Broken and defective logs and mature standing timber

*Note: Implies the approximate time-lag for fuel moisture to reach equilibrium with the atmospheric moisture content following a period of continuous rainfall or drying out.

Table 2.11 illustrates the effect that three different fuel treatments had on the FF mass of a mature, second rotation *P. patula* PLP stand in Swaziland (Germishuizen, 1979; Morris, 1986). After the first rotation was clearfelled the fuel was either broadcast, stacked and then burnt or was broadcast and then burnt. The FF load was then determined when the second rotation reached clearfelling age. What is also clear in this table is the large build-up of the FF in a relatively short space of time. In all three compartments the “no burn, broadcast” option resulted in the heaviest FF load in the second rotation. In two of the compartments stacking and burning of the fuel resulted in the lowest FF loads. This table serves to illustrate that the initial fuel management decision can have a major impact on the resulting fuel load in the second rotation. Burning as opposed to just broadcasting the fuel results in smaller FF loads at the end of the second rotation. Stacking and burning instead of broadcasting and burning reduced second rotation FF loads even further. This is because fire intensities in stacked fuel are greater, resulting in a greater proportion of the fuel being burnt.

Table 2.11: Forest floor mass under 15 year-old second rotation *P. patula* stands following three different fuel treatments at re-establishment.

Slash Treatment	**Site**		
	mass (t ha^{-1})		
	Site 1	**Site 2**	**Site 3**
No burn, broadcast	167	195	123
Stacked and burnt	127	162	99
Broadcast and burnt	149	134	106

2.2.9.1 Fuel retention

Harvest residue represents an important asset to forestry sites and fuel retention ensures that nutrient pools and soil properties are not negatively affected by successive rotations (Morris, 1986). Allan *et al*. (2001) note that retaining as much fuel on the site as possible ensures that successive rotations have a minimal impact on the nutrient capital and soil structure of the site, and minimises soil loss through erosion. A large proportion of the nutrients of a plantation are concentrated in the leaves, twigs, bark, cambium and roots of the tree (Hendrik, 1979 cited by Norris, 1995). During most harvesting operations, this material is left on site and as it decomposes nutrients are released slowly without excessive leaching (Norris, 1995). The main objections to leaving fuel in place are that it complicates site preparation and planting operations and increases the risk of fires (Allan *et al.*, 2001).

Windrowing is commonly used for site preparation after clearfelling (McNab *et al*., 1978; Norris, 1993; personal observation, 2003). It is commonly used for site preparation on sites utilised for the production of PLP in SA. **Photograph 2.5** shows a typical windrow fuel distribution pattern on a PLP stand in KZN. This material is generally then burnt and the site re-established. If the HR has been windrowed, even the largest branches and tops can be consumed by a prescribed fire resulting in a much hotter fire and almost completely clean site (Little *et al.*, 1996). The amount of HR in a windrow available to be burnt is difficult to determine because of the variations that exist between piles such as the ratio of fine to large material, differences in fuel moisture content and the amount of soil incorporated into the windrow (Johansen *et al*., 1977). Burning windrowed slash generates high fire intensities with a long residence time that greatly influence the nutrient pools contained in the HR and underlying soil, particularly at the centre of the row where the fire intensity is the highest. Windrowing HR can also lead to re-establishment difficulties, as it is diffuicult to create planting pits in these windrows, which can lead to poor pit quality and subsequent poor seedling survival and growth. Seedlings established along lines that were burnt often exhibit faster initial growth than those established along the inter-rows, which were not burnt. This is however influenced by the intensity of the fire and the resulting damage to the nutrient pools and soil. The fuel is very concentrated leading to extremely high temperatures when burnt, particularly at the centre of the row. Evidence of this can be seen in **Photograph 2.6** by the white ash in the centre of the burn with black ash along the edges of the row where there was less material and the temperatures were lower.

Photograph 2.5: Windrowing of *P. patula* fuel on a PLP site in the KwaZulu-Natal Midlands.

The alternative to burning windrowed fuel is to broadcast it once the harvesting operation has been completed. This is another common method of dealing with windrowed fuel in SA. Planting pits dug manually in heavy fuel often result in poor seedling survival owing to the poor quality of the pits that can be made through heavy fuel. **Photograph 2.7** shows a PLP site in KZN where the fuel was first windrowed to facilitate extraction and then broadcast once all the timber had been removed.

Photograph 2.6: Burnt fuel rows indicating the different temperatures that resulted in the row, KwaZulu-Natal Midlands.

2.2.9.2 Mechanical break-up

Mechanical break-up of fuel using chopper-rollers is expensive and generally suited to relatively smooth flat terrain (Allan *et al*., 2000). It can often only be carried out effectively once the fuel has been properly broadcast which results in further expense. Chopper-rolling has been associated with nutrient losses due to increased sediment run-off (McColl and Powers, 1984 cited by Allan *et al*., 2001). Other methods of breaking up the fuel include the Coulter ripper, which both cuts the fuel and prepares a planting position, and the fuel mulcher that also cuts up the fuel to improve access, reduces fire hazard and speeds up decomposition rates. Both of these machines have been developed by the ICFR (Norris, 1995).

2.2.9.3 Burning

Burning is a common method of treating HR in SA and around the world, as it is a relatively inexpensive operation that results in a clear site (Fisher and Binkley, 2000; Kruger and Bigalke, 1984 cited by De Ronde, 1988; De Ronde 1996; 1997 cited by Allan *et al*., 2001; Norris, 1992, 1995). While fire can be a useful management tool, a poorly executed burn can have a deleterious effect on a site (Fisher and Binkley, 2000). Forest managers applying prescribed burning for hazard reduction and silviculture are often hindered by a lack of quantitative measures of fuels and this can lead to unexpected fire behaviour with sometimes disastrous consequences (Kiil, 1965). A measure of the accumulation of the FF plus the HR produced by thinning or harvesting (fuel load) is one of several key variables needed to predict fire behaviour before the fuel can be safely burnt (Johansen and McNab, 1977; Johansen *et al*., 1977).

Photograph 2.7: Broadcast fuel (after windrowing), *P. patula* PLP stand, KwaZulu-Natal Midlands.

The effects of fire on site fertility are difficult to determine, but are highly dependent on fire intensity. The impact of a wildfire is in most cases severe as the protective H layers are consumed. In prescribed fuel and under canopy fires some or all of the H layer remains and the impact of these fires is less severe (De Ronde, 1988). Some impacts, such as volatilisation, are immediate, while others such as plant growth in burnt soils are difficult to interpret (Attiwill and Leeper, 1987). The effects of burning on nutrient supply are more the result of the actual removal of the residues, than changes in soil physical properties. In a study to determine the long-term effects of broadcast burning on the physical and chemical properties of forest soils, Kraemer *et al*. (1979) found no statistically significant differences between properties of burned and unburned soils. This suggests that broadcast burning (at the intensities applied in that study) does not have a lasting effect on chemical and physical properties of soils (Fisher and Binkley, 2000; McKee, 1982). Evidence to support this, from a study reported by Fisher and Binkley (2000), is presented in **Figure 2.5** and shows the net loss of nitrogen after 30 years of repeated prescribed burning. The black portion of the graph refers to the nitrogen lost from the FF, the darker grey that lost from the first 10 cm of the soil and the light grey from a depth of 10-20 cm deep in the soil. The greatest loss is from the FF with a slight increase in the nitrogen levels of the soil.

Figure 2.5: Net loss of N after thirty years of repeated prescribed fires in *P. taeda* - *P. longifolia* forests (Binkley *et al*., 1992 in Fisher and Binkley, 2000).

In areas with relatively infertile soils, the loss of nutrients through repeated burning could become a significant factor in the long-term productivity of managed forests, particularly in the case of hot, high intensity fires (McKee, 1982). The time between burns also plays a role and shorter rotations followed by burning or an increase in the occurrence of wildfires can have negative effects on the nutrient pools of a site. Fuel consumption (which is a measure of fire intensity) tends to increase with increasing time between fires (Fisher and Binkley, 2000). Uptake and mineralisation of N in soil have been found to be higher following a fire (Adams and Attiwill, 1991). Fisher and Binkley (2000) state that although nutrients are lost during fires, the amount if nutrients available to trees after a fire may increase. Levels of ammonium, nitrate and plant-available P commonly increase temporarily after bruning as a result of increased pH and microbial activity (Fisher and Binkley, 2000; De Ronde, 1992b). Reduced competition among plants or the release of elements from organic matter may also contribute to this ‘flush’ of available nutrients. Improvements of P levels in the topsoil have been recorded following a prescribed burn in the Tsitsikamma in the southern Cape by De Ronde (1992a). Burning may also lead to increased weed growth on the site (Little *et al.*, 1996; 2000; Morris, 1986). Fires result in increased soil temperatures up to a depth of 30 cm. Soil temperature is affected by the rate of burn, amount of fuel consumed, the soil moisture and the conductivity properties of the soil. Fires result in the loss of nutrients through five processes: oxidation of compounds, vaporisation of compounds, and convection of ash particles, leaching of ions and, through accelerated erosion (Fisher and Binkley, 2000). As organic matter burns, nutrients such as N and S may volatise as gases when temperatures exceed about 300ºC (Attiwill and Leeper 1987; Binkley, 1986 cited in Norris, 1995). **Figure 2.6** shows that the percentage of N lost from the soil increases sharply after the fire temperature reaches approximately 200ºC. It starts to level off once the temperature exceeds 400ºC and is lost more gradually thereafter.

After burning, the increased precipitation reaching the soil surface results in further losses in nutrients, through leaching and surface movement. Furthermore, the soil surface is exposed to the damaging erosive forces of wind and raindrops. Where the soil reaches high temperatures, soil organic matter can be destroyed leading to a breakdown in soil structure and thus resulting in greater susceptibility to erosion (Hendrik, 1979 cited by Norris, 1995). Another negative impact resulting from burning is fire induced water repellency, resulting in soils, which resist wetting by water. This occurs as organic matter burns and gases, containing hydrophobic substances, condense within the soil, producing a hydrophobic organic coating around soil particles. This coating results in the soil in burnt areas resisting wetting by light precipitation and slows down seasonal soil recharge (Allan and Carlson, 1998). The more intense the fire, the more severe the water repellency produced in a soil, with repellency stretching from the soil surface to depths of up to 15 cm (Allan and Carlson, 1998; De Bano, 1981 cited by Norris, 1995). Soil surface temperatures experienced during a fire can range between 200-300ºC but may reach as high as 500-600ºC. Burning can lead to other problems such as those caused by *Rhizina undulata,* which is a common disease of pine seedlings when re-establishment takes place following a hot wildfire or burning operation. The occurrence of this fungus may be related to the frequency and heat of the fire, season and rainfall (Atkinson, 1999; Germishuizen, 1979). There are a number of methods of classifying fire intensity. Little *et al.* (1996) classified fire intensity in terms of ‘cool’, ‘moderate’ and ‘hot’ fires. A ‘cool’ burn results when HR is broadcast and moist conditions are present and only branches smaller than 4 cm in diameter are commonly consumed (Johansen *et al.*, 1977; Little *et al.*, 1996).

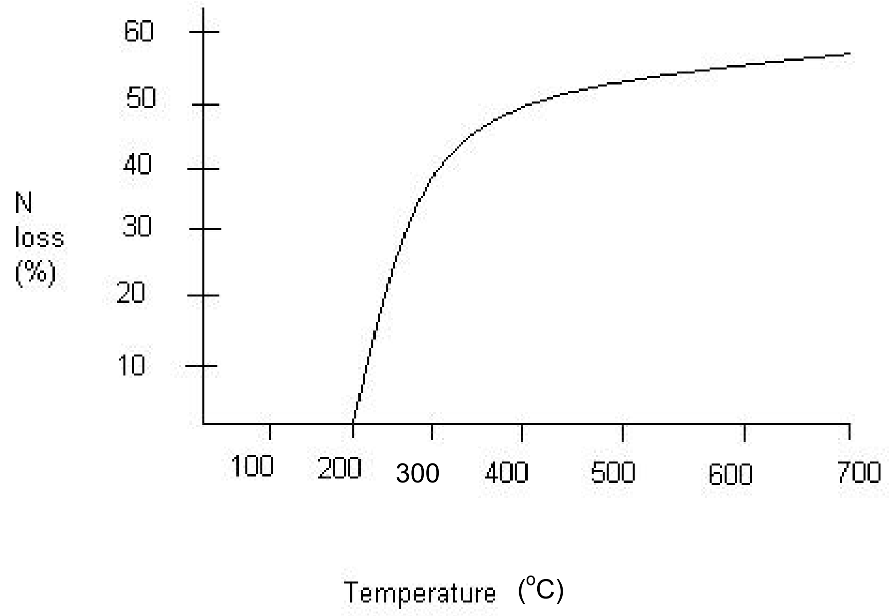

Figure 2.6: Conceptual graph of nitrogen oxidation and loss. N oxidation and loss rise rapidly as temperatures increase above 200°C (Knight, 1966 in Fisher and Binkley, 2000).

Prescribed under-canopy burning is one method that can be applied to reduce fuel build-up prior to clearfelling (De Ronde, 1988, 1992a; Wade *et al*., 1993). Even though this method is generally only applied to mature ST stands due to the sensitivity of *P. patula* to fire, it has been applied in stands of species such as *P. elliottii* as young as three years (De Ronde, 2003). The objective of prescribed under canopy burning is to remove the L and F layers while leaving the H Layer untouched. The H layer protects the topsoil against the direct impacts of fire and soil erosion (De Ronde, 1988). **Photograph 2.8** shows a prescribed, under-canopy burn carried out beneath a mature *P. elliottii* compartment near Sabie, Mpumalanga.

Photograph 2.8: Prescribed under-canopy burn in a mature *P. elliottii* ST stand, Sabie, 2004.

2.2.10 Fuel characterisation and quantification

In order to manage fire risk it is critical to be able to predict how a fire will behave under various conditions (Teie, 2003). It is important to have an estimate of the quantity of fuel and its fuel load properties prior to harvesting to enable the correct management decisions to be implemented (Howard, 1978). The capability to estimate fuel load and to model fire behaviour makes it possible to quantitatively appraise fire behaviour potential. Forest managers need a rapid method of estimating the amount of fuel in harvested pine stands, which is necessary in planning prescribed burning operations (Bailey, 1970; Johansen and McNab, 1977; Morris, 1970). Fuel assessment is a procedure that estimates the quantity of residue following a harvesting operation and is used to monitor and ensure the maintenance of harvesting utilisation levels (O'Hehir and Leech, 1997). Fuel is difficult to quantify before it is created and as a result, associated management concerns are difficult to determine and evaluate. Harvesting and management operations have a mixing effect on the pre-existing layers of the FF which leads to difficulties for fuel sampling due to the high spatial variability of the fuel load across the site (Dames, 1996; Schutz, 1990). Prediction of fuel loads does not guarantee easy solutions to management problems but it does provide a sound foundation for making decisions and planning. Estimates of fuel loads are important for various reasons: i) for communicating the magnitude of residue problems, ii) describing potential for utilisation, iii) determining costs of treatments and selecting alternative treatments, and iv) appraising potential fire behaviour of fuels (Snell and Brown, 1980).

Traditional methods of fuel assessment were carried out using fixed area plots after harvesting was completed. Fixed plots are simple to apply but are costly and inefficient as they involve the collection of large quantities of material from the plot and its subsequent separation into size classes followed by the determination of its dry weight per unit area (Johansen and McNab, 1977; May and Hartong, 1959; O'Hehir and Leech, 1997; Ringvall and Ståhl, 1999). Methods for quantifying fuel loads on a macro-scale, such as line-intersect sampling (LIS) and planar-intersect sampling, (PS), which indirectly measure fuel quantities, are designed for general estimation of fuel quantities in fire research (Brown, 1971; O'Hehir and Leech, 1997; Van Wagner, 1968; Warren and Olsen, 1964). Photo series provide a fast and meaningful method of fuel load determination using visual assessment supplemented by a limited amount of fuel depth measurement. These methods are used for the estimation of fuel loads over large areas.

2.2.10.1 Line- (LIS) and planar- (PS) intersect sampling

Line intersect sampling was initially developed for the measurement of the volume of HR above a certain minimum size limit in *P. radiata* plantations in New Zealand (Van Wagner, 1968; Warren and Olsen, 1964) but is now used for a wide range of forest management operations (O'Hehir and Leech, 1997). These include estimating the quantity of fuel on a site after clearfelling for policy decisions or management planning, fire and timber management, development of residue models for yield prediction, and monitoring harvesting operations to ensure prescribed utilisation levels are achieved (Hazard and Pickford, 1978; Nalder *et al.*, 1997; O'Hehir and Leech, 1997). Data gathered using this technique can be used to calculate the mass of stemwood, branchwood and needles (Burrows, 1980). It is a non-destructive method and uses only the cross-sectional area (CSA) of pieces crossed by a line to estimate volume per hectare. LIS requires a diameter tally of pieces intersected by a sample line, appropriate values for specific gravity, piece tilt angle and the application of a formula. The accuracy of estimates of volume per hectare is affected by variation in the volume, length, distribution and orientation of the pieces as well as the length and orientation of the sampling line. This method is suitable for assessing HR on both cable skidder and cable yarder logged areas (Bailey, 1970). A practical example of the PS method is demonstrated in **Photograph 2.9**.

Photograph 2.9: Line-intersect sampling technique, *P. patula* ST site, KZN.

Planar intersect sampling is a modified version of the original line intercept sampling technique and applies to a wider range of fuel conditions and is rapid and easy to use. Put simply, the PS method requires the measuring of pieces of HR that pass through an imaginary vertical plane superimposed along a random bearing from a sample point (Benson and Johnson, 1976). Planar intersect sampling was initially developed to provide estimates of fuel loading as part of an effort to appraise fire behaviour potential for planning fire management strategies (Benson and Johnson, 1976). It involves counting intersections of fuel with vertical sampling planes that resemble guillotines dropped through the fuel (Brown, 1970). The number and length of the sample planes vary but the reliability of the sample increases as the total sample length increases (Roussopoulos and Johnson, 1973). Volume is estimated, and then mass is calculated from volume by applying estimates of specific gravity of woody material. It requires a tally of the intersections between sampling planes and fuel components categorised by size and shape classes (Brown, 1974).

2.2.10.2 Other Methods

Windrowing is commonly used for site preparation in SA, particularly on sites utilised for the production of PLP. It is often difficult to estimate the quantity of material present on the site after it has been windrowed, as windrows often exceed 2 m in height, and are extremely compact. The CSA method is a method that can be applied to assist management in evaluating the windrowed biomass (McNab and Saucier, 1980). The amount of wood at any given sample point along a windrow is correlated with two factors, namely: the average diameter of wood residues greater than 7. 6 cm observed at that point, and the height of the windrow. Therefore, the weight and volume of fuel can be estimated by measuring the average diameter of the residue, the average windrow height, the average horizontal distance to the windrow midpoint and the total length of the windrow. Fuel diameter and the maximum height of the windrow are then used to calculate the volume of fuel. Fuel load can be determined from volume by multiplying by the specific gravity of the woody material. The total CSA, or volume, of the windrow is required to determine the mass of fuel of the entire windrow. This is obtained by determining the height and the horizontal distance to the windrow centre. The length of the windrows and the number of windrows on the site are then needed to calculate the total fuel load on the site (McNab and Saucier, 1980).

Transect relascope sampling combines relascope and line-intersect sampling theory. Estimation of the fuel load is based on a count of the downed logs using a relascope instrument along survey lines. Every piece of downed woody material and a length that fills the relascope gap is counted. This method is limited for fuel assessment (Ståhl, 1998). Light interception sampling was developed by Allan (2000). This technique was used to estimate fuel loads surrounding young seedlings and other factors affecting seedling survival. The quantity of fuel surrounding a point on the ground will affect the level of light detected at the point. A higher fuel load will result in more shade experienced on the ground. This method is applicable specifically for the indirect estimation of the quantity of fuel in the immediate vicinity of individual trees and is therefore only useful for estimating localised fuel mass and then only once the fuel load exceeds 40 t ha^{-1} (Allan, 2000). Sampling of fuel using remote sensing has been used where ground travel is slow, difficult and somewhat hazardous. This makes obtaining the necessary measurements of the fuel components from aerial photos more practical. Logs and tops as small as 10 cm in diameter can be accurately measured using large-scale aerial photos (Ingram, 1966 cited by Morris, 1970).

2.2.10.3 Photo-series techniques

Silvicultural and harvesting operations generate large fuel loads on an annual basis. The amount of fuel generated is influenced by the many factors such as the condition of the stand, topography, harvesting system and specifications. Some fuel is beneficial for nutrient cycling and soil protection; however, excessive fuel loads adversely affect the site in many ways such as increased fire risk. *P. patula* is a prime example of a species that produces heavy fuel loads during clearfelling to such an extent that it becomes unacceptable from a management, protection and environmental point of view. Estimates of existing and expected fuel loads are necessary in order to implement management practices to reduce loads to acceptable levels (Maxwell and Ward, 1976). Estimates of acceptable fuel load levels are needed to minimise potential fire danger. Acceptable fuel load levels depend on resource values, management objectives, patterns of ownership and fire-fighting capability. To make a decision on the quantity of fuel that is acceptable requires the integration of many factors. Management objectives and values at risk need to be considered along with fuel load prediction and characterisation (Snell and Brown, 1980).

Photo series are designed to provide a reliable, inexpensive, fast, easy-to-use tool for quantifying fuel complexes that are adequate for most management requirements. With a photo series, the manager can visually relate given combinations of fuel weight to fire behaviour (Wade *et al*., 1993). A photo series consists of an array of photographs with each photo showing different fuel load levels generated from similar harvesting systems. According to Maxwell and Ward (1980), the major objectives in forming a photo series are to provide an array of loadings of fuel that will enable logical comparative estimates of loadings by size classes in similar stands to be made and to quantify desirable fuel loads. Information obtained from the photo series can be used to evaluate impacts of fuel on various aspects of forest management, identify areas of acceptable fuel loads, identify priority areas for management, estimate the amount of utilisable material remaining on the site and predict fire behaviour characteristics. Site-specific silvicultural objectives can be met if the amount of fuel that must remain on the site can be specified to meet environmental and production concerns (Blonski and Schramel, 1981; Maxwell and Ward, 1976). Photo series can also be used to estimate the quantity of fuel that will be produced prior to clearfelling and changes in the fuel load arising from different treatments. Photo series offer a basic aid for predicting the expected quantity of residue as this is affected by numerous complex factors. Expected fuel loads can be predicted by comparing volume and size information from cruise data with the information provided in the photo series. Estimated changes in the fuel load from different treatments are important in identifying treatments that will reduce the load to the desired level, selecting the most cost-effective treatments, and estimating the amount of fuel that will be consumed by fire (Maxwell and Ward, 1976).

3. FOREST FLOOR FUEL LOADING UNDER SAWTIMBER AND PULPWOOD STANDS OF *Pinus patula* IN SOUTH AFRICA

3.1 Introduction

Commercial plantations of *P. patula* in southern Africa can develop some of the heaviest FF fuel loads for this species in its established range. These accumulate under a cool climate (at high altitudes) and result in a hindrance at re-establishment, which can ultimately lead to poor transplant survival and growth, and a fire hazard within standing plantations. These FFs also contain significant nutrient pools, which are unavailable for growth or may be lost from the system in the event of a wildfire. This problem is accumulative where stands are re-established for several rotations, particularly at high altitude without reduction measures being taken, leading to extremely thick FFs and a corresponding decline in stand productivity over successive rotations (Evans, 1974, 1975; Morris, 1986, 1993; Schutz, 1990). More recent studies have reported lower FF load figures for *P. patula* in the MPUE region (Bird, 2001; Carlson and Allan, 2001; Dames, 1996).

The factors that drive biomass (needle) production and decomposition, leading to a net accumulation of organic material on the FF, are complex. Biogeochemical nutrient cycling is dominated by biomass production and decomposition (O'Connel and Sankaran, 1997) which are driven by inputs (incoming radiation (light), the carbon dioxide concentration of the atmosphere, temperature and soil water, nutrient availability) and the presence of decomposer organisms which result in decomposition and an output of nutrients from the system (Fisher and Binkley, 2000; O'Connell and Sankaran, 1997). Accumulation depends on an imbalance of ecosystem processes and the absence of disturbances such as fire or harvesting operations (Dames, 1996; Hendrikson, 1987 cited by Carlson and Allan, 2001; Norris, 1993). This accumulation of organic material constitutes a fuel complex that represents a potential fire hazard. Limited work has been conducted on the effect of fuel loads on fire behaviour and the practical application of this for prescribed, under-canopy burning or wildfire risk assessment (Bird, 2001; Bird and Scholes, 2002b; De Ronde, 1980, 1983, 1988, 1990, 1996 and 1997).

In light of the catastrophic wildfires that destroyed large areas of plantations in 2003 it has become increasingly important to manage the fire risk pro-actively. This can be achieved through improved protection in high-risk situations or through prescribed fuel load reduction as part of an integrated regional fire management plan managed in conjunction with fire protection agencies (De Ronde, 1980, 1983, 1999 and 2003; du Toit *et al.*, 2003; Potgieter, 2003; Teie, 2003). Fire risk can be quantified, and behaviour of fires can be modelled accurately if the daily and hourly weather conditions, fuel load by fuel class, composition and moisture content of the FF, and topographical variables are known (Ferguson *et al.*, 2002;

Pook *et al*., 1993; Teie, 2003). Much of this information is limited or unavailable for *P. patula* plantations in SA. It is therefore imperative to determine the fuel load by layer across sites as the first step towards fuel load management and fire protection. Knowledge of the FF load will also improve our ability to manage the risk of transplant mortality, to address nutrient lock-up problems and ultimately ensure the sustainability of commercial forestry plantations in the country.

This chapter deals with the FF component and its major objectives are listed below.

1. To determine if the FF load differs in different geographical regions and with shorter rotations;
2. To determine how accurately the FF load can be predicted using depth and mass data collected on site, or a modelling approach using environmental and stand variables, and the level of accuracy required for accurate fire behaviour prediction;
3. To investigate and quantify the variation in the FF load within a specific compartment and the implications of this variation for fuel load management, fire behaviour and prescribed burning;
4. To investigate how changes in FF load, and resulting changes in the FF moisture content, affect fire behaviour and risk for commercial forestry in SA using available fuel and fire behaviour prediction models.

3.2 Materials and Methods

3.2.1 Study sites

A total of 39 compartments were selected and the locations of the sites selected for final inclusion in this project is shown in **Figure 3.1**. The major criterion for site selection was that compartments had to be in the process of being, or been recently clearfelled. Although this was the major factor considered, a number of other criteria were also included for site selelction. These criteria included stand age, rotation and altitude. Sites were sampled during or just after harvesting and before any site preparation operations had taken place to allow for the measurement of the undisturbed FF and HR to ensure greater accuracy of the results. Field sampling began in June 2003 and continued until March 2004.

Study sites included several thinned and unthinned compartments and were located in the KwaZulu-Natal Midlands (KZN), southern KwaZulu-Natal (SKZN), the Mpumalanga Highveld (MPUH) and the MPUE region. These sites were selected to cover the planted range of *P. patula* in terms of age at clearfelling, altitude, temperature, rainfall, parent material, and management regimes as comprehensively as possible. Stand ages of the selected compartments ranged from 11 to 37 years and covered an altitude range from 960 m above sea level (a.s.l.) to 1890 m a.s.l. with both first, second and third rotation sites included. The sites covered a latitudinal range from 24° to 30° S. Mean annual precipitation for the sites ranged from 732 to 1350 mm, and mean annual temperatures (MAT) from 13.7 to 18.6 °C. Compartment information is provided in **Appendix 3.1**.

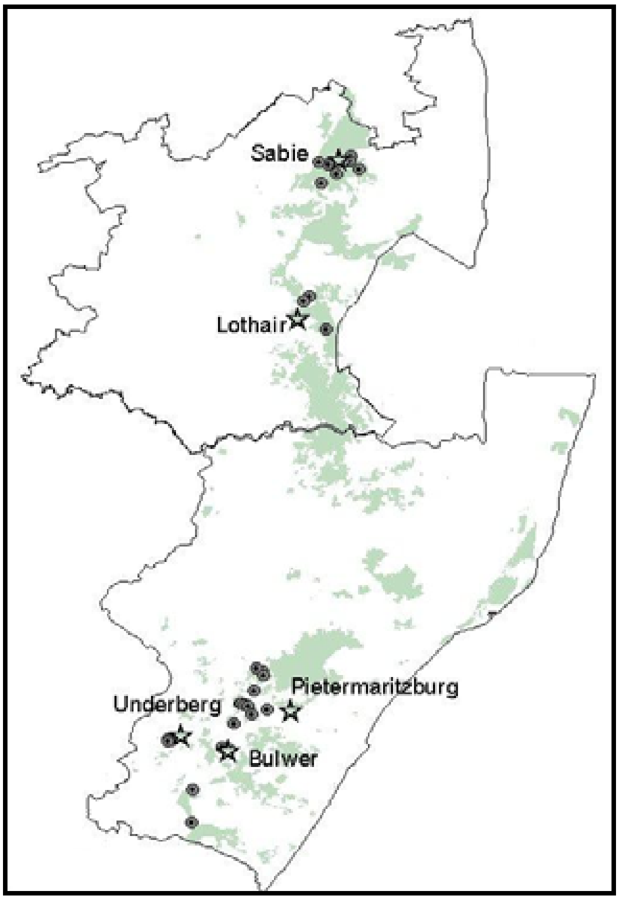

Figure 3.1: Map showing the location of study sites included in this study in relation to nearby towns.

3.2.2 Forest floor collection and quantification

Destructive FF samples, involving the collection of the FF to determine load and depth relationships, and a number of random depth measurements surrounding the destructive sample were collected (**Figure 3.2**). Sampling points within stands were chosen randomly and a single destructive sample of 1 m^2, marked out using a height rod, was collected and recorded in each of the sites based on methods described in Bird (2001). At each destructive sample point, all the FF material above the mineral soil was collected. This size frame was chosen to account for variation in the FF load as well as the micro-topography of the soil. It was assumed that by increasing the destructive sample size, rather than taking a greater number of smaller samples, the variability of the FF could be reduced, particularly in areas of pruning or thinning residue, which can exceed depths of 200 mm (Grove, 2004, *pers.*

comm.[3]; Nambiar, 2004, *pers. comm.*[4]). Previous studies using similar procedures have opted for a greater number of smaller samples to account for variation in the micro-topography of the FF (Dames 1996; Morris, 1986; Schutz *et al.*, 1983).

The FF was cut to the mineral soil using a sharpened spade as outlined in Morris (1986) and the surrounding FF cleared away from the edges of the sample. Two depth measurements were taken along each side of the sample with a ruler. These were later averaged to obtain a single depth for each destructive sample point, which would provide a direct relationship to the mass of the material collected from that point. The cut sample was separated into L, F and H layers, where visible, and placed into plastic bags. Each of these layers influences fire behaviour differently and have a certain level of associated risk.

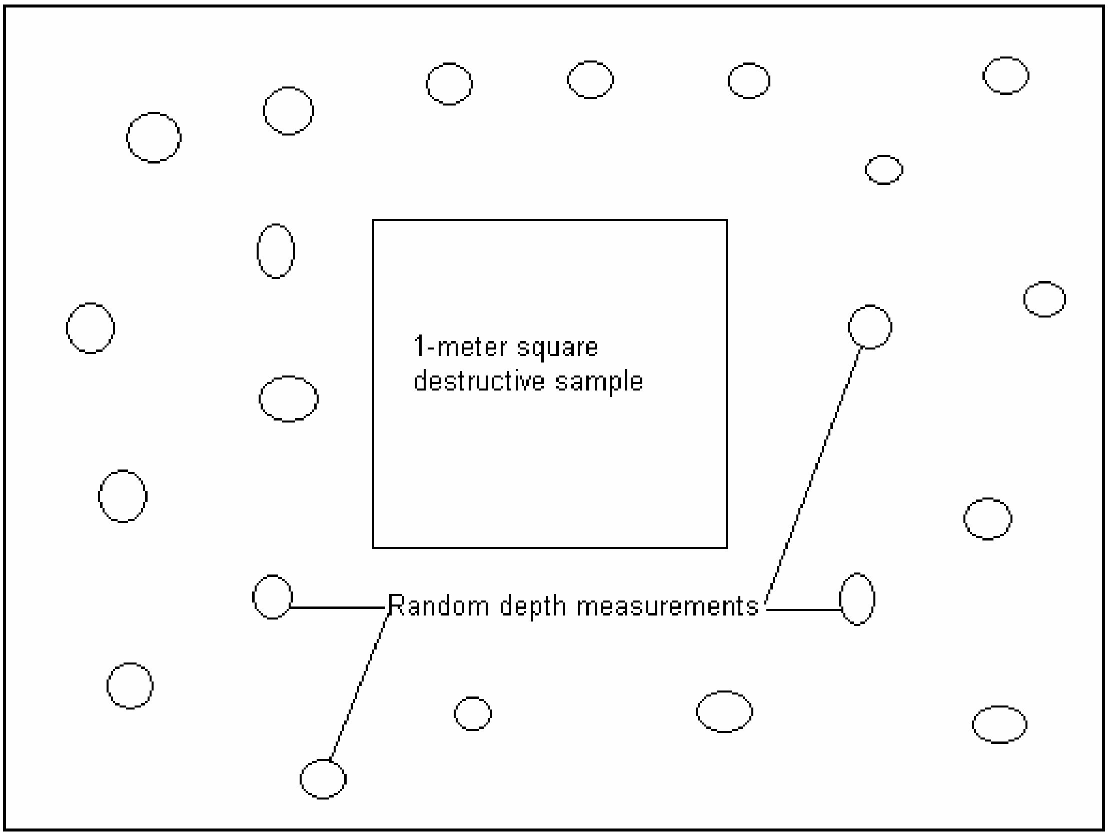

Figure 3.2: Forest floor collection procedure showing the destructive sample collected to establish mass and depth relationships and the 20 random samples to determine the variability of the forest floor.

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[3] Grove, T. 2004. Personal communication. Research Scientist, CSIRO Forestry and Forest Products, Australia.

[4] Nambiar, EKS. 2004. Personal communication. Science Director, CSIRO Forestry and Forest Products, Australia.

A further 20 depth measurements were randomly located around the destructive sample (See **Figure 2.1**). These were summed and used to calculate an average FF depth for each site. The depths were also used to calculate a point FF mass value using both the model developed in this study and other published models (Dames, 1996; Morris, 1986; Schutz *et al*., 1983). The L, F and H layers were oven-dried at 60 ºC until constant mass was achieved. Oven-dry mass for each layer was summed and converted to a mass per unit area. A sub-sample from each layer was analysed to determine the ash-free mass. Samples were ground, sieved and 5 g sub-samples were heated in a vacuum oven at 105 °C for two hours and then in a muffle furnace for eight hours at 500 ºC. The organic matter content was estimated by quantifying the loss of mass after ignition. The average organic matter content for each layer was used to convert all dry mass determination into ash-free dry mass (Dames, 1996; Donkin *et al*., 1993).

3.2.3 Analyses

Linear regression was used to analyse the relationships between the FF load (oven-dry mass and ash-free mass) and depth. A best subsets multiple regression was used to analyse relationships between the mass, and stand and site variables to choose the independent variables yielding the most significant contributions to the mass. Mallow's Cp-criterion as well as the multiple correlation coefficient was used as a selection criterion (Mallows, 1973; Neter *et al*., 1996). Relative contributions of the ash-free mass of each layer to the total mass of the sample were also investigated. Random depth samples were averaged and the standard errors (SE) calculated, and these values plotted to provide insight into the variability of the FF and average FF depth with increasing mass.

A factorial analysis of variance (ANOVA) was conducted to determine the differences in depth between sites and products (ST and PLP). Bonferroni multiple comparison procedures were used to investigate significant differences among the levels of the main factors and interaction effects if no significant interactions were observed. Appropriate non-parametric procedures, such as the Kruskal-Wallis test or a bootstrap procedure were used when residuals proved to be non-normal. Analyses were carried out using Statistica 6 (Statsoft, 2003).

3.2.4 Modelling effects of forest floor load on fuel moisture dynamics

The effect of increasing fuel load (from 0 to 25 t ha^{-1}) and moisture content (from 5 to 25% at 5% intervals) on FLI was investigated using the fire behaviour prediction programme BehavePlus (www.fire.org). The effect of the fuel load and moisture content values on the generated FLI was noted. Other variables for BehavePlus were obtained from fuel model 20 developed by De Ronde (1996) (De Ronde, 2003; Trollope *et al*., 2004).

3.3 Results

3.3.1 Forest floor depth-mass relationship

Total FF loads (collected from the destructive sample) in this study ranged from 21.8 to 168.4 t ha^{-1} and 27.2 to 72.8 t ha^{-1} for ST and PLP stands, respectively. A significant correlation (r^2 = 0.78, n = 31, SE = 17.42) was obtained for the relationship between uncorrected FF mass and depth for a combination of thinned and unthinned stands. The relationship between mass (unadjusted for contamination) and depth is presented in **Figure 3.3**, showing a significant, positive and linear correlation. Basic summary statistics for a range of sawtimber and pulpwwod sites are given in **Table 3.1.**

Table 3.1: Basic summary statistics for the forest floor depth, mass and ash-free mas for a range of *P. patula* sawtimber and pulpwood sites in South Africa.

	LD (mm)	LM (t ha^{-1})	LM$_{loi}$ (t ha^{-1})
Mean	106.48	65.30	48.36
Standard Error	8.28	6.53	5.64
Median	95.10	54.13	37.05
Standard Deviation	46.11	36.34	31.43
Sample Variance	2126.11	1320.30	987.68
Range	199.80	146.62	123.36
Minimum	42.50	21.79	14.57
Maximum	242.30	168.41	137.93
Count	31	31	31
Confidence Level(95.0%)	16.91	13.33	11.53

Forest floors (mass and depth) of thinned and unthinned stands are not fundamentally different from each other across all ages and site types. There is a continuum from thin to thick layers, with more ST stands tending toward the thick side, then grading into a mixture of ST and PLP stands and then finally only PLP stands on the thin side (**Appendix 3.1**). Mature PLP stands, clearfelled between 11 and 15 years can therefore be viewed simply as young ST stands that have undergone one pruning and one thinning. The PLP stands included in this study covered a much narrower range in both mass and depth than ST stands, although there were a number of outliers recorded in some PLP stands where random depth measurements fell on pruning rows. This contributed to the fact that the mass-depth correlation was poor when tested on the PLP subset alone. An ANOVA indicated significant differences between the uncorrected mass [F (1, 29) = 7.40, p = 0.01], the ash-free mass [F (1, 29) = 6.12, p = 0.02], and the random sample FF depths of the ST and PLP stands [F (1, 618) = 141.96, p < 0.00].

The average depths of the destructive and random FF samples recorded in this study were entered into three other existing models (Dames, 1996; Morris, 1986; Schutz *et al.*, 1983) to test the application of these models over wider geographical areas and data sets (**Appendix 3.2**). The model developed in this study (uncorrected for contamination) is given in **Equation B**. The predicted results from the existing models with the current data set are presented in **Figure 3.3** and compared to the relationship observed in this study.

Equation B: Model to predict FF mass from depth for *P. patula* ST and PLP stands in the summer rainfall region of SA (this study).

$$\mathrm{LM} = 0.70(\mathrm{LD}) - 8.71$$

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

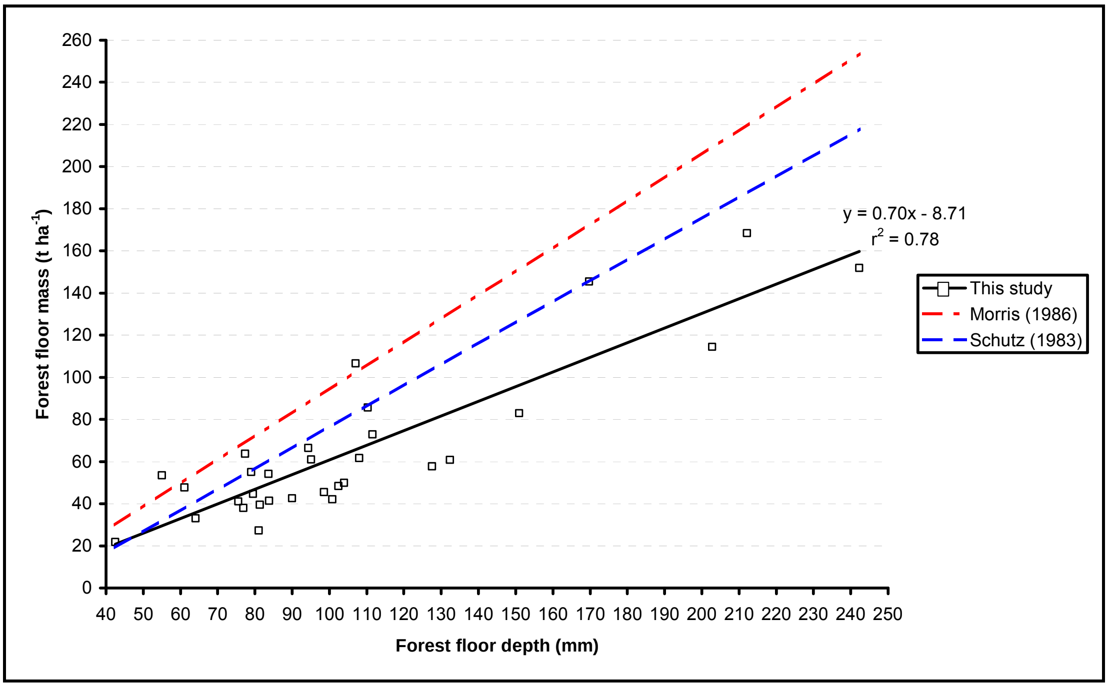

Figure 3.3: Relationship between FF depth and mass for a combination of ST and PLP stands in SA, compared with existing models.

3.3.2 Litter depth and ash-free mass relationship

Ash-free total FF loads in this study ranged from 14.6 to 137.9 t ha^{-1} and 19.5 to 52.8 t ha^{-1} for ST and PLP stands, respectively. A significant correlation ($r^2 = 0.89$, $n = 31$, SE = 10.48) was obtained between ash-free FF mass and destructive sample depth for a combination of thinned and unthinned stands, showing a significant, positive and linear relationship. This relationship was used to calculate an ash-free FF load for each stand, based on the mean FF depth calculated from the 20 random samples. There was a weak, significant, exponential relationship between the mass of the L layer and the FF depth ($r^2 = 0.22$, $n = 26$, SE = 2.89). A significant, positive, linear correlation (r^2 = 0.88, n = 31, SE = 0.09) was obtained for the relationship between the ash-free mass of the duff layer and the total depth of the destructive sample (**Figure 3.4**).

Soil contamination in the L layer was minimal, and ash-free percentage values ranged from 93 to 97%, F layer values from 42 to 97% and H layer values from 28 to 87%. The relationship between the FF depth (destructive sample) and the ash-free mass produced a better relationship than for the mass-depth relationship before ashing, and provides a more realistic and accurate prediction of the actual total FF fuel load available for consumption during a fire. The model developed in this study for the relationship between FF depth and ash-free mass (r^2 = 0.89) (**Figure 3.4**) is given in **Equation C** and that for the ash-free mass of the duff (F+H) layer (r^2 = 0.88) and depth is presented in **Figure 3.4**. **Figure 3.5** shows the comparison between the mass and as-free mass versus the forest floor depth developed in this study.

Equation C: Model to predict ash-free FF mass from depth for *P. patula* ST and PLP stands in the summer rainfall region of SA (this study).

$$\mathrm{LM}_{Ash-free} = 0.64(\mathrm{LD}) - 20.20$$

Where: $\mathrm{LM}_{Ash - free}$ = Ash-free FF mass (t ha^{-1})
LD = Forest floor depth (mm)

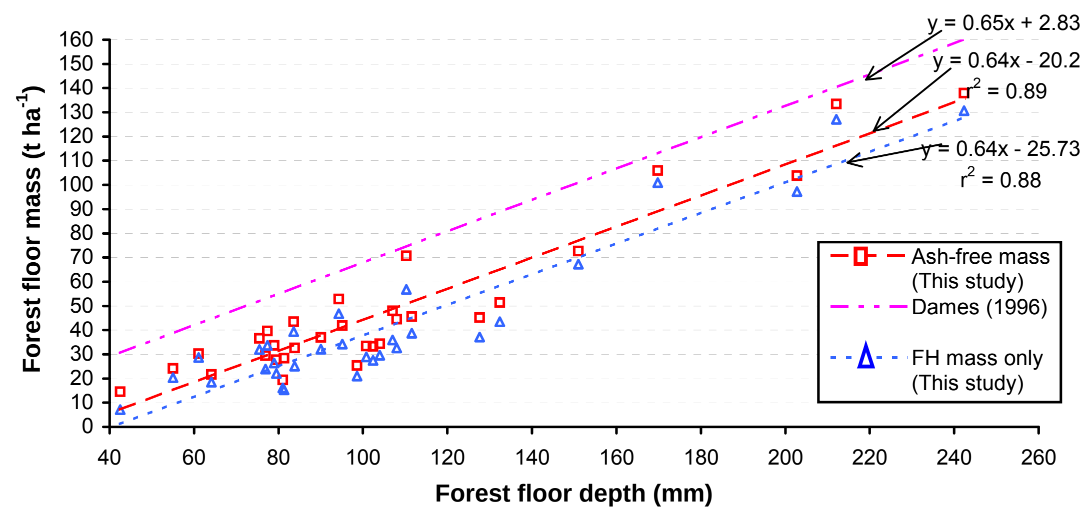

Figure 3.4: Relationship between FF depth and ash-free mass for a combination of ST and PLP stands in SA. FH mass only shows the relationship between the mass of the F + H (duff) layer and the depth of the destructive sample.

The L layer mass increased slightly with total ash-free mass, although the relationship was weak ($r^2 = 0.18$). The mass of the F ($r^2 = 0.94$) and H ($r^2 = 0.51$) layers increased significantly with total ash-free mass. The F layer accounted for the largest proportion (60% to 80%) of the total mass of the six heaviest FF samples. Due to the uncertainty of the boundary between the F and H layers, the two layers were combined into an FH or duff layer. This resulted in an almost direct correlation ($r^2 = 0.99$) between the mass of the duff layer and increasing total ash-free mass (**Figure 3.6**). As the total FF mass increased, the F layer contributed a greater proportion of the total mass, in comparison to the L and H layers (**Figure 3.7** and **Figure 3.8**). Basic summary statistics for the destructive sample depth, mass and ash-free mass of the FF are provided in **Table 3.1** and summary statistics for the random FF depth measurements are shown in **Table 3.2**.

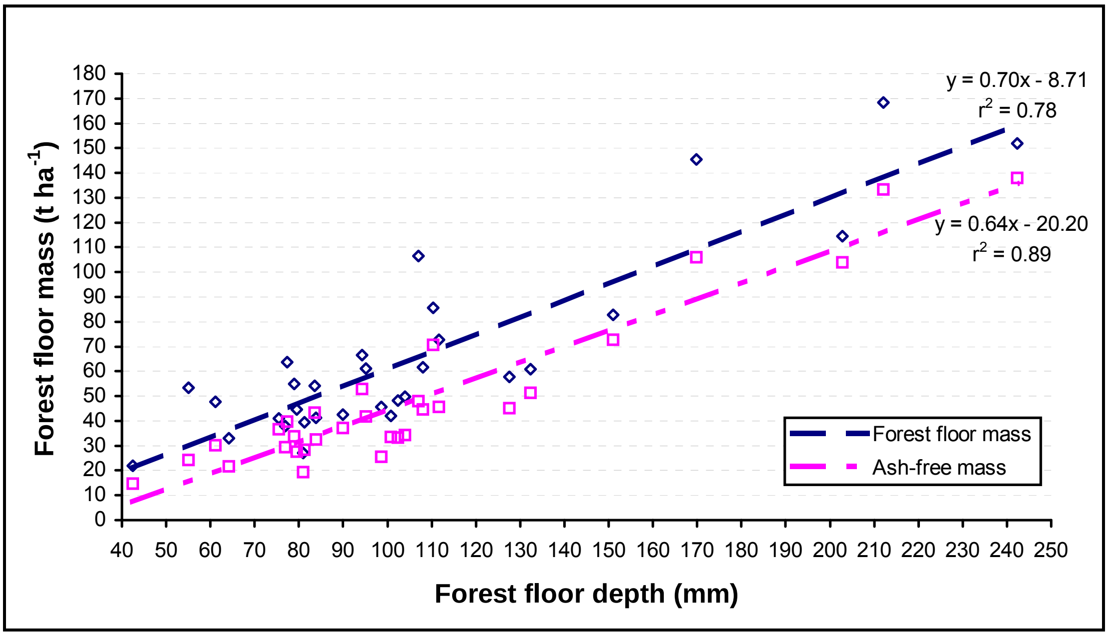

Figure 3.5: Forest floor mass and ash-free forest floor mass versus forest floor depth.

3.3.3 Litter mass-site and stand variables

Two existing models (Morris, 1986 and Dames *et al*., 1998), developed for the prediction of FF mass using altitude and stand age, are summarised in **Appendix 3.2**. These models were both developed within relatively narrow geographical ranges for *P. patula* PLP stands in Swaziland, and ST stands in MPUE, respectively.

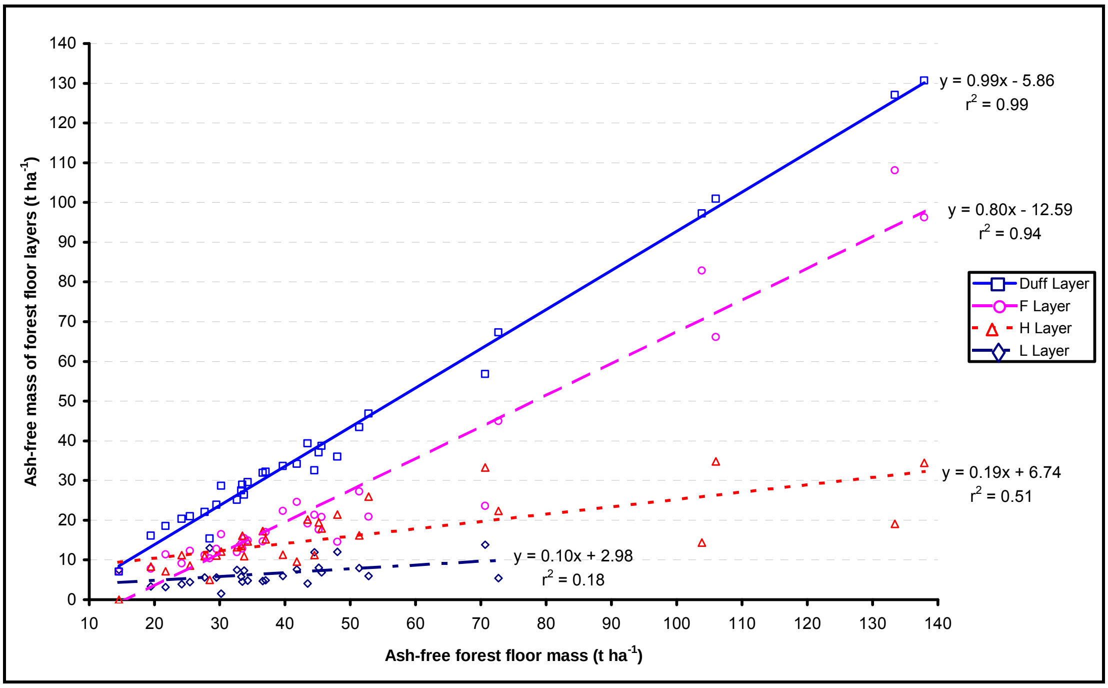

Figure 3.6: Mass of the L, F and H layers as a proportion of the total ash-free mass.

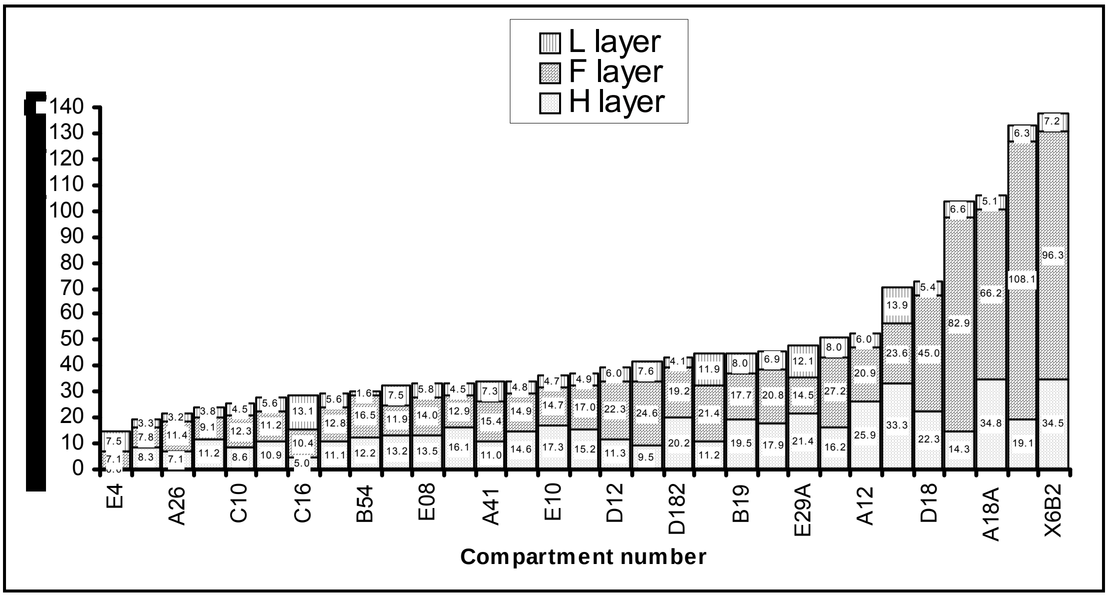

Figure 3.7: The total ash-free FF mass for a number of ST and PLP stands in SA. Sites are arranged in order of increasing total ash-free mass (t ha^{-1}).

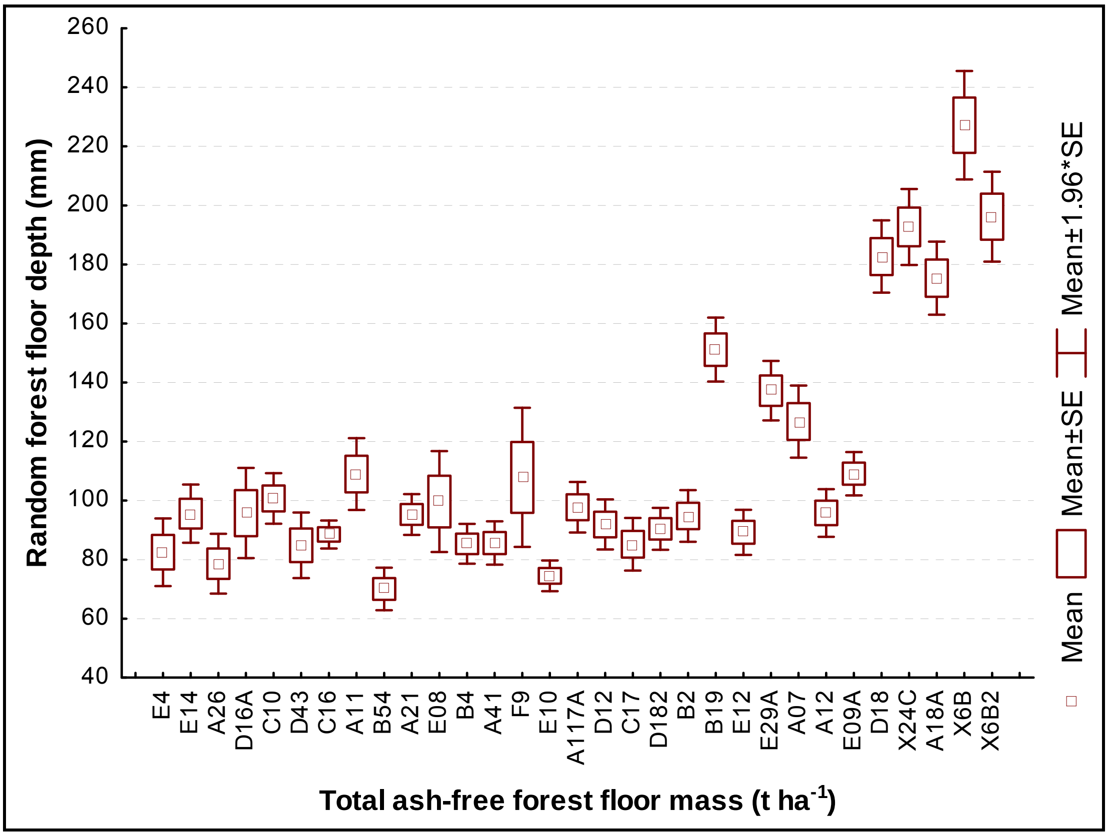

Figure 3.8: Variation of FF across the site for a number of ST and PLP stands in SA. Sites are arranged in order of increasing total ash-free FF mass (t ha-1).

Multiple regression with best subsets selection (Statsoft, 2003) was used to determine which of the site and stand variables in this study could best be used to predict FF. Age, altitude, MAP, MAT, soil depth, number of rotations, MAI and final stems per hectare were entered into the model. The multiple regression analysis showed that age, altitude and MAP provided the best variable subset and accounted for 72% (n = 24, SE = 19.47) of the variation in the ash-free mass, although age was not significant (*p* = 0.09). Mallow's Cp criterion (Mallows, 1973; Neter *et al*., 1996) verified that these three factors provided the best fit. The multiple regression model developed in this study is presented in **Equation D**. This equation (**Equation D**) was developed on a narrow range of stand ages and site altitudes. The use of this model is therefore restricted to mature sawtimber and pulpwood stands ranging from 11 to 37 years old and 1000 to 1800 m. a.s.l in altitude. The application of this model to sites that fall outside this range will result in incorrect predictions of the FF load.

Equation D: Model predicting ash-free FF mass using age, altitude and MAP for a combination of ST and PLP stands in SA (Multiple r^2 = 0.72, SE = 19.47) (this study).

$$LM_{Ash-free} = 1.17(Age) + 0.08(Alt) + 0.11(MAP) - 193.71$$

Where: $LM_{Ash\text{-}free}$ = Ash-free FF mass (t ha^{-1})
Age = Stand age (years)
Alt = Stand altitude (m)
MAP = Mean annual precipitation (mm)

3.3.4 Variability of the litter in terms of depth and mass

The average random FF depths per compartment are presented in **Figure 3.7**. Variability in the random FF depth did not increase significantly with increasing FF destructive sample mass. The average destructive sample depth for ST stands was 124.3 mm (n = 15, SE = 11.2 mm) and for PLP stands, 89.8 mm (n = 16, SE = 10.8 mm). Random mean FF depths, SEs, confidence intervals and number of depth measurements are presented in **Table 3.2**. The thickest destructive sample depth of 242.3 mm (151.9 t ha^{-1} or an ash-free mass of 137.9 t ha^{-1}) was recorded under a 37-year-old thinned stand at an altitude of 1625 m a.s.l. at Komatiland Forest's (KLF) Tweefontein Plantation. The thinnest depth recorded was 42.5 mm (21.8 t ha^{-1} or an ash-free mass of 14.6 t ha^{-1}) at an altitude of 1015 m a.s.l. at KLF Witklip Plantation (compartment E4) (**Appendix 3.1**).

Table 3.2: ST and PLP random FF depth, SE, confidence intervals and number of measurements.

Product	Mean FF Depth (mm)	SE	Confidence Interval (-95%)	Confidence Interval (+95%)	N
ST	134.0	2.5	129.1	138.8	300
PLP	93.0	2.4	88.3	97.7	320

Although there is variation in the total FF load between sites and products, the mass of the L layer remains fairly constant across both. The average L layer mass was 7.4 ± 3.0 and 5.7 ± 2.6 t ha^{-1} for ST and PLP, respectively. The F (16.6 ± 5.5 t ha^{-1}) and H layers (13.5 ± 5.4 t ha^{-1}) of PLP stands were also fairly constant, irrespective of layer thickness. The largest variation (in absolute terms) occurred in the F and H layers of ST sites, with average values of 36.6 ± 34.7 and 18.0 ± 10.0 t ha^{-1}, respectively.

3.4 Discussion

3.4.1 Litter depth-mass relationship

It is important to understand what causes the build-up of the FF, how it is partitioned into various layers and how these are arranged in order to pro-actively manage it for fire protection purposes. Relationships can be developed between known stand characteristics and FF loads to allow simpler methods for acquiring necessary information to be used for making fuel management decisions. Forest floor depth is one variable known to be directly related to the FF load (Dames, 1996; Harrington, 1986; Morris, 1986; Schutz *et al.*, 1983). A close relationship between mass and depth, once established, allows for only depths to be measured and then converted to a measure of oven-dry mass ha^{-1}. However, once a relationship has been established for one area or species, its applicability to other species, sites and areas is unknown. Caution should be used in the wide application of these relationships due to obvious differences in loads under adjacent stands of the same and different species and less evident differences in the bulk density of the FF material (Harrington, 1986; Schutz *et al.*, 1983). The models published prior to this study were all developed in relatively narrow geographical areas on either unthinned or thinned stands, and their applicability to a combination of thinned and unthinned stands over a wider geographical range was uncertain.

It has been reported that FF loads under stands of *P. patula* can exceed 300 t ha^{-1} (Schutz, 1982; Schutz *et al.*, 1983; Schutz, 1990). Loads exceeding 200 t ha^{-1} under unthinned stands in Swaziland have also been presented by Morris (1986). Forest floor loads under mature *P. patula* average 6.2 t ha^{-1} in Tanzania (Lundgren, 1978), and range from 7.9 to 23.2 t ha^{-1} in India (Singh, 1982). Dames (1996) reported ash-free loads ranging from 31.4 (± 13.5) t ha^{-1} to 65.5 (± 29.5) t ha^{-1} for an age series of *P. patula* ST stands and Carlson and Allan (2001) a figure of 54.1 (± 6.9) t ha^{-1} (not corrected for contamination).

The model developed in this study takes into account the rotation ages currently found in commercial forestry over a broad, geographically-diverse range of sites. A single model is presented for the prediction of FF mass (not corrected for contamination) from a measure of the FF depth. The results obtained in this study are consistent with more recent estimates (Bird, 2001; Carlson and Allan, 2001; Dames, 1996) of the FF load under *P. patula* in SA, and indicate loads are typically not as thick as have been reported in the past.

The two earlier models (Morris, 1986; Schutz *et al.*, 1983) applied to the data in this study predicted much higher values than were actually weighed at each of the study sites (**Figure 3.3**). This is largely due to the older stand ages included in the model development (Morris, 1986; Schutz *et al.*, 1983) and the fact they were developed using masses not corrected for soil contamination, and the smaller geographical range in which they were developed. The more recent model (Dames, 1996), was developed using ash-free mass, and predicted values that correspond very closely to the weighed (uncorrected for contamination) masses in this study. Dames' model (**Figure 3.4**) predicted similar values to the measured masses prior to ashing, higher values at the lower end of the depth range and very similar values at the top end of the range, but higher than those determined after ashing. This could be as a result of differences in stand age, the geographical range of that study, and the fact that only ST stands were included. What is clear is that Dames' model, although it over-predicted ash-free values, better reflects current rotation ages and silvicultural regimes, and predicts more realistic FF loads that are in line with those measured in the current study, than the two earlier models (Morris, 1986; Schutz *et al.*, 1983).

3.4.2 Litter depth- ash-free mass relationship

The nature of the FF and the collection of large samples mean that measured masses can be largely inflated due to sample contamination with soil. This is particularly evident in the F and H layers and in thinned stands where the layers are well mixed with the mineral soil. A loss on ignition procedure ensures that the mass of any soil collected is excluded from the final measured loads and that a better relationship is achieved between the ash-free mass and the depth of the FF. Dames (1996) reported ash-free values ranging from 73 to 95% for the L layer and 26 to 84% for the duff layer.

Forest floors found under *P. patula* stands in this study, given current rotation lengths and pruning and thinning regimes, are not as thick as those reported previously in the literature. Trees are grown on shorter rotations and are pruned and thinned according to standard regimes that are implemented across the board. Many of the excessively heavy loads previously reported were measured in stands that are today the exception rather than the rule (De Ronde, 2004, *pers. comm.*[5]). The relationship formulated by Schutz *et al.* (1983) was developed in a 44-year-old stand with stocking levels and stand ages that are not currently used in commercial plantations, and the ash-free mass was not taken into account. Standardisation of the collection procedure, by taking the ash-free mass into consideration into the development of a model, has lead to lower and more realistic loads being measured and predicted and therefore, will facilitate more accurate fire behaviour modelling and risk prediction.

3.4.3 Litter mass-site and stand variables

Organic material accumulates on the FF as a result of the imbalance between the input and output processes of the system and is not as a result of increased biomass production (Dames, 1996). Decomposition is controlled by the quality and physical structure of the organic material, temperature, moisture, relative humidity, pH, microbial activity and the

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[5] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

composition of soil micro flora and fauna (Dickinson and Pugh, 1974 cited in Dames; Swift *et al*., 1979, cited in Dames, 1996) and the mass of the FF has been shown to increase with a decrease in the quality of organic material, i.e. in the ratio of nitrogen to tannins, polyphenolics, lignin, and cellulose. Environmental factors such as temperature, moisture and pH, which affect microbial activity, are responsible for accumulation at high altitude (Dames, 1996). These conditions (cooler temperatures, more precipitation and mist) lead to the F and H layers remaining moist for long periods, resulting in anaerobic conditions, which are not suitable for soil floral and faunal activity. Although the F layer of the FF is regarded as the most microbiologically active area (Woods and Raison, 1982 cited in Dames, 1996), unfavourable conditions at high altitudes are responsible for its accumulation.

The total mass of the FFs in this study increased with both age and altitude. The mass of the L layer remained fairly constant regardless of age or altitude, while the mass of the F and to a lesser extent the H layer, increased with both age and altitude and accounted for a greater proportion of the total FF load. Age, altitude and MAP accounted for 72% of the variation in the ash-free mass observed in this study. **Equation D** shows that a good prediction of the ash-free mass can be calculated simply by knowing these three factors, which can be obtained from compartment records and from the ICFR's Toolbox programme (ICFR, 2004; Schulze, 1997). A good prediction of ash-free FF mass can be obtained by combining a number of site and stand factors (Dames, 1996, Dames *et al*., 1998; Morris, 1986; Schutz, 1990). Models for FF prediction are useful for determining where accumulation is, or has the potential to become a problem, and highlighting those stands where fuel management could be implemented to reduce the fire risk. Forest floor mass increases with stand age, however, the range in mass also increases with age. This suggests that other factors play a role in determining the rate of accumulation (Morris, 1986). Dames (1996) showed that accumulated FF mass was greater in high altitude (above 1200 m a.s.l.) than in low altitude stands (below 1200 m a.s.l.), and that the L layer accounted for a greater proportion of the total mass in higher altitude sites and in older stands. She also reported that the mass of the F layer as a proportion of the total FF mass declined with age at high altitude, which is in contrast to the observations of the present study. She attributed the amount of woody residue in the FF to silvicultural operations, HR remaining from previous rotations and natural pruning (Dames, 1996). The differences may have resulted from the way that the FF layers were defined in the sampling process.

Dames (1996) concluded that a slow decomposition rate was the major driver of FF accumulation. Altitude, latitude, rainfall, slope position and stand factors including site index, mean annual increment, basal area, and height and stand age are all determinants of FF mass. Morris (1986) examined altitude, slope position, site index, stand age, basal area and height as predictors of FF mass and found that age and altitude provided the best correlation

(r^2 = 0.89). Dames (1996, and *et al*.; 1998) found that altitude accounted for 41% of the variability in the mass observed and that a combination of age and altitude (r^2 = 0.38) provided the best correlation with ash-free FF mass. The diffence in the relationships of site and stand factors to the mass of the FF of these two studies could be as a result of the geographical diversity of these two studies, different products (ST versus PLP) and site elevation and stange age differences.

3.4.4 Variability of the litter in terms of depth and mass

Information regarding previous preparation operations for the sites included in this study was limited. A survey was conducted at the beginning of the study and companies were asked to estimate the proportion of their area under *P. patula* that is burnt before re-establishment and answers ranged from 10 to 90%, but no compartment specific data were available. It is likely that the majority of these sites were burnt at some point in history as fuel burning was a routine practice before the 1970s (Carlson and Allan, 2001; Morris, 1986) and was still commonly used in the 1980's and 1990s. There was evidence of charcoal below the FF in some compartments, indicating that a comparatively recent fire had burnt through these compartments resulting in the thin FF, or that the fuel was burnt at re-establishment. Given that *P. patula* is susceptible to fires, it is more probable that these fires were burnt before re-establishment (or that the stand was re-established after a serious wildfire as it is uncommon to practice prescribed burning inside *P. patula*) and therefore that the age of the FF is the same as the age of the stand. These stands also occurred at lower altitude, which is a further reason for the thin FF, as FF loads have been shown to accumulate at high altitude above 1200 m a.s.l. (Dames, 1996). The variability of the random FF depths around the site mean has been attributed to the heterogeneous nature of the FF, changes in micro-topography, rotation of the stand, FF decomposition rate, pruning and thinning operations, and whether the stand was burnt after clearfelling or wildfires (Dames, 1996; De Ronde, 1983). Schutz *et al*. (1983) also reported thicker FFs at the base of trees, with thickness decreasing with an increasing distance from the tree. The major differences in FF depth observed in the compartments included in this study were as a result of changes in the micro-topography of the stand (rocky outcrops and hollows) and the presence of residue from pruning and thinning operations. Rocky outcrops were most often encountered on steep slopes with shallow soils and resulted in areas with almost no FF accumulation. Steep, rocky sites are generally of poor quality and this often results in trees having a lower leaf area and a lower turnover rate of needles on these sites. All depth outliers were recorded in areas of old pruning and thinning residue. Pruning rows in PLP stands are often still visible at rotation end due to the short space of time between pruning and clearfelling. Pruning rows in ST stands have mostly decomposed but residue from thinning operations is often still present (De Ronde, 2004, *pers. comm.*[6]).

An effort was made to locate stands that had average FF depths similar to those previously reported in the literature but none exceeding an average total depth of 240 mm could be found. It was in fact rare to find compartments that had depths exceeding 200 mm. Only six plots had an average random depth deeper than 150 mm. The random depth measurements recorded in this study (20 - 280 mm) are lower than those reported by Schutz (1990) (30 - 350 mm) but are closer to those obtained by Dames (1996) (39 - 121 mm) and Morris (1986) (25 - 210 mm). It must be noted that stands selected for this study were considered to be mature and were either in the process of being clearfelled or, were scheduled for felling within the near future. Dames (1996) included stands as young as 5 years in her study. These lower depths can be accounted for, to a large extent, by the younger stand ages included in this study and in the study by Dames (1996), as well as the absence of 'abnormal' sites. Average ages were 29 and 16 years for ST and PLP stands, respectively in this study, 18 years (ST) in Dames (1996), 38 years in Schutz (1990), and 44 years in Schutz *et al*. (1983). The average age of the PLP stands in Morris (1986) was 18 years. The oldest stand that could be found for inclusion in this study was a 37-year-old second rotation thinned stand on KLF's Tweefontein plantation and the youngest, two eleven-year-old unthinned stands on Natal Co-operative Timber's (NCT) Peak plantation and Mondi's Goodhope plantation.

The results from this study indicate that i) a good relationship between the FF depth and ash-free mass exists for *P. patula* across the summer rainfall region, ii) a single model can be used to predict ash-free FF mass for both thinned and unthinned sites and iii) it is unnecessary, in the case of *P. patula*, to separate PLP and ST stands when predicting the ash-free FF mass in the summer rainfall region of SA.

3.4.5 Required accuracy level

In applying the FF load prediction models reported in this study, and other existing models, to predict ash-free FF fuel loads for use in fire behaviour prediction and prescribed under-canopy burn planning, it is important to determine the level of accuracy required to meet management requirements. Stand level estimations of fuel loads can be predicted from a number of methods, each with inherent levels of accuracy and limitations. The level of accuracy required will determine the method of load determination. This chapter has presented two methods for predicting the FF load of a *P. patula* stand. Models predicting fuel

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[6] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

load from direct depth-mass relationships provide a greater level of accuracy than models that predict the fuel load from a number of site and stand factors that are only indirectly related to the mass. In the first model (**Equation C**), FF depth accounted for 78% of the variation of the FF ash-free mass. The depth-ash-free mass equation can accurately predict the ash-free load within a SE of 10.5 t ha^{-1} (Adjusted $r^2 = 0.89$, $n = 31$, $SE = 10.48$). If a fairly high level of accuracy is required then this is the preferred method, although it requires the collection of a number of depth measurements from the stand in question. The depth mass relationship in this study was developed using the average of the eight depth measurements from the destructive sample to provide a more accurate estimate of the average depth of the sample. It is important to collect several depth measurements and obtain the average to take the variability of the FF across the stand into account and to provide a more accurate prediction of the FF load. In the second model (**Equation D**) age, altitude and MAP accounted for 72% of the variation (Adjusted $R^2 = 0.68$, $n = 24$, $SE = 19.47$) in the ash-free mass of the FF. This model can predict ash-free mass within 19.5 t ha^{-1}. The adjusted R^2 value reflects both the number of explanatory variables in the model and the sample size, and is necessary to consider when comparing two or more regression models that predict the same dependent variable but have different numbers of explanatory variables. A comparison of the adjusted R^2 values shows the greater accuracy of the first method. Although this method (**Equation D**) is less accurate, it can still predict the FF mass reasonably accurately. It can be used where the required level of accuracy is lower, such as for strategic planning on a regional scale, without having to record FF depth measurements from each compartment. Results can be calculated by inserting computer based compartment information into the model.

3.4.6 Management Implications

The FF fuel load has an indirect effect on fire behaviour through its influence on the moisture content and bulk density of the FF. Fire behaviour is determined by the percentage 1-hr fuel load available (De Ronde, 2004, *pers. comm.*[7]). The main factors contributing to high fire intensity are abundant light fuels, low relative humidity and wind (Joubert, 2004, *pers. comm.*[8]). Forest floor fuel moisture content or the fine fuel moisture content (FFMC) is the most important factor influencing fire behaviour, as it affects the rate at which the fuel will burn, and the moisture distribution in the FF affects the amount of fuel available to burn (Lawson *et al*., 1997; Little and Ohmann, 1988; Tolhurst and Cheney, 1999 in van der Sijde, 2003). Fine fuel moisture content influences the potential for ignition, intensity, and the effect of fire duration on the depth of the burn and what portion of the fuel actually ignites and

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[7] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

[8] Joubert, S. 2004. Personal communication. Fire Consultant, Wildfire Afrique, White River, Mpumalanga.

sustains combustion at the fire front. The FFMC is dynamic and is driven by the gradient between atmospheric and fuel moisture as well as the size of the fuel and the composition of layers. The magnitude of the change in the moisture content of the FF is driven by changes in the relative humidity. It is difficult to measure the moisture content of the FF layers because the structure and composition of the organic material is highly heterogeneous (Ferguson *et al*., 2002). The FFMC can be monitored by destructive sampling of the FF at regular intervals, using fuel moisture sticks or using *in situ* time-domain reflectometer (TDR) probes (Beck, unpublished; Ferguson *et al*., 2002).

The amount and duration of rain affect the level of penetration of moisture into the FF and also how much water is absorbed. A very light rain might only wet the L layer but heavier rain would be needed to wet the F and H layers. Shallow floors exhibit sharp increases in moisture content after every rainfall event, while thick FFs only respond to heavy and sustained rain events. The moisture content of the L layer only reaches levels comparable to the F and H (duff) layers during the heaviest rainfall events and then drops off quickly. This is largely due to the porous structure of the FF, which is efficient at absorbing moisture, and the difference in the bulk densities of the L and duff layers. The L layer wets and dries more quickly than the duff layer due to its high porosity, which allows air to circulate more readily (Ferguson *et al*., 2002). Thin layers are highly dynamic and are able to burn shortly after a rainfall event and therefore pose a relatively high fire risk. Thick layers stay wet for much longer periods, are denser and therefore have less oxygen available to sustain combustion and represent a lower risk for most of the year because of their sustained, high FFMC. It is not only the lack of aeration that suffocates burning under a crown canopy, but the crown canopy and stem density also reduce wind speed and air temperature, and increase relative humidity with the result that thinned stands with a lower stand density and percentage crown cover can burn within 24 to 48 hours after rainfall, while others with a higher stand density and crown cover can only burn after a drying out period of 10 to 14 days (De Ronde, 2004, *pers. comm*.[9]).

Forest floor layers have differing time lag lengths, which is the number of hours or days the moisture content of the layer takes to reach equilibrium with the surrounding atmosphere. Time lag lengths differ with temperature and fuel type. Lawson *et al*. (1997) report that the time lag period for the L layer (with a nominal depth of 1.2 cm) to reach equilibrium is approximately 16 hours in western Canada. The time lag for loosely packed duff (which corresponds to the F layer with a nominal depth of 7 cm) is approximately 2 weeks and that of deep, compact organic layers (deep F and H layers with a nominal depth of 18 cm) is approximately 2 months for FFs under average climatic conditions experienced there. The

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[9] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

summer rainfall region of SA experiences long, dry winters, with dry periods from three to five months, which could lead to the drying out of the thickest layers to below a critical level required for ignition and sustained burning. This means that the moisture content of stands with lower fuel loads that dry out more quickly are much more volatile and have the potential for much greater fire intensity than stands with thick, moist FFs which tend to be more stable. The drying rate of the available fuel depends on the 1-hr fuel loading and density (De Ronde, 2004, *pers. comm.*[9]). Generally, it is the L layer that burns off during a fire (Bird, 2004, *pers. comm.*[10]). However, if this is followed by further dry weather and needle drop from the burnt stand, fire may again burn through the compartment, either from flare-ups from smouldering duff layers or from a completely new fire (Joubert, 2004, *pers. comm.*[11]). The impact on soil will depend on the amount of fuel consumed. There will be little impact where a substantial bottom 1-hr layer or duff remains unburned and significant impacts where all FF material is consumed. Where the majority of the FF is burned off, the impact is related to the FLI and length of time that the soil was exposed to fire. In fuel the impact will be patchy as a result of the disturbed nature of the fuel loading. A prescribed harvest residue (HR) burn carried out after clearfelling will have a greater FLI and burn for longer than an under-canopy burn (i.e. with a longer residence time). The fire impact on the soil will be lower when an under-canopy burn is applied (De Ronde, *pers. comm.*, 2004[12]).

The characteristics of any biomass burn follow a fairly regular pattern. Shortly after ignition a flaming phase continues for several minutes, after flaming, woody material begins to smoulder. In compartments with deep duff layers and rotten wood, a residual smouldering phase can continue from a few hours to several days. If the duff layer is moist, smouldering will not occur; smouldering can occur where 100% of the FF is consumed, and where significant H layer and/or humus pockets and old root channels are present (Bird, 2004, *pers. comm.*[13]; De Ronde, 2004, *pers. comm.*[12]). The magnitude of the consumption depends on the fuel loading, and moisture and oxygen availability. The duration of each phase is primarily a function of the size, distribution, packing, and the moisture content of the fuel. The duff layer has a tendency to burn laterally rather than downwards, and will burn independently of the L layer below a moisture content of 30%, and will hardly burn above moisture content levels of 120%. Between these levels, the amount of the duff layer consumed by a fire will depend on its moisture content and the amount of heat from the surface fire (Brown *et al.*, 1985, Brown *et al.*, 1991). A further factor influencing duff consumption during a fire is the pre-burn duff depth. The relationship between the total FF

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[10] Bird, TL. 2004. Personal communication. M.Sc. in prescribed burning under *P. patula*. Randburg, Gauteng.

[11] Joubert, S. 2004. Personal communication. Fire Consultant, Wildfire Afrique, White River, Mpumalanga.

[12] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

[13] Bird, TL. 2004. Personal communication. M.Sc. in prescribed burning under *P. patula*. Randburg, Gauteng.

depth and the ash-free mass of the duff layer presented in **Appendix 3.2** will assist in future fire risk and behaviour analysis and prediction.

3.5 Conclusions and Recommendations

The results from this study indicate that FF loads found under thinned and unthinned *P. patula* stands in the summer rainfall region of SA, given current rotation lengths and pruning and thinning regimes, are not as thick as those reported previously in the literature for southern Africa. A good relationship exists between FF depth and ash-free mass for *P. patula* across the region and a single model can be used to predict ash-free FF mass for both thinned and unthinned sites, to within 10 t ha^{-1}. A model to predict the ash-free mass of the pre-burn duff layer has also been presented. The amount of duff consumed by a fire and the resulting effect on the nutrient pools of the site depend to a large extent on the pre-burn duff depth and the moisture content of the duff layer. The flammability of the duff layer is important because duff consumption is one of the main sources of the energy produced in forest fires (Lawson *et al*., 1997). This model for the prediction of ash-free duff mass will play a role in determining the amount of duff present on the site, how much could be consumed in a fire and ultimately, the effect of fire on the nutrient pools present on the site. The amount of nutrients contained in the FF can be determined by knowing the mass and nutrient concentration of the FF. If the pre-burn FF load and nutrient mass are known and the post-burn FF load is determined, an estimate of the nutrients lost from the site can be obtained.

Forest floor depth has a greater range under ST stands (as a whole) than under PLP stands although outliers were observed in PLP stands. This is largely due to the age differences and the effect of pruning and thinning operations. Although there is variation in the total FF depth and load between sites and products, the mass of the L layer remains fairly constant across both. Individual layer depths were not measured in this study but an average layer load was determined for each layer for both ST and PLP stands. Any soil contamination of the sample as a result of the sampling process can be removed by conducting a loss on ignition process on sub-samples of the FF. A loss on ignition procedure provided a better fit between FF depth and ash-free mass, allowing for the more accurate prediction of fuel available for consumption within the compartment. Ash-free mass can also be predicted accurately by using site and stand variables such as age, altitude and MAP. The level of accuracy required for management purposes will determine the method to be used to predict the FF fuel load as part of fuel load and fire management.

There is lack of understanding of the moisture dynamics in standing *P. patula* plantations in SA, particularly where thick L and duff layers accumulate, and knowledge of the moisture profile drying rates is urgently required (De Ronde, 2004, *pers. comm.*[14]). The need for improved fire behaviour prediction and pro-active fire management has resulted in the need for more informed information regarding the FF as a fuel component (Barney *et al*., 1981). Information regarding the FF is absolutely necessary in evaluating the effects of fire, either wildfire or prescribed burning. Fuel load has an indirect effect on fire behaviour and intensity. The FF load is directly related to the moisture dynamics of the fuel complex and it is the FFMC that is the most critical factor affecting FLI and fire behaviour. Thick, moist FFs will carry fires of lower intensity, and are more stable than thin FFs whose moisture content fluctuates widely. A modelling exercise to determine the effect of increasing fuel load and FFMC under known environmental and topographical variables was carried out using BehavePlus and is presented in **Appendix 3.3** and **Appendix 3.4**. There are currently no suitable FFMC (L and duff layer) data available in SA to accurately predict fire behaviour and risk, although some fire hazard – risk classifications have been developed in southern Africa as part of integrated fire management studies (De Ronde, 2004, pers. comm.[14]). Future research on fire risk and behaviour in commercial plantations in SA would require the measurement and monitoring of the FFMC over both time and space. An index of fire risk based on the depth of the L and duff layers, the moisture content of these layers, FLI, fuel density and maximum spotting distances should to be developed (from BehavePlus) for a range of *P. patula* fuel models. This would improve fire risk analysis and fire behaviour prediction within the SA context. Fine fuel moisture content should be modelled across the range of FF depths to determine the effects that it has on fire behaviour and risk.

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[14] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

4. HARVEST RESIDUE FUEL LOADING AFTER CLEARFELLING *Pinus patula* SAWTIMBER AND PULPWOOD STANDS IN SOUTH AFRICA

4.1 Introduction

Harvest residue (HR) is one of the most obvious results of a harvesting or thinning operation and consists of needles, crown tops, branches, unmerchantable logs and stumps. It can potentially cause a variety of problems, such as creating a fire hazard and affecting wildfire behaviour, impeding silvicultural activities (especially site preparation and planting, which in turn lead to poor transplant survival and growth), and providing a habitat for insects and disease (Allan *et al*., 2001; Goldammer, 1981; Hall, 1991; Howard, 1973; Rolando and Allan, 2004). Very little work has been done in South Africa (SA) on quantifying forest floor (FF) (consisting of needles, branches, twigs, bark, cones and strobili prior to clearfelling) and HR loads (following clear felling) in terms of fuel classes for fire behaviour prediction and for the development of custom fuel models for *Pinus patula* (Bird, 2001; Carlson and Allan, 2001; De Ronde, 2003; Teie, 2003).

According to Anderson (1982), an accurate description of the fuels on a site requires the identification and characterisation of the fuel components, which include the FF (litter and duff layers), the woody material, grasses, shrubs, regeneration and timber. Fire behaviour prediction programmes (such as BehavePlus) require descriptions of fuel load properties, representing stylised fuel situations, as inputs to calculations of fire behaviour potential. These stylised fuel situations are termed fuel models (a simulated fuel complex for which all the fuel descriptors of the mathematical fire spread model have been specified). Fuel models generally describe four general fuel situations, namely grass, shrub, FF and HR, the last two of which are dealt with in this chapter. The fuel load and depth play a large role in determining if a fire will ignite, its rate of spread and its intensity, which is the most important factor to consider when determining the impact of a fire on the nutrient pools of the site. A fuel model is described by the fuel load, the surface-to-area volume (SAV) ratio for each fuel class, the depth of the fuel and the fuel moisture. The finer the fuel, the higher its SAV ratio, the more quickly it will release its moisture and less heat will be required to ignite it. The fuel moisture at which the fire will not spread is also included in the model and is termed the moisture of extinction (Anderson, 1982; Andrews, 1986). A fire will burn in the fuel that is best able to support it and situations may occur where more than one fuel model will be required to describe the fuel conditions present on the site or the rate of spread and fire intensity. Due to the variety of fuel, climatic and site conditions that exist, the selection and use of fuel models needs to remain flexible. Under-canopy fires are generally slow burning with low flame lengths, although flame lengths will increase if the fire encounters areas of dead, woody material. These fuel loads only pose a serious threat under severe weather conditions of high temperatures, low humidity and high wind speeds (Anderson, 1982). Light, patchy and ageing HR provides limited fire potential and will only be able to sustain small, slow moving fires. On sites where the HR has been broadcast, or is fairly continuous and well distributed, the fuel load will sustain rapidly spreading fires with high intensities until a fire break or change in the fuel load, such as an extraction road is reached. On sites with heavy, continuous HR loads containing a large proportion of 100- and 1000-hr fuels, fires will spread quickly through the fine fuels and the intensity will build up as the large fuels ignite. Flaming will be sustained for long periods and firebrands may develop leading to spotting (Anderson, 1982).

In order to manage fire risk it is critical to be able to predict how a fire will behave under various conditions (Teie, 2003). It is important to have an estimate of the quantity of HR, and its fuel load properties, prior to harvesting, to enable the correct management decisions to be implemented (Howard, 1978). To accurately predict fire behaviour and fire intensity using fuel models, the fuel class distribution has to be known. Harvest residue is divided into fuel classes that are determined by the time it takes for the fuel to reach moisture equilibrium with the surrounding atmosphere, also known as the fuel time-lag (Anderson, 1982; Teie, 2003; van Wagner, 1982a). Presently there are no means available in SA for estimating or accurately predicting the HR load by fuel class on a large scale. Previous HR studies have tended to focus on the effects of HR management on silvicultural aspects of re-establishment (Allan, 1999; Norris, 1993; Pierovich and Smith, 1972; Rolando and Allan, 2004). Harvest residue needs to be characterised and quantified in terms of fuel classes and nutrient pools to provide a greater understanding of its effect on fire behaviour and site nutrition and the implications for management on the long-term sustainability of short rotation plantation sites.

Traditional methods of fuel assessment are carried out using fixed area plots after harvesting was completed. Fixed plots are simple to apply but are costly and inefficient as they involve the collection of large quantities of material from the plot and its subsequent separation into size classes followed by the determination of its dry weight per unit area (Johansen and McNab, 1977; May and Hartong, 1959; O'Hehir and Leech, 1997; Ringvall and Ståhl, 1999). Methods for quantifying HR loads such as the line-intersect sampling (LIS) method, which indirectly measure fuel quantities, are designed for general estimation of fuel quantities in fire research. This particular method has been used extensively internationally for determining the mass of HR and for fire utilisation research (Brown, 1971, 1974; Brown and Roussopoulos, 1974; Brown *et al*., 1982; Catchpole and Wheeler, 1992; De Ronde, 2003; Hazard and Pickford, 1977; Howard, 1973, 1978; O'Hehir and Leech, 1997; Snell and Brown, 1980; Van Wagner, 1968, 1982a; Warren and Olsen, 1964), but has not been applied in SA for quantifying post-harvest fuel loads.

This chapter deals with the HR component and the major objectives are listed below:

1. Harvest residue loading by fuel class and silvicultural regime: to characterise and quantify HR loads generated from clearfelling *P. patula* PLP and ST stands across its planted range in SA using the LIS technique, and provide a number of constants that can be used when calculating HR loads using this technique;
2. Fuel models: to construct a set of custom fuel models for PLP and ST stands, both under-canopy and post-harvest, that will assist in fuel management of *P. patula*;
3. Fire behaviour prediction: to theoretically investigate the effects of HR load and the proportion of the fuel classes on fire behaviour and risk for commercial forestry in SA using the fuel models developed in this study.

4.2 Materials and Methods

4.2.1 Study sites

Information regarding study sites used in this study is presented in **Paragraph 3.2.1** and **Appendix 4.1**. Where possible, the same sites were used for the collection of the FF and HR residue data. All the sites used for the collection of the HR data are given in **Appendix 4.1**.

4.2.2 Harvest residue characterisation and quantification using the LIS method

The LIS method is essentially a strip sample (plot) of infinitesimal width and requires a tally of intersections between sampling planes (sub-plots) and HR pieces categorised by size or hour classes (Anderson, 1982; Teie, 2003; van Wagner, 1982a). These intersections, and the average diameter of each fuel class, result in a number of cross-sectional areas (CSAs), which are summed and divided by the total sample line length to provide an estimate of the average CSA of each fuel class. The fuel load (t ha^{-1}) is then calculated by multiplying the CSA of each fuel class by the mean class HR density. The LIS technique assumes that the pieces of HR to be sampled are oriented at random in a horizontal plane, that pieces are circular in shape, and that there is a normal distribution within diameter classes. The underlying assumptions of the LIS theory were not investigated in this study.

This study involved the determination of the average diameter and density values for each fuel class required to calculate the HR load by fuel class, and the HR depth using the LIS technique. Average slope correction factors (*c*) were calculated using the percent slope of each sampling plane using the formulae provided in Brown (1974). The mass of HR per unit of actual ground area can be converted to a measure of the mass per unit of horizontal area by multiplying by the angle of the slope of the sampling plane (slope correction factors). This is required where knowledge of the HR is needed for fire behaviour modelling. The non-horizontal correction factors (*a*) adjust mass estimates for the fact that all particles do not lie horizontally as assumed in the underlying LIS method theory.

4.2.3 Choice of line layout

There are no available prescriptions regarding the number and size of sampling planes when using the LIS method for quantifying *P. patula* HR in SA. Sampling precision can be controlled by altering the number of plots and the length of the sampling planes, and the more HR present on a site, the fewer the number, and the shorter the length of sampling planes required to achieve a given level of precision (Brown, 1974). Brown (1974) reports that 20 or more sampling planes are sufficient and result in errors of 20% or less, which have been shown to be adequate levels of precision for assessing most fuel problems. Van Wagner (1982a) reported that one plot (triangle sampling method) per 20 hectares of compartment would result in a similar level of precision.

Three-transect lines were laid out in a triangle at angles of 60° (**Figure 1**). Each transect line was divided into five sample planes, each 10 m in length, that followed the direction of the main transect line. The slope of the ground of each sampling plane was also measured from the transect line to the end of the sample plane using a Blumeleiss hypsometer. Harvest residue pieces that intersected the sampling plane were tallied by 0.0 - 0.6 (i), 0.6 - 2.5 (ii), 2.5 - 7.6 (iii), and > 7.6 (iv) cm fuel classes which correspond to the average 1-, 10-, 100-, and 1000-hr fuel classes using a pre-calibrated gauge (Brown, 1974; Teie, 2003). Intersected pieces of HR falling into the first fuel class (i) were tallied over the first metre of each sample plane; HR pieces falling into class (ii) were tallied over the first 2 m and pieces in class (iii) and (iv) were tallied over the full 10 m of each sampling plane. This method of tallying HR pieces falling into different fuel classes takes into account the fact that the smaller diameter pieces are far more numerous and a shorter distance is required for tallying purposes (Brown, 1974). Larger diameter pieces are generally fewer and farther between and require a longer sampling distance to provide a sufficient level of accuracy. The formulae for the calculation of the fuel load in the LIS method (See **Equation E** and **Equation F**) takes this into account by including the number of intersections and the total measured line length per fuel class. The diameters of all intersected pieces, 7.6 cm in diameter and larger, were measured at the point of intersection with the sample line, to the nearest millimetre, using callipers. A total of 25 diameters were randomly recorded for (i), (ii) and (iii) to provide an average diameter value for each fuel class for each site.

Three HR depth measurements, from the average top of the L layer (litter layer, which consists of, unaltered dead plant and animal remains) to the average top of the highest consumable particle (Burgan and Rothermel, 1984), were also taken at 1 m intervals along the sampling plane (within each sub-plot) starting from the sample point using a height rod marked in 10 cm intervals. The HR depths of all the subplots were averaged and 70% of the final depth value taken as the final average HR depth to account variability of the HR (Brown, 1974). The HR is extremely variable in both height and spatial distribution and the 30% reduction in the height of the HR takes this into account.

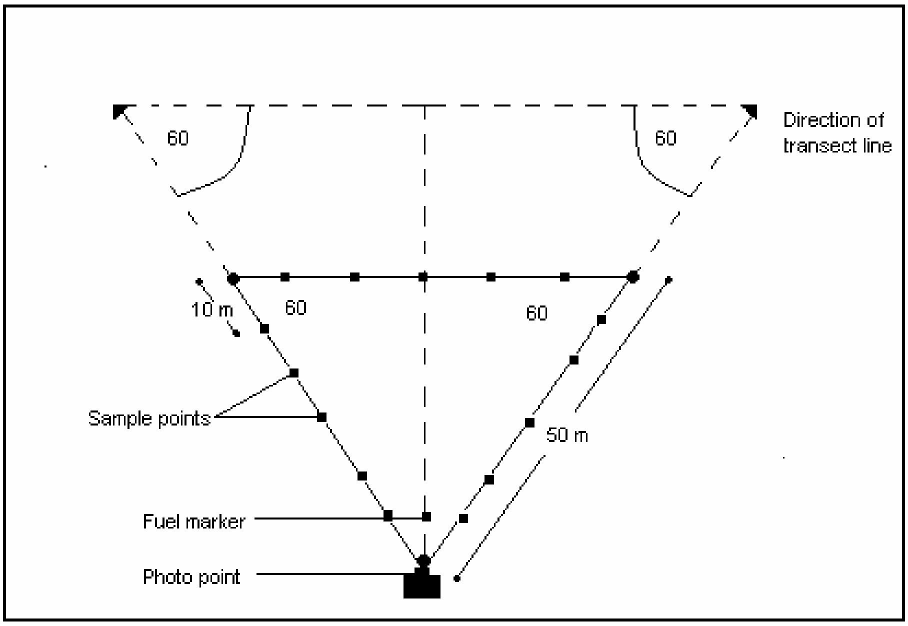

Figure 4.1: An example of the triangle method for line-intercept sampling.

4.2.4 Quantification of the harvest residue mass using the LIS method

The HR loads for each fuel class were calculated using the formulae given in Brown (1974) and shown below in **Equation E** and **F**.

Equation E: Calculation of the mass (t ha^{-1}) of the 1-, 10-, and 100-hr fuel classes for the line-intersect method (Brown, 1974)

$$M_{(1-,10-,100-hr)} = \frac{1.23 * n * d^2 * s * a * c}{N * l}$$

Equation F: Calculation of the mass (t ha^{-1}) of the 1000-hr fuel hour class for the line-intersect method (Brown, 1974)

$$M_{(1000-hr)} = \frac{1.23 * \sum d^2 * s * a * c}{N * l}$$

Where: $M_{(1\text{-}, 10\text{-}, 100\text{-hr})}$ = the mass (t ha^{-1}) of the 1-, 10-, and 100-hr fuels
$M_{(1000\text{-hr})}$ = the mass (t ha^{-1}) of the 1000-hr fuels
1.23 is simply π/8
n = the number of intersections in each fuel class per plot
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
N = the total number of intersections in each fuel class per plot
l = the total line length of each fuel class

The calculated correction factors for slopes ranging from 0 to 110% are provided in **Appendix 4.1**. The squared average quadratic mean diameters (d^2) for each fuel class were first calculated on a per plot basis and then an average d^2 was taken for each fuel class across all sites and products (**Appendix 4.1**). Estimates of d^2 are required for each HR fuel class for the calculation of the fuel load when using the LIS method (van Wagner, 1982b). Non-horizontal correction factors were not calculated in this study but were taken from Brown (1974). These values are given in **Appendix 4.1**.

An average density value was determined for each fuel class (**Appendix 4.1**) and no distinction was made between PLP and ST branch wood. The density of the individual fuel classes for each site was determined using the oven-dry (or moisture-free) volume method. Using a chainsaw, a destructive HR sample was taken, ensuring that each fuel class within the sample was represented. Sub-samples were collected by selecting pieces of HR, from each fuel class, and cutting them into equal and manageable lengths, where necessary. Discs were cut from HR falling into the largest diameter class. Harvest residue sub-samples were weighed and then oven-dried at 105 °C until constant mass was reached. The still-warm discs were then dipped in hot paraffin wax resulting in the formation of a thin layer of wax and allowed to dry. The volume of the sub-samples was determined by suspending them in a beaker of water on a balance and recording their mass. The difference in mass before and after the sub-samples were dipped in wax was determined and multiplied by the density of the wax (δ=0.9) (to provide an estimate of the volume of the wax). This was subtracted from the volume determined in the water, resulting in a more realistic value of wood volume. Wood density was determined by dividing the oven-dry mass by the wood volume (without wax).

The 1-hr fuel load values calculated using the LIS technique do not account for the mass of needles retained on the branches, as this technique does not include measurements of needle loads (Brown, 1974; Burgan and Rothermel, 1984). It is necessary to include the retained needle mass as they form an important component of the fine, or 1-hr fuels. The mass of the needles retained in the HR in the 1- and 10-hr fuel classes were estimated by calculating the ratio of needles-to-branches (Brown, 1974; Burgan and Rothermel, 1984) from a number of biomass studies carried out on *P. patula* ST and PLP stands in southern Africa (Bosch, 1985; Carlson and Allan, 2001; Dames, 1996; Germishuizen, 1979; Morris, 1995) and a ST stand from India (Singh, 1982). The average needle-to-branch ratios for ST (0.35) and PLP (0.38) were then multiplied by the calculated branch mass for the 1- and 10-hr fuel classes. The needle mass was not calculated for the 100- and 1000-hr fuel classes, which are made up of stem wood and large branches that do not contain needles (Brown, 1974).

Two FF (under-canopy) fuel models **(Model 1** and **2**) and two HR (post-harvest) fuel models (**Models 3** and **4**) were developed in this study using the NEWMDL programme of BEHAVE in consultation with De Ronde (2004, *pers. comm.*[15]). Only the 1-hr FF fuel load was measured in this study and the final 1-, 10- and 100-hr fuel loads were calculated in the BEHAVE programme. These values and the rest of the output values from BEHAVE are presented in **Table 4.3** and **Table 4.4**, along with a model (**Model 20**) developed by De Ronde (1996), **Model 8** (Closed timber litter form BehavePlus) and three models (**Light**, **Medium** and **Heavy**) from BehavePlus. For fuel modelling purposes, the distribution range of each fuel class by regime combination (**Figure 4.2**), is sufficiently small to accommodate within two fuel models. BehavePlus also provides a number of built-in fuel models for fire behaviour prediction that cover a range of FF and HR conditions. The majority of the HR loads measured in this study fall within the light to medium range of fuel models provided in BehavePlus (www.fire.org). A description of **Models 3** and **Model 4**, and the **Light**, **Medium** and **Heavy** models from BehavePlus is given in **Appendix 4.2**.

4.2.5 Analyses

A 2 x 4 factorial analysis of variance (ANOVA) (based on the least squared means) was used to investigate the differences in the masses of the fuel classes between ST and PLP sites. The factors were Product Type (ST and PLP) and Fuel Class (1-, 10-, 100-, 1000-hr). The measure response was t ha-1 of fuel within a particular product type and size class. Mean fuel class masses from each site were used for the analyses. If the product type by size class interaction was significant, then one-way ANOVAs were done to identify differences between ST and PLP at each fuel class level. A bootstrap procedure was done to

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[15] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

compute standard errors (SE) for each of the eight treatment combinations due to non-normality of residuals. Then 95% confidence intervals were calculated from bootstrap standard errors. Relative contributions of the calculated mass of each fuel class to the total mass of the sample were also investigated. Analyses were carried out using Statistica 6 (Statsoft, 2003).

4.2.6 Modelling effects of harvest residue load on fire behaviour

In order to manage fire risk it is critical to be able to predict how a fire will behave under various conditions (Teie, 2003). It is important to have an estimate of the quantity of HR, and its fuel load properties, prior to harvesting, to enable the correct management decisions to be implemented (Howard, 1978). Predictions of wildland fire behaviour are made for a point in time and space given simple user-defined fuel, weather, and topography.

BehavePlus uses site-specific input data to predict fire behaviour for a point in time and space. The BehavePlus Fire Modeling System replaces the 1984 BEHAVE Fire Behaviour Prediction and Fuel Modeling System (Andrews 1986, Andrews and Chase 1989, Burgan and Rothermel 1984). The FUEL subsystem of BEHAVE consists of the NEWMDL and TSTMDL programmes (Burgan and Rothermel 1984). The NEWMDL programme facilitates the development of input parameters for development of custom fuel models. BehavePlus uses essentially the same mathematical models as the original BEHAVE but is limited in that it doesn’t provide for the development of custom fuel models and the NEWMDL and TSTMDL programmes of the FUEL subsystem of the old BEHAVE package still have to be used for fuel model development and testing (Burgan and Rothermel, 1984; Trollope *et al*., 2004). BehavePlus does allow for the user to define a custom fuel model via direct input of the fuel characteristics and to display graphs of module input parameters with any of the output values as was possible via the TSTMDL programme.

BehavePlus works on the actual available fuel that is in a 1-hr, 10- or 100-hr state of combustion and the 1-hr fuel load is the most important fuel component as it is responsible for driving the fire. (Andrews, 1986). For the purposes of modelling fire behaviour in BEHAVE, litter is defined as the vertical distance from the top of the F layer to the general upper surface of the L layer (Burgan and Rothermel, 1984). The mass of the L layer of the FF is included separately in BEHAVE for the development of the fuel models (Brown, 1974). The total available 1-hr fuel load, used in BehavePlus was calculated by summing the mass of needles retained on the 1- and 10-hr fuel class HR material, the calculated mass of the 1-hr dead woody fuel and the mass of the L layer of the FF. Fuel models were developed using the NEWMDL programme of the fuel subsystem of BEHAVE, in consultation with De Ronde

(2004, *pers. comm.*[16]), and the models were run using BehavePlus (Burgan and Rothermel, 1984; www.fire.org). The effect of fuel bed depth on FLI given a constant wind speed and zero slope was investigated using BehavePlus.

The effect of fuel bed depth on the FLI given a constant wind speed and zero slope was investigated, using BehavePlus, for under-canopy and post-harvest fuel models. Other models (**Model 20**, **Model 8** and three BehavePlus models, **Light**, **Medium** and **Heavy**, have been included in the study for comparative purposes. BehavePlus works on the actual available fuel that is in a 1-hr, 10- or 100-hr state of combustion and the 1-hr fuel load is the most important fuel component as it is responsible for driving the fire (Andrews, 1986). For the purposes of modelling fire behaviour in BEHAVE, the forest floor is defined as the vertical distance from the top of the F layer to the general upper surface of the L layer (Burgan and Rothermel, 1984). The mass of the L layer of the FF is included separately in BEHAVE for the development of the fuel models (Brown, 1974). The total available 1-hr fuel load, used in BehavePlus, was calculated by summing the mass of needles retained on the 1- and 10-hr fuel class HR material, the calculated mass of the 1-hr fuel and the mass of the L layer of the FF which was determined by Ross and du Toit (2004).

Interactions between fuel model, topography and environmental parameters and the mathematical fire spread model are so numerous that attempting to present all the possible results is unreasonable (Burgan and Rothermel, 1984). The mathematical fire spread model provides a means to estimate the rate at which a fire will spread through a uniform fuel array that may contain fuel particles of mixed sizes (Burgan and Rothermel, 1984).

4.3 Results

4.3.1 Harvest residue characteristics and loading

There was a general trend of decreasing wood density with increasing branch diameter (density values were higher in the 100-hr (0.55 g/cm^3) fuel class than in the 10-hr (0.52 g/cm^3) fuel class) and density values were highest in the 0.0 - 0.6 cm fuel class (0.58 g/cm^3) and lowest in the > 7.6 cm fuel class (0.50 g/cm^3) (**Appendix 4.1**). The HR loads differed visually in physical characteristics between the ST and PLP sites included in this study, a characteristic also observed by Allan (2000), and this was reflected in the data. A two-way cross-classification on the 1-, 10-, 100- and 1000-hr fuel class mass data revealed that there was a significant interaction between product and size (F = 5.65, $p < 0.01$, n = 136). A bootstrap procedure showed that the two silvicultural regimes generated two distinctly different fuel complexes with HR on PLP sites consisting of a significantly greater proportion

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[16] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

of 1-hr (F = 6.00, *p* = 0.02, n= 34), and 10-hr (F = 17.48, *p* < 0.01, n = 34) fuels. As a result, HR on PLP sites tended to be much less compact and deeper than that generated from a ST regime. Harvest residue from ST stands consisted of a larger proportion (not significant) of thick, heavy branches falling into the 100- (F = 0.50, *p* = 0.50, n = 34) and a significantly greater amount of 1000-hr (F = 4.54, *p* = 0.04, n = 34) fuel classes, which resulted in the fuel becoming much more compact than was the case with the PLP stands. Basic summary statistics for a range of sawtimber and pulpwood sites are provided in **Table 4.1** and **Table 4.2.**

Table 4.1: Basic summary statistics for the harvest residue mass, average squared diameter and density for a range of sawtimber sites in South Africa.

	1-hr			10-hr			100-hr					
	d^{2*}	$s^{\#}$	$mass^{\$}$	d^{2*}	$s^{\#}$	$mass^{\$}$	d^{2*}	$s^{\#}$	$mass^{\$}$	$SUMd^{2*}$	$s^{\#}$	$mass^{\$}$
Mean	0.14	0.59	2.27	2.90	0.53	12.28	15.83	0.53	20.06	7111.33	0.48	18.86
SE	0.01	0.01	0.25	0.16	0.01	0.98	0.72	0.02	1.63	1530.55	0.01	3.65
SD	0.02	0.05	0.96	0.62	0.03	3.79	2.81	0.06	6.33	5927.79	0.04	14.14
Min	0.12	0.48	1.06	1.31	0.48	4.94	11.43	0.40	10.56	1537.60	0.40	5.31
Max	0.21	0.68	4.32	3.94	0.61	17.15	20.43	0.65	31.93	24275.24	0.52	59.91

* - cm

\# - g cm-3

\$ - t ha^{-1}

Table 4.2: Basic summary statistics for the harvest residue mass, average squared diameter and density for a range of pulpwood sites in South Africa.

	1-hr			10-hr			100-hr					
	d^{2*}	$s^{\#}$	$mass^{\$}$	d^{2*}	$s^{\#}$	$mass^{\$}$	d^{2*}	$s^{\#}$	$mass^{\$}$	$SUMd^{2*}$	$s^{\#}$	$mass^{\$}$
Mean	0.16	0.58	3.12	3.43	0.54	16.54	14.37	0.56	17.81	2645.98	0.51	10.69
SE	0.01	0.01	0.20	0.13	0.01	0.61	0.56	0.02	1.43	316.39	0.02	1.25
SD	0.03	0.07	0.89	0.58	0.04	2.73	2.48	0.07	6.39	1414.93	0.09	5.61
Min	0.08	0.45	1.25	2.15	0.48	10.48	10.50	0.42	8.98	643.00	0.40	2.56
Max	0.22	0.71	4.46	4.36	0.63	21.90	21.92	0.70	39.12	6183.74	0.71	23.70

* - cm

\# - g cm-3

\$ - t ha^{-1}

Although the total average post-harvest fuel load (excluding the needles retained on the branches) was not significantly different between the two regimes (F = 0.16, *p* = 0.70, n = 34), the range in mass was greater for PLP (mean = 48.2 t ha^{-1}) than for ST (mean = 49.6 t ha^{-1}) sites. Recorded average HR mass (including the needles retained on the branches) was slightly lower for ST (mean = 54.6 t ha^{-1}, SE = 3.04) than for PLP (mean = 55.6 t ha^{-1}, SE = 2.36) stands and again this difference was not significant (F = 0.07, p = 0.79, n = 34). Mean harvest residue depths ranged from 9.6 to 30.3 cm and 15.4 to 32.4 cm for ST and PLP sites, respectively.

The average mass of the 1-, 10-, 100-, and 1000-hr fuel loads (excluding the needles retained on the branches) is shown in **Table 4.1**, **Table 4.2** and **Figure 4.2**. The 1-hr fuel load masses do not include the needles retained on the branches or the mass of the L layer of the FF present on the site prior to clearfelling. Needle mass retained on the branches of the 1- and 10-hr fuel classes was 0.8 ± 0.09 t ha^{-1} and 4.3 ± 0.34, and 1.2 ± 0.08 t ha^{-1} and 6.3 ± 0.23 t ha^{-1} for ST and PLP, respectively. If the mass of the L layer of the FF prior to clearfelling is included (Ross and du Toit, 2004), total average fuel load values recorded in the study range between 46.5 and 85.4 t ha^{-1} (mean = 62.2 t ha^{-1}, SE 3.46) and 46.2 and 86.6 t ha^{-1} (mean = 61.2 t ha^{-1}, SE 2.31) for ST and PLP stands, respectively. Relative percentage contributions of the calculated mass of each fuel class to the total mass of the HR were 4.7%, 24.1%, 39.1% and 32.1% for ST and 6.5%, 34.3%, 37.0% and 22.2% for PLP.

4.3.2 Fuel models for *P. patula* ST and PLP stands in South Africa

The FF layer is made up of needles, twigs and a small amount of herbaceous material, as there is generally little undergrowth in a mature stand, particularly where there is a high percentage crown cover and high stand density (De Ronde, 2004, *pers. comm.*[17]). According to Anderson (1982), an accurate description of the fuels on a site requires the identification and characterisation of the fuel components, which include the FF (litter and duff layers), the woody material, grasses, shrubs, regeneration and timber. Fire behaviour prediction programmes (like BehavePlus) require descriptions of fuel load properties, representing stylised fuel situations, as inputs to calculations of fire behaviour potential. These stylised fuel situations are termed fuel models (a simulated fuel complex for which all the fuel descriptors of the mathematical fire spread model have been specified). Fuel models generally describe four general fuel situations, namely grass, shrub, timber and slash (or HR). The fuel load and depth play a large role in determining if a fire will ignite, its ROS and its intensity, which is the most important factor to consider when determining the impact of a fire on the nutrient pools of the site. A fuel model is described by the fuel load and the ratio of SAV for each fuel class, the depth of the fuel and the fuel moisture. The finer the fuel, the higher its SAV ratio, the more quickly it will release its moisture and less heat will be required

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[17] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

to ignite it. The fuel moisture at which the fire will not spread is also included in the model and is termed the moisture of extinction (Anderson, 1982; Andrews, 1986).

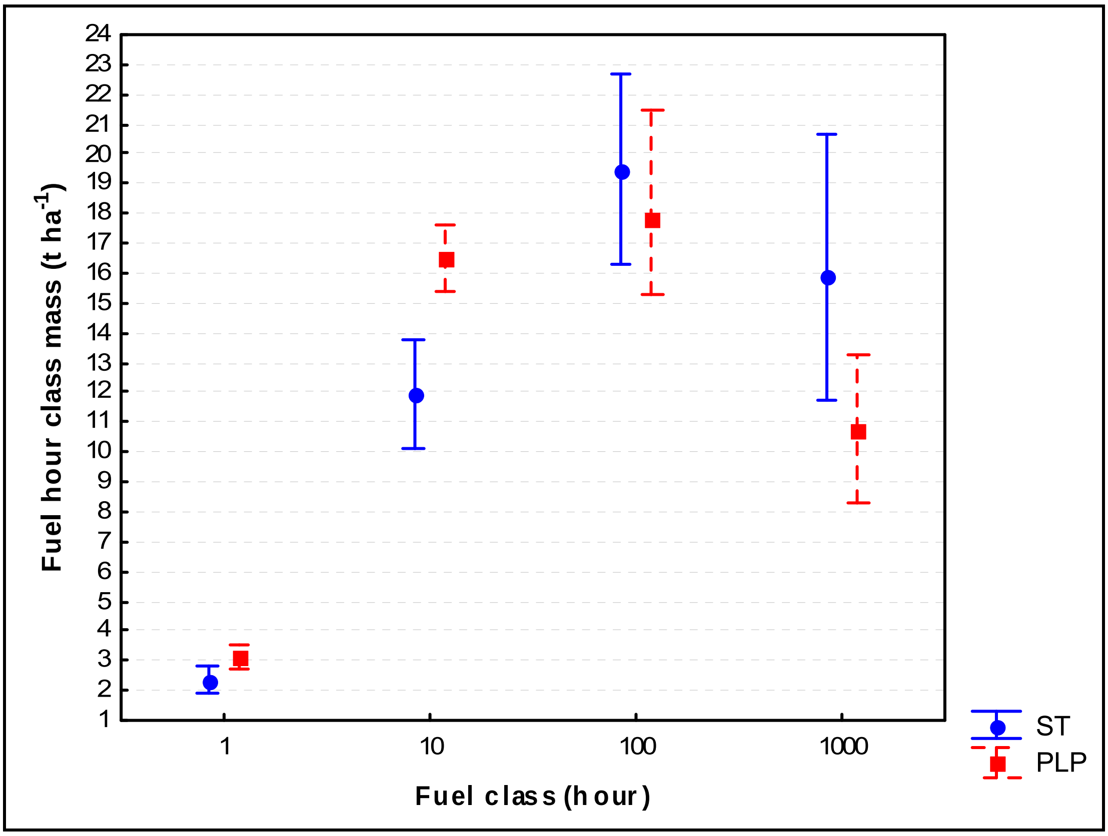

Figure 4.2: Average mass (t ha^{-1}) of the individual fuel classes for each product. The mass of the 1-hr fuel class does not include the mass of the needles retained on the branches. Bars represent 95% bootstrap confidence intervals for the mean mass of each fuel class for ST and PLP sites.

Two FF (under-canopy) fuel models (**Models 1** and **2**) and two HR (post-harvest) fuel models (ST and PLP) (**Model 3** and **Model 4**) were developed from the data collected in-field. These are presented in **Table 4.3** and **Table 4.4** along with **Model 20** (De Ronde, 1996), **Model 8** (BehavePlus) and three HR models (**Light**, **Medium** and **Heavy**) from BehavePlus (Anderson, 1982). For fuel modelling purposes, the distribution range of each HR fuel class by regime combination (**Figure 4.2**), is sufficiently small to accommodate within two HR fuel models. BehavePlus also provides a number of built-in fuel models for fire behaviour prediction that cover a range of FF and HR conditions. The majority of the post-harvest HR loads measured in this study fall within the light to medium range of fuel models provided in BehavePlus (Anderson, 1982). A description of **Models 3** and **4**, and the **Light**, **Medium** and **Heavy** models from BehavePlus is given in **Appendix 4.2**.

4.3.3 Modelled output to demonstrate the interaction between the harvest residue fuel load and its moisture content on fire behaviour

The effect of increasing fuel bed depth (with constant wind speed and zero slope) on FLI, was examined for the under-canopy fuel models (**Models 1, 2, 8 and 20**) and post-harvest models (**Models 3, 4, Light, Medium** and **Heavy**), and the results are presented in **Appendix 4.3**. Fireline intensity was calculated for a low moisture scenario. The moisture content of the dead woody fuel in the low moisture scenario (as provided in BehavePlus) is 3, 4 and 5% for the 1-, 10- and 100-hr fuel classes respectively and the slope was specified as zero degrees. Wind speed was specified as 3 km hr^{-1} for the under-canopy fuel models and 10 km hr^{-1} for the post-harvest fuel models. For the under-canopy fuel models, FLI for **Model 1** (3 – 215 kW m^{-1}) and **Model 2** (1 – 262 kW m^{-1}) were similar up until a fuel bed depth of 0.1 m, after which the FLI of **Model 2** increased at a faster rate than **Model 1**. The FLI for **Model 20** ranged from 0 to 645 kW m^{-1}, the FLI for **Model 8** from 0 – 49 kW m^{-1}. For the post-harvest fuel models, the FLI increased with increasing fuel bed depth and was higher for PLP (**Model 3**) fuel loads (9 - 5760 kW m^{-1}) when compared to ST (**Model 4**) fuel loads (9 - 4852 kW m^{-1}). The FLIs for the **Light**, **Medium** and **Heavy** models from BehavePlus were 16 – 1093, 0 – 3573 and 0 – 3626 kW m^{-1} respectively (**Appendix 4.3**).

The fire behaviour model on which BehavePlus is based is limited in that it assumes a fire to be a line burning in surface fuels. The fire model is intended to predict fire behaviour produced by fine fuels at the perimeter of the fire (fire front) and works best in uniform, continuous fuels such as grass, long-needle pine litter, uniform bush and continuous HR and therefore, results should be interpreted with caution (Burgan and Rothermel, 1984).

Table 4.3: A set of timber (under-canopy) fuel models that can be used for *P. patula* ST and PLP stands in South Africa.

Model	Model 1 PLP	Model 2 ST	Model 20 De Ronde (1996)	Model 8 BehavePlus
1-hr fuel load (t ha^{-1})	5.0[#]	6.8[#]	28.2	3.36
10-hr fuel load (t ha^{-1})	0.6	0.7	1.0	2.24
100-hr fuel load (t ha^{-1})	0.0*	0.1	0.4	4.48
Live herb fuel load (t ha^{-1})[!]	0.0*	0.0*	0.0*	0.0
Live woody fuel load (t ha^{-1})[!]	0.0*	0.0*	0.0*	0.0
1-hr SAV (m^2/m^3)	6562	6562	6562	6562
Live herb SAV (m^2/m^3)	0.0[$]	0.0[$]	4921	4921
Live woody SAV (m^2/m^3)	0.0[$]	0.0[$]	0.0*	4921
Fuel depth (m)	0.03	0.04	0.10	0.06
Fuel moisture extinction (%)	31	31	29	30
Dead fuel heat content (kJ kg^{-1})	18000	18000	17989	18622
Live fuel heat content (kJ kg^{-1})	0.0[$]	0.0[$]	17989	18622
Wind speed adjustment factor	0.4	0.3	0.4	0.3

*Usually a small component under closed canopy stands or directly after clearfelling *P. patula*. The contribution of these components can be visually assessed with the aid of a photo series.

[!] Fuel load is the weight of fuel per area. Live herbaceous fuel load is a fuel model parameter. Live herbaceous fuels are grasses and forbs that are living. Herbaceous fuels can be either annual or perennial. Live woody fuel load is a fuel model parameter. Live woody fuels are shrubs that are living.

[$] Not determined in this study as the live herb and likve woody fuel loads were not assessed and they are very site specific. Use can be made of the values sgiven in Model 20 (De Ronde, 1996).

4.4 Discussion

4.4.1 Harvest residue characteristics and loading

Harvest residue distribution across a site is characterised by an extremely high level of spatial variability (Allan, 2000). The volume of HR at a site varies greatly by soil type, climate, topography, product, species and diameter at breast height (dbh), and different silvicultural management regimes and felling methods can have profound effects on the amount and type of HR left on the site (Allan, 2000; Anderson, 1982; Carlson and Allan 2001; Kiil, 1965; Welch, 1978). Available fuel refers to the fuel that is available during a fire for combustion and is made up largely of 1- and some 10-hr fuels. The duff layer (fermentation plus humus layers) of the FF is not generally considered to be available fuel and is not included in BehavePlus. When developing a fuel model with BEHAVE, the available 1-hr fuel is defined as the load 0.0 - 0.6 cm twigs plus air dry needles still attached to the branches (Burgan and Rothermel, 1984). Calculated needle mass retained on the branches of the 1-hr fuel class was 0.8 ± 0.09 t ha^{-1} and 1.2 ± 0.08 t ha^{-1} for ST and PLP, respectively. Needle mass retained on the branches of the 10-hr fuel class was 4.3 ± 0.34 and 6.3 ± 0.23 t ha^{-1} for ST and PLP, resulting in a mean calculated total needle mass (1-hr plus 10-hr needle mass) of 5.1 and 7.5 t ha^{-1} for ST and PLP stands, respectively. The masses of the needles retained on the branches were calculated by multiplying the measured mass of the 1- and 10-hr branches by the ratio of needles-to-branches. The stands included in this study were mature stands that were in the process of being clearfelled. The difference in the calculated masses is due to the higher mass of 1- and 10-hr branches measured in the pulpwood stands. These values compared well with other southern African studies on *P. patula*. Reported needle mass values ranged from 3.8 t ha^{-1} (Morris, 1995), 4.7 t ha^{-1} (Bosch, 1985), 5.7 t ha^{-1} (Germishuizen, 1979), 7.5 t ha^{-1} (Carlson and Allan, 2001), 10.6 t ha^{-1} (Du Plooy, 1978) to 14.3 t ha^{-1} (Dames *et al*., 2002).

Table 4.4: A set of HR (post-harvest) fuel models that can be used for *P. patula* ST and PLP stands in South Africa.

Product	PLP	ST	BehavePlus Models		
Model	Model 3	Model 4	Light	Medium	Heavy
1-hr fuel load (t ha^{-1})	13.5[#]	12.7[#]	3.4	9.0	15.7
10-hr fuel load (t ha^{-1})	11.9	16.5	10.1	31.4	51.7
100-hr fuel load (t ha^{-1})	19.4	17.8	12.4	37.1	62.9
Live herb fuel load (t ha^{-1}) [!]	0.0*	0.0*	0.0	0.0	0.0
Live woody fuel load (t ha^{-1}) [!]	0.0*	0.0*	0.0	0.0	0.0
1-hr SAV (m^2/m^3)	3500	2900	4921	4921	4921
Live herb SAV (m^2/m^3)	0.0[$]	0.0[$]	4921	4921	4921
Live woody SAV (m^2/m^3)	0.0[$]	0.0[$]	4921	4921	4921
Fuel depth (m)	0.2	0.1	0.3	0.7	0.9
Fuel moisture extinction (%)	22.0	24.0	15.0	20.0	25.0
Dead fuel heat content (kJ kg^{-1})	18500	18500	18622	18622	18622
Live fuel heat content (kJ kg^{-1})	0.0[$]	0.0[$]	18622	18622	18622
Wind speed Adjustment factor	0.6	0.5	0.6	0.6	0.5

*Usually a small component under closed canopy stands or directly after clearfelling *P. patula*. The contribution of these components can be visually assessed with the aid of a photo series.

[!] Fuel load is the weight of fuel per area. Live herbaceous fuel load is a fuel model parameter. Live herbaceous fuels are grasses and forbs that are living. Herbaceous fuels can be either annual or perennial. Live woody fuel load is a fuel model parameter. Live woody fuels are shrubs that are living.

[$] Not determined in this study as the live herb and likve woody fuel loads were not assessed and they are very site specific. Use can be made of the values sgiven in Model 20 (De Ronde, 1996).

[#] Calculated as the sum of the mean values for the L layer, the needles on 1- and 10-hr branches and the 1 hr woody fuels (i.e. the fine twigs).

The proportion of the 1-, 10- and 1000-hr fuels differed significantly in PLP and ST post-harvest compartments and was confirmed in the statistical analyses which showed that PLP sites had a higher proportion of 1- and 10-hr fuels and ST sites had a higher proportion of 1000-hr fuels. The HR data collected in this study also compared favourably with other local HR studies, Allan (2000) found that the HR loads of a *P. patula* PLP stand in Swaziland and a *P. patula* ST stand in the Mpumalanga escarpment region differed visually and quantitatively in physical characteristics on two different trial sites. The PLP HR (52 t ha^{-1})

consisted largely of tops, which carried a high proportion of primary and secondary branches and needles. The ST HR (221 t ha^{-1}) consisted of a larger volume of thicker, heavier branches with less needle material (Allan, 2000). Carlson and Allan (2001) noted that the HR composition of a *P. patula* ST site in the same region was made up largely of primary and secondary branches, with tops contributing only a small proportion to the total HR load (161 t ha^{-1}). This implies that the branching pattern is affected to some degree by management decisions such as pruning and thinning regimes. As a result of thinning, ST stands have more available space for branch development than PLP stands and develop larger, thicker branches. Carlson and Allan (2001) reported a value of 38.1 t ha^{-1} of woody HR remaining on site after clearfelling a ST stand in the Mpumalanga escarpment r region. Harvest residue sampled from two trial sites siuated in KZN (PLP) and the Mpumalanga escarpment region (ST) by Rolando and Little (2004) were found to be in the region of 61 16 t ha-1 and 136 40 t ha-1 respectively. Rolando and Little (in press) also reported HR loads in the region of 24-28 t ha-1 for two PLP sites in Swaziland and 33 12 t ha-1 for a ST site in the Mpumalanga escarpment region.

Traditional methods of HR assessment, carried out using fixed area plots after harvesting, or through biomass studies prior to clearfelling, are simple to apply but are costly and inefficient as they involve the collection of large quantities of material from the plot and its subsequent separation into fuel classes followed by the determination of its dry mass per unit area (Carlson and Allan, 2001; Johansen and McNab, 1977; May and Hartong, 1959; O'Hehir and Leech, 1997; Ringvall and Ståhl, 1999). Methods for quantifying HR loads on a macro-scale, such as the LIS sampling technique, which indirectly measure HR quantities, are designed for general estimation of fuel quantities in fire research (Brown, 1970; O'Hehir and Leech, 1997; Van Wagner, 1968; Warren and Olsen, 1964) and avoid the time-consuming and costly task of collecting and weighing HR. The LIS method returned HR loads that compared well to loads from other destructive sampling methods. The accuracy of the estimate of the fuel load per hectare is affected by the spatial distribution, volume, depth and orientation of the HR, which is high in the case of *P. patula.* The accuracy of the estimate is also affected by the size of the sample, and the length and orientation of the sampling line.

4.4.2 Fuel models for *P. patula* sawtimber and pulpwood stands in South Africa

A fire will burn in the fuel that is best able to support it and situations may occur where more than one fuel model will be required to describe the fuel conditions present on the site or the ROS and fire intensity. Due to the variety of fuel, climatic and site conditions that exist, the selection and use of fuel models needs to remain flexible. Under-canopy fires are generally slow burning with low flame lengths, although flame lengths will increase if the fire encounters areas of dead, woody material. These fuel loads only pose a serious threat under severe weather conditions of high temperatures, low humidity and high wind speeds (Anderson, 1982). Light, patchy and ageing HR provides limited fire potential and will only be able to sustain small, slow moving fires. On sites where the HR has been broadcast, or is fairly continuous and well distributed, the fuel load will sustain rapidly spreading fires with high intensities until a fire break or change in the fuel load, such as an extraction road is reached. On sites with heavy, continuous HR loads containing a large proportion of 100- and 1000-hr fuels, fires will spread quickly through the fine fuels and the intensity will build up as the large fuels ignite. Flaming will have a long residence time and firebrands may develop leading to spotting (Anderson, 1982). Spotting will only take place under extreme fire behaviour conditions, and then only in the direction of maximum fire spread. It should never occur under prescribed burning conditions (De Ronde, 2004, pers. comm.[18]).

4.4.3 Modelled output to demonstrate the interaction between the harvest residue fuel load and its moisture content on fire behaviour

harvest residue fuel load and its moisture content on fire behaviour

Fireline intensity was higher for PLP fuel loads (9 - 5760 kW m^{-1}) when compared to ST fuel loads (9 - 4852 kW m^{-1}), using the same climatic inputs as described at the beginning of section 4.3.3. The FLI for **Model 20** ranged from 138 to 412 kW m^{-1}. The difference in FLI between both under-canopy and post-harvest PLP and ST fuel loads is as a result of the total 1-hr fuel load, the ratio of the fuel classes, fuel depth, and the compactness and packing of the fuels. The difference in FLI between **Model 1** and **2** and **Model 20** (De Ronde, 2003) is due to the difference in the 1-hr fuel load. The 1-hr fuel load in **Model 20** includes the whole FF whereas the 1-hr fuel load in **Models 1** and **2** only includes the L layer. This results in **Models 1** and **2** having a higher initial FLI. The FLI for **Model 20** reaches a much higher value due to the heavier 1-hr fuel load as well as the inclusion of 10- and 100-hr fuels in the model. The post-harvest models (**Models 3** and **4**) also reach higher FLI values than the **Light**, **Medium** and **Heavy** models from BehavePlus due to the much higher 1-hr fuel loads and lighter 10- and 100-hr fuel loads. Further differences between **Model 3** and **4** and the BehavePlus models are as a result of the differences in the fuel bed depth, which are deeper in the BehavePlus models. The FLIs predicted for **Model 1** and **Model 2** for under-canopy burns are within the range found by Bird (2001) for a light and Medium intensity fires. Bird's study recorded FLIs of 134, 277 and 761 kW m^{-1} for a low, medium and high intensity burn respectively for an under canopy burn in the Mpumalanga highveld region of SA. Fires with an intensity of as low as 134 kW m^{-1}, have been shown to result in little tree damage yet are still capable of reducing FF fuel loads by up to 16 % (Bird, 2001). Fires with predicted fireline intensities of less than 1000 kW m^{-1} are suitable for prescribed under canopy burning

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[18] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

as they have a lower potential for tree damage and will result in lower nutrient loss and are easier to control. (Bird, 2001; Bird and Scholes, 2002a).

Fire behaviour depends to a large extent on the physical properties of individual and collective fuel components. The amount of fuel, and its structure and arrangement are the most important factors affecting fire behaviour (Luke and McArthur, 1977). Teie (2003) lists seven fuel characteristics that control fire behaviour in different ways: loading, compactness, horizontal and vertical continuity, chemical content, size and shape, temperature and moisture content. Knowing the size of the fuel present is important because small pieces (1- and 10-hr fuel classes) are critical to fire behaviour (Brown, 1971; Roussopoulos and Johnson, 1973). Small diameter fuels ignite and burn readily, while large fuels such as logs have a low ratio and release moisture slowly; more heat is therefore required to ignite such fuels and to sustain combustion. Heavier fuels cannot be ignited unless fine fuels are present (Luke and McArthur, 1977). Large fuels require much greater heat before burning takes place than is required for small fuels to burn.

The fire spread model (Rothermel, 1972) is extremely sensitive to changes in the input parameters. The sensitivity of the model to a range of parameters was tested in the fuel modelling component of BehavePlus for each model developed in this study and **Model 20** (De Ronde, 1996) by varying the fuel loads, fuel bed depth, surface area-to-volume ratio (SAV), dead fuel moisture of extinction and the heat content and keeping all other input parameters constant. Fuel loads have a direct and indirect effect on all the variables of the fire spread model (**Equation A**). An increase in the fuel load will cause the reaction intensity (I_r) to increase more than the ROS. The ROS may decrease because more fuel must be raised to ignition temperature (Burgan and Rothermel, 1984). It is the compactness (the spacing between fuel particles of the fuel complex) that influences the ease with which a fuel will burn. Compact fuels burn more slowly than loosely packed fuels as there is less surface area exposed to the flames and there is also less oxygen available to sustain combustion. The sensitivity of the fuel model to wind and slope is increased by reducing the fuel load, thereby decreasing the packing ratio (compactness of the fuel bed). If the 1-hr fuel load is increased, the ROS and flame length will increase until the fuel becomes to tightly packed, after which the ROS decreases. Addition of 10- and 100-hr fuels will decrease the ROS, while the flame length may either increase or decrease (Burgan and Rothermel, 1984). Increasing the depth reduces the packing ratio of the fuel making the model more sensitive to both wind and slope. Fuel depth is critical for fire behaviour prediction as it determines the bulk density of the fuel. Increasing the depth reduces the bulk density resulting in an increase in the ROS. In loosely packed fuels, increasing the SAV ratio of the 1-hr fuels will increase the ROS and flame length and also the models sensitivity to wind (Burgan and Rothermel, 1984; Williams, 1977 cited by Albini and Brown, 1978). The greater the difference between the moisture content of the 1-, 10- and 100-hr fuels and the fuel moisture of extinction, the more intense the predicted fire behaviour. When the moisture content of the 1-hr fuels is between 5 and 10%, the risk of ignition is high, combustion is rapid, FLI is high and occasional crown fires may be experienced. Below a moisture content value of 5%, ignition occurs very easily, burning conditions are critical and spotting is common (Harrington, 1982). The heat content of the fuel has a direct effect on all fire behaviour outputs and a higher heat content results in a higher intensity fire (Burgan and Rothermel, 1984).

Bird (2001) tested the sensitivity of BEHAVE for a range of fuel moisture contents and wind speeds. She reported that the FLI, flame length and reaction intensity showed rapid changes when the fine fuel moisture content dropped below 10% and that heat per unit area tended to respond to changes in the fine fuel moisture content before the other output parameters. She also reported that at higher moisture levels, wind speed had little or no effect on the heat per unit area and reaction intensity. As the wind speed increased, the rate of spread, FLI and flame increased.

4.5 Conclusions and Recommendations

This chapter has provided methods to quantify and characterise the fuel load, by fuel classes for under-canopy and post-harvest stands of *P. patula* in SA. The post-harvest fuel class loads remain fairly constant for PLP and ST sites and do not change with standing biomass within each product. This is due, in part, to the silvicultural practices and management regimes applied to plantations which produce uniform PLP and ST stands and also to biological and topographic factors. A single tree growing on a given site is only able to produce and carry a limited leaf area, and as a result the amount of needles and branches making up the fuel remain fairly constant across sites. Significant differences were observed for 1-, 10- and 1000-hr fuels between ST and PLP sites and confirmed visual differences in the depth and level of compaction of the HR of the two products. The fuel models developed in this study provide managers with a means of estimating post-harvest fuel loads and possible prescribed scenarios, and provide a means for predicting the expected fire behaviour and risk for standing and clearfelled stands of *P. patula*. These models form the basis of fire risk assessment, fuel management planning and prescribed burning operations both prior to and following clearfelling. The fuel models can be used when assessing the potential fire risk to a site, different fuel management options and whether these are required at all.

A number of constants have been calculated and are provided in this chapter for the general application of the LIS method for HR load and fire behaviour assessment and planning.

These are: Fuel load, by size class, average fuel class wood density, average fuel class squared diameter values, slope correction factors and the mass of needles retained on the HR. The LIS technique has been successfully implemented to measure the quantity of HR. The LIS method was found to be applicable to all broadcast HR situations and is adequate for assessing HR on both skidder and cable yarder harvested areas. This technique is not suitable where HR has been piled in windrows; other methods are required and should be implemented for the accurate determination of fuel loads in these scenarios. Inferences of the quantity of fuel in windrows can be made from the information presented in this chapter. The ratio of fuel classes has been presented and does not change, whether the HR is broadcast or has been placed in windrows. The next step in assessing fuel loads and potential fire risk and behaviour would be the development of fuel models and photo series for all the major commercial species planted in SA, for a range of ages. They are critical to our understanding of fire behaviour, predicting fire risk and assessing and implementing fuel management strategies that will not only reduce the risk of catastrophic wildfires but ensure the maximum and continued productivity of the available plantation area.

This chapter has shown that fuel load is indirectly related to the FLI within the parameters of this study. A heavier fuel load does not necessarily mean higher fire intensities, as a number of factors have to be considered. Lighter fuel loads with a higher proportion of 1-hr fuels result in fires with a higher intensity than heavier fuel loads with a greater proportion of 100- and 1000-hr fuels. If, however, there are sufficient fine fuels to heat the 10-, 100- and 1000-hr fuels to ignition temperature, resulting fires will burn for longer periods followed by smouldering of the 1000-hr fuels.

5. NUTRIENT POOLS IN *Pinus patula* FUEL LOADS ACROSS ITS PLANTED RANGE IN SOUTH AFRICA

5.1 Introduction

Fuel management, wildfire and harvesting practices such as whole-tree utilisation, coupled with fuel wood harvesting; result in the net removal of nutrients from a plantation ecosystem. When trees are harvested and removed, or when prescribed burning is applied to reduce excessive fuel loads, or a wildfire burns through a stand, the nutrient status of the site is altered, perhaps even permanently if the disturbance is large enough (Hough, 1981). The continued productivity of a plantation over successive rotations requires that nutrient losses be balanced by inputs. Losses should be quantified and ameliorated through the alteration of fuel management and harvesting practices, or the addition of fertilisation, to ensure long-term site sustainability (Dovey *et al*., 2004). The FF and HR form critical nutrient pools in the forest ecosystem and the key to maintaining the productivity of plantations is through the proper management of these pools to reduce excessive immobilisation of nutrients and potential loss through planned and unexpected events.

Several studies have quantified the nutrient pools present in plantation residues (Bird, 2001; Bird and Scholes, 2002b; Carlson and Allan, 2001; Dames, 1996; De Ronde, 1988, 1992a; du Toit and Scholes, 2002; Morris, 1986; Schutz, 1990). Forest floor accumulation and high HR loads have a number of negative effects on a plantation site. These include the acidification of the soil through immobilisation of nutrients within the fuel and the development of a fuel complex, which increases fire risk. However, one of the most extensive threats to the long-term productivity of plantations is the excessive immobilisation of nutrients in the FF. Nutrient immobilisation in the fuel complex and subsequent loss through wildfire has important implications for sustainable plantation management. This is particularly true of mature, high altitude stands of *P. patula* that can develop thick FF layers due to an imbalance between the rate of litter production and decomposition (Dames, 1996; Morris, 1986; Schutz, 1990).

The effects of fire on site fertility are difficult to determine, but are highly dependent on the fire intensity and period of fire exposure (fire residence time) (Bird, 2001; De Ronde, 1990; Geldenhuys *et al*., 2004). The fuel load and the amount consumed during a fire determine the effect of fires on the physical and chemical properties of the soil (Geldenhuys *et al*., 2004). Complete consumption of the fuel load can lead to increased soil temperatures, water-repellency and erosion. Effects are also dependent on fuel quality and quantity, fire duration and frequency (Geldenhuys *et al*., 2004). Fires result in a reduction in ecosystem biomass, loss of nutrients through various processes and increases in the availability of N and P (De Ronde, 1992a). Different fire intensities (low, medium and high) can be applied to assess the impact of fire intensity on nutrient pool sizes of a site. The impact of a high intensity wildfire is in most cases severe as the protective duff (F+H layers of the FF) layers are consumed, while in medium and low intensity prescribed burns and under canopy fires, some or all of the duff layer remains and the impact of these fires is less severe (Bird, 2001; Bird and Scholes, 2002b; De Ronde, 1988 and 1990). In areas with relatively infertile soils, the loss of nutrients through repeated burning could become a significant factor in the long-term productivity of managed forests, particularly in the case of hot, high intensity fires (Geldenhuys *et al*., 2004; McKee, 1982). The time between burns also plays a role and shorter rotations followed by burning or an increase in the occurrence of wildfires can have negative effects on the nutrient pools of a site (Fisher and Binkley, 2000). This chapter deals specifically with the nutrient pools recorded in both the FF and HR components and its major objectives are listed below:

1. Nutrient pools. To quantify the nutrient pools present in the FF layers and HR components of *P. patula* and identify specific areas of immobilisation within these different layers and components.
2. Potential nutrient loss. To investigate the effect of fires of different intensity on the nutrient pools found in the FF and HR and to provide an estimate of the potential amount of nutrients that could be lost through prescribed burning (low and medium intensity) and wildfires (high intensity) from these complexes.

5.2 Materials and Methods

5.2.1 Study sites

Study sites used in this study are discussed in **Paragraph 3.2.1**. Nutrient pools are related to the concentration of the nutrient and the mass of the FF and HR, by being able to predict or estimate the mass of the FF and HR and by knowing the nutrient concentration of the relative components, an estimate of the nutrient pools on a site can be obtained. The sample set of 34 sites included the L, F and H layers of the FF and the 1-, 10-, 100-, and 1000-hr fuel classes. The FF, by layer, and the HR, by fuel class, were analysed for the five macronutrients, N, P, K, Mg, and Ca, assessed on a dry mass concentration basis and pools determined by using the nutrient concentrations and the FF and HR loads determined in these studies. All nutrient analyses were carried out at the ICFR laboratory in Pietermaritzburg. Details of the nutrient analyses have been published by the ICFR (Donkin *et al*., 1993).

5.2.2 Analyses

The mean and SDs were calculated for the concentration of nutrients in each tree component. Values that were greater or less than twice the SD from the mean concentration for each layer or component were re-analysed or excluded as outliers (Dovey *et al*., 2004). Mean nutrient concentrations for each site were calculated and multiplied by the sample mass of each FF layer or HR component mass per unit area to estimate the total mass of nutrients in the fuel complex for the whole stand. A factorial analysis of variance (ANOVA) was used to determine differences in the nutrient concentrations of the FF layers and HR components within and between products, sawtimber (ST) and pulpwood (PLP) and one-way ANOVA's were used to identify differences in the main effects to test for interactions between the different layers and product. Analyses were carried out using Statistica 6 (Statsoft, 2003).

5.3 Results

5.3.1 Nutrient concentrations of the forest floor layers

A two-way cross-classification on the concentration of N, P, K, Ca and Mg in the layers of the FF of ST and PLP sites, revealed that there was no significant interaction between product and layer for any of the nutrients, N ($p = 0.54$), P ($p = 0.28$), K ($p = 0.46$), Ca ($p = 0.13$) and Mg ($p = 0.64$), and nutrient content calculations in **Table 5.1** represent the species as a whole. One-way ANOVAs on individual nutrient concentration between layers, across products, showed that there was a significant difference between the nutrient concentration and layers for all nutrients, N ($p < 0.01$), P ($p < 0.01$), K ($p < 0.01$), Ca ($p < 0.01$) and Mg ($p < 0.01$) (**Table 5.1**). No significant differences were observed between FF layer nutrient concentration, and product, for N ($p = 0.97$) and P ($p = 0.74$), while significant differences were observed for K ($p < 0.01$), Ca ($p < 0.01$), and Mg ($p < 0.01$).

Nitrogen had the highest average concentration (%) for all layers across products, 0.76 ± 0.21 % in the L layer, 1.03 ± 0.24% in the F layer and 0.85 ± 0.22% in the H layer. These nutrient concentration values translate into a mean N mass (kg ha^{-1}) of 50.4 ± 28.7, 283.1 ± 268.8 and 157.1 ± 100.8 kg ha^{-1} in the L, F and H layer respectively when multiplied by the mean layer mass across products.

Figure 5.1 clearly shows the large amount of N contained in the FF, and particularly, in the F and H layers for ST and PLP sites. This has important implications for fuel load management and prescribed burning. If a prescribed, under-canopy burn is implemented, under the correct conditions, only the L layer of the FF is likely to be burnt off, leaving the F and H layers intact (De Ronde, 2004, *pers. comm.*[19]). The remaining FF layers contain the largest nutrient pools and will also serve to protect the mineral soil from erosion.

Table 5.1: The mean and standard deviation of the nutrient concentrations (%) and masses (kg ha^{-1}) of the forest floor layers.

Layer		N	P	K	Ca	Mg
L	**%**	0.76±0.21^{a}	0.05±0.01^{a}	0.15±0.07^{a}	0.47±0.18^{a}	0.12±0.04^{a}
	Kg ha^{-1}	50.4±28.7	3.6±1.9	9.7±6.0	30.3±17.7	7.8±4.4
F	**%**	1.03±0.24^{b}	0.06±0.02^{b}	0.08±0.04^{b}	0.45±0.27b^{l}	0.10±0.05^{b}
	Kg ha^{-1}	283.1±268.8	17.6±17.0	17.7±10.5	87.5±69.3	18.5±10.8
H	**%**	0.85±0.22^{c}	0.04±0.02^{c}	0.07±0.04^{c}	0.25±0.19^{c}	0.07±0.04^{c}
	Kg ha^{-1}	157.1±100.8	7.3±5.0	12.2±9.1	36.4±30.0	11.3±7.1
Duff (F + H)	**Kg ha^{-1}**	440.14±309.06	24.54±17.98	29.55±14.80	123.88±88.35	29.75±14.31

[1]Mean values of 36 sites and SDs are given.

[a,b,c,d]Different superscript characters, for a given nutrient, indicate significant differences between layers.

Mean and SDs of the nutrient concentrations of the FF layers under *P. patula* prior to clearfelling (first row) and the calculated mass of the nutrients (second row) from this study are presented in **Table 5.1** (superscript characters indicate significant differences between layers). These concentrations and masses represent bulked samples from each destructive sample and include small twigs, bark and strobili. **Table 5.1** clearly shows the increase of the N and P concentration in the F and H layers of the FF. The concentrations of Ca, Mg, and K decrease from the L to the F and H layers. The mean concentrations for each site in our study are compared with other studies on *P. patula* in SA. The results of these studies are summarised in **Appendix 5.1**.

5.3.2 Nutrient concentrations of the harvest residue components

A two-way cross-classification on the concentration (%) of N, P, K, Ca and Mg in the fuel classes of the HR of ST and PLP sites, revealed that there was no significant interaction between product and fuel class for P (p = 0.35), K (p = 0.72), and Ca (p = 0.60), and a significant interaction between product and fuel class for N ($p < 0.01$) and Mg ($p < 0.01$). One-way ANOVAs on individual nutrient concentration between fuel classes showed that there was a significant difference between the nutrient concentration and fuel classes for P ($p < 0.01$), K ($p < 0.01$) and Ca ($p < 0.01$). The nutrient concentrations of the fuel classes decreased in the following order: 1-hr > 10-hr > 100-hr > 1000-hr. Again N had the highest concentration for all size classes and **Figure 5.2** shows the amount of N contained in the

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[19] De Ronde, C. 2004 Personal communication. Fire Specialist, SILVA Forest Services, Sedgefield, Western Cape.

various fuel classes. The reason for the wide deviation in the concentration of the 1000-hr ST fuel class was due to the small number of samples (two) included in the analyses.

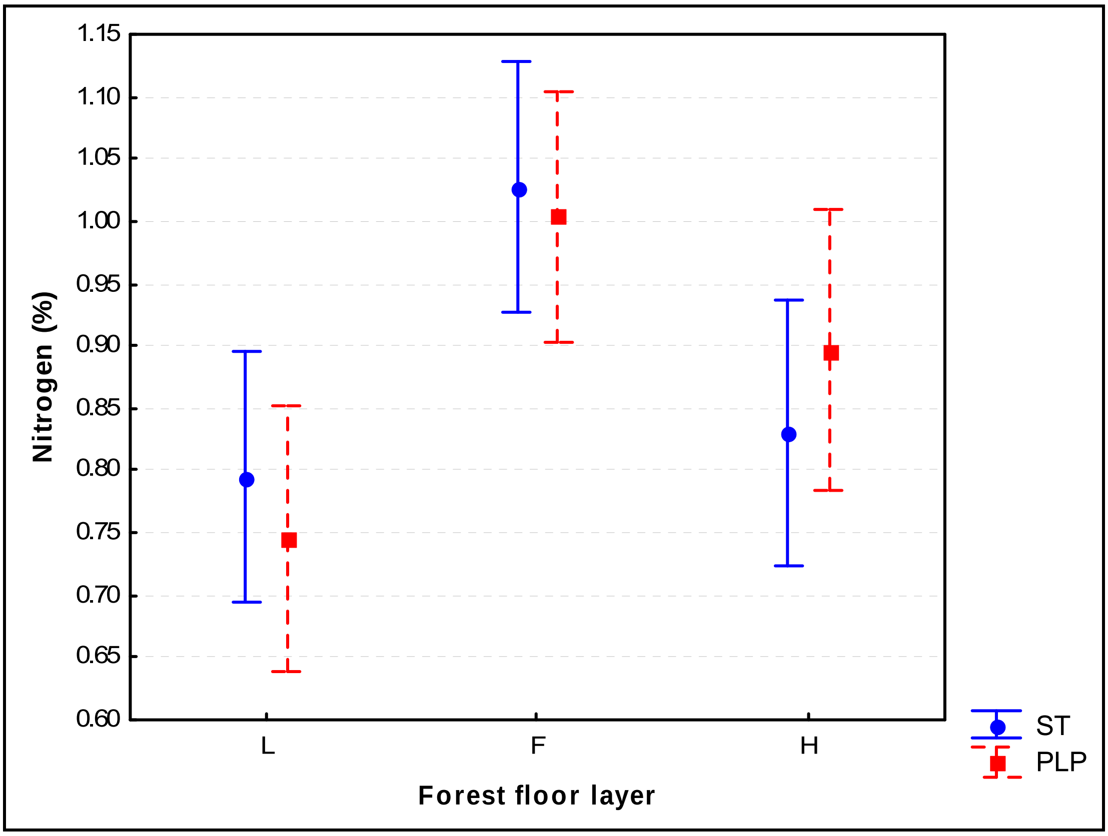


Figure 5.1: The mean concentration of nitrogen held in each of the FF layers of ST and PLP sites.

Mean and SDs of the nutrient concentrations (first row) and the estimated nutrient content (second row), across all ages and products, of the HR components (fuel classes) generated form clearfelling *P. patula* from this study are presented in **Table 5.2**. These concentrations represent bulked samples from each destructive sample and include woody residue and bark. The mean concentrations for each site in this study are compared with other studies on *P. patula* in SA. The results of these studies have been summarised in **Appendix 5.2**.

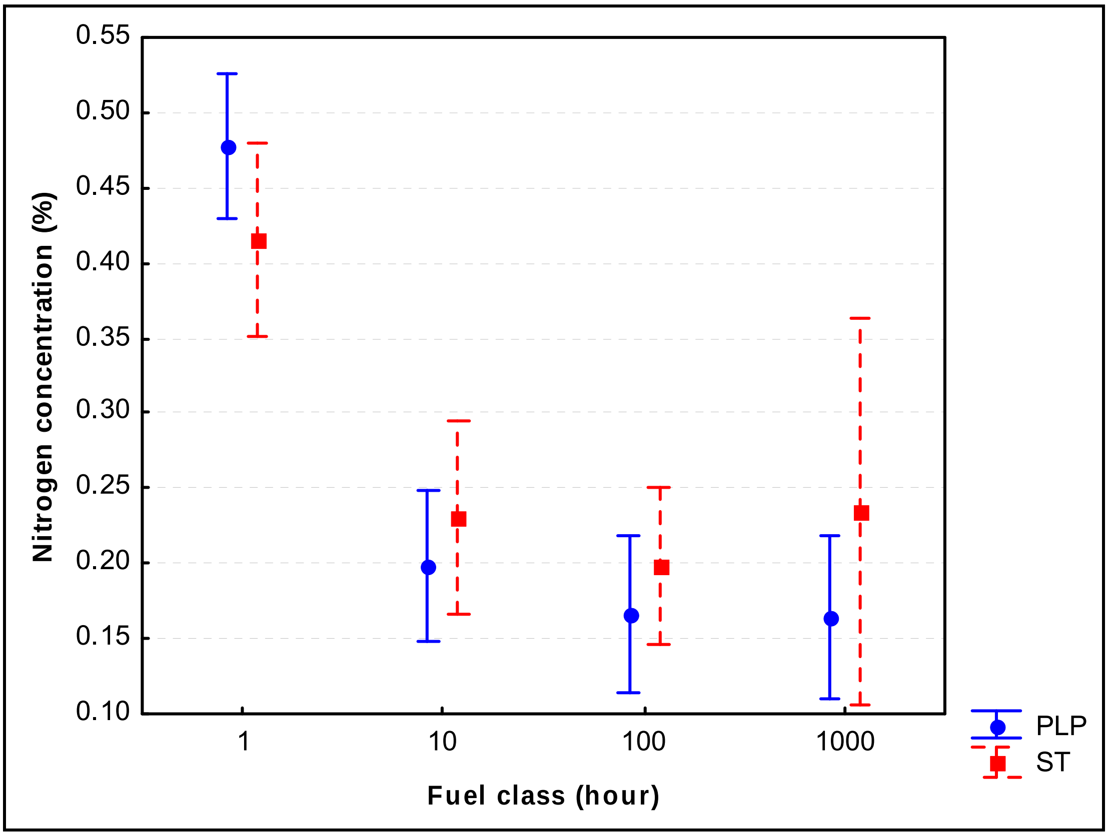


Figure 5.2: The mean concentration of nitrogen held in each of the HR fuel classes of ST and PLP sites.

5.3.3 Nutrient concentrations of the needles retained on the harvest residue

The nutrient pools presented thus far have only included the layers of the FF and the woody component of the HR by fuel class. When estimating the amount of nutrients held in the total fuel load, it is important to include the quantity of nutrients held in the needles retained on the 1- and 10-hr branches of the HR, as these too form an important part of the 1-hr fuel load of the site, and influence fire behaviour. The HR was sampled in winter and early spring, within six months of the trees being clearfelled and often while felling was taking place, so the needles were still fresh and green. On sites that were sampled several weeks and months after harvesting, the needles had changed colour but were still retained on the branches. The nutrient concentrations of the needles retained on the branches were not determined in this study, but concentration values have been obtained from existing foliar studies on *P. patula* in SA, averaged and used to calculate the pools contained in the needles (**Table 5.3**). These pools were added to those in the FF layers and the woody components of the HR to provide an estimate of the total nutrient pool contained in the fuel.

Foliar nutrient concentrations from a number of studies on *P. patula* in SA are given in **Appendix 5.3**. The average of the mean values for each nutrient was multiplied by the mass of the needles retained on the branches falling into the 1- and 10-hr fuel class (Ross and du

Toit, 2004b). This provided an estimate of the mass of nutrients held in the needles and was added to the nutrient contents of the FF and woody HR residue to estimate the total nutrient pool of the fuel complex. Needle mass retained on the branches of the 1- and 10-hr fuel classes were 0.8 ± 0.09 and 4.3 ± 0.34 t ha^{-1} for ST, compared to 1.2 ± 0.08 and 6.3 ± 0.23 t ha^{-1} for PLP. A full description of the determination of the mass of needles retained on the branches of the different HR fuel classes is given in Ross and du Toit (2004b).

Table 5.2: Nutrient concentrations (%) and nutrient content (kg ha^{-1}) of the harvest residue components.

Fuel class		N	P	K	Ca	Mg
1	**%**	0.44±0.15^{a}	0.04±0.02^{a}	0.19±0.13^{a}	0.20±0.17a^{j}	0.14±0.14^{a}
	kg ha^{-1}	13.4±7.6	1.3±0.8	5.7±4.9	5.7±5.9	4.6±5.4
10	**%**	0.18±0.08^{a}	0.01±0.01^{b}	0.07±0.06^{b}	0.07±0.08^{b}	0.08±0.09^{a}
	kg ha^{-1}	27.9±10.7	1.8±1.9	11.9±10.5	11.3±13.2	14.3±16.1
100	**%**	0.16±0.05^{a}	0.01±0.01^{c}	0.07±0.04^{c}	0.07±0.06^{c}	0.07±0.07^{a}
	kg ha^{-1}	29.5±17.2	1.7±1.2	13.3±10.0	12.5±12.0	14.9±21.5
1000	**%**	0.19±0.12^{a}	0.01±0.01^{d}	0.06±0.04d^{i}	0.03±0.03^{d}	0.12±0.13^{a}
	kg ha^{-1}	24.5±22.7	1.3±1.5	6.8±6.3	3.7±7.3	14.4±16.3

^{2}Mean values of 28 sites and SDs are given

^{a,b,c,d}Different superscript characters, for a given nutrient, indicate significant differences within nutrients between fuel classes

Table 5.3: Average foliar nutrient concentration and nutrient pools in the 1- and 10-hr fuel classes.

Fuel class		N	P	K	Ca	Mg
Average	**%**	1.64	0.14	0.68	0.24	0.26
1	**kg ha^{-1}**	16.7	1.5	7.0	2.7	2.5
10	**kg ha^{-1}**	89.1	7.9	37.1	14.0	16.7

5.3.4 Total nutrient pools contained in the fuel

The total nutrient content contained in the fuel load of a *P. patula* site can be estimated by summing the mass of the nutrients in the layers of the FF, the HR fuel classes and the needles retained on the branches falling into the 1- and 10-hr fuel classes. The FF contributes the largest proportion of the nutrient content when compared to the HR and needles retained on the HR. The range in the depth and mass of the FF varies between sites and silvicultural regimes while the range in HR depth and mass is less variable (Ross and du Toit, 2004a and 2004b). A method for predicting the ash-free mass of the FF from site and stand factors has been presented in **Chapter 3** and for quantifying the HR and needle mass in **Chapter 4**. This relationship was used this relationship to predict the FF load for a ST and PLP stand, of a fixed age and MAP, at two different altitudes (**Table 5.4**).

The mean nutrient content for each product and altitude class was calculated using the weighted nutrient concentrations for each layer of the FF determined in Ross and du Toit (2004a) and the average fuel loads for each fuel class (Ross and du Toit, 2004b) in the three altitude classes. The mean nutrient content in the fuel, for each altitude class, of a clear felled *P. patula* site is presented in **Table 5.5**. This provides an average fuel load at three altitude classes under 'normal' rotation lengths for each regime and demonstrates the magnitude of the nutrient lock-up at different altitudes.

Table 5.4: The average age, altitude and MAP and the predicted FF mass (t ha^{-1}) for an average ST and PLP stand in SA.

Product	Altitude class (m)	Average Age (yrs)	Average Altitude (m)	Average MAP (mm)	Forest floor mass (t ha^{-1})
ST	1200-1600	30	1319	950	51.4
	1600-2000		1725		83.9
PLP	1000-1400	17	1254		31.0
	1400-1800		1609		59.4

5.4 Discussion

Knowledge of the nutrient content of FF layers and HR components is essential for the consideration of different management options that can result in the removal of nutrients from the site (Hendrickson, 1987). Nutrients are lost from the system in a number of ways; these include nutrient removal through harvesting, wildfire, and leaching and re-establishment practices such as burning (Adams and Attiwill, 1991). It is important to determine the amount of nutrients contained in the fuel, to provide insight into the potential nutrient loss that could result from a site through management practices, in order to improve or at least maintain the current levels of site productivity in SA. Nutrient loss depends on the amount of fuel removed or burnt, i.e. the fuel load and type, on the nature and moisture content of the fuel and on climatic conditions (Attiwill and Leeper, 1987; Fahey *et al*., 1991). Large quantities of N and P are lost from a site by burning (up to 100% of N is lost from burnt fuels depending on the intensity of the fire), therefore, nutrient losses during prescribed burning can be minimised if fuel consumption is minimised. Fires may result in large amounts of ash remaining on the site. This ash may contain considerable amounts of nutrients with 20 to 100 kg N ha^{-1}, 3 to 50 kg P ha^{-1} and 40 to 1600 kg Ca ha^{-1} respectively being reported by Fisher and Binkley (2000). This ash is susceptible to increased erosion after a fire due to greater amounts of rainfall reaching the surface. The loss of N (through volatilisation) due to the L and F layers of the FF being removed by fire are compensated for by the increase in the total N content of the underlying soil. Nitrogen levels in the topsoil have been reported as 933 mg N kg^{-1} before burning and 1434 N mg kg^{-1} after prescribed burning (De Ronde, 1992a). Fires can also result in a decrease in the total and available N in the FF and an increase in the availability of N and P in the unburnt layers and underlying soil as a result if the downward movements of N compounds during the fire (Binkley *et al.*, 1993 cited by Bird, 2001; Mroz *et al.*, 1980 cited by Bird, 2001). Improvements of P levels in the topsoil have been recorded following a prescribed burn in the Tsitsikamma in the southern Cape by De Ronde (1992a). The ability to predict nutrient loss from burning allows managers to implement a prescribed burn that has minimal negative impacts on the nutrient status of the site (Fahey *et al.*, 1991).

The proportion of nutrients in the various fuel complex components from this study are compared with other studies on *P. patula* in SA (Bird, 2001; Bird and Scholes, 2002b; Carlson and Allan, 2001; Dames, 1996; Freimond, 1993; Schutz, 1990), Swaziland (Germishuizen, 1979; Morris, 1986), Tanzania (Lundgren, 1978), and India (Singh, 1982). Each element is shown as a nutrient mass percentage contained in each fuel portion in relation to the total fuel complex nutrient mass.

Table 5.5: Total mean nutrient mass (kg ha^{-1}) contained in the fuel load of a post-harvest pulpwood stand at low (< 1400 m) (top half of table) and high altitude (> 1400 m) (bottom half of table).

Fuel	Layer	N	P	K	Mg	Ca	N	P	K	Mg	Ca
	(t ha^{-1})	%					(kg ha^{-1})				
Low altitude sites (< 1400 m)											
FF	31.0	0.95	0.05	0.09	0.12	0.51	293.0	16.7	27.3	36.0	157.9
1-hr	2.7	0.44	0.04	0.19	0.14	0.20	12.0	1.1	5.2	3.8	5.5
10-hr	14.2	0.18	0.01	0.07	0.08	0.07	25.6	1.4	10.0	11.4	10.0
100-hr	18.6	0.16	0.01	0.07	0.07	0.07	29.8	1.9	13.0	13.0	13.0
1000-hr	13.3	0.19	0.01	0.06	0.12	0.03	25.3	1.3	8.0	16.0	4.0
n1-hr*	1.0	1.64	0.14	0.68	0.26	0.24	16.5	1.4	6.8	2.6	2.4
n10-hr*	5.2	1.64	0.14	0.68	0.26	0.24	85.9	7.3	35.6	13.6	12.6
Total	**86.1**						**488.0**	**31.1**	**105.9**	**96.4**	**205.3**
High altitude sites (> 1400 m)											
FF	59.4	0.85	0.05	0.11	0.12	0.47	504.0	31.5	63.9	69.0	277.0
1-hr	2.7	0.44	0.04	0.19	0.14	0.20	12.0	1.1	5.2	3.8	5.5
10-hr	14.2	0.18	0.01	0.07	0.08	0.07	25.6	1.4	10.0	11.4	10.0
100-hr	18.6	0.16	0.01	0.07	0.07	0.07	29.8	1.9	13.0	13.0	13.0
1000-hr	13.3	0.19	0.01	0.06	0.12	0.03	25.3	1.3	8.0	16.0	4.0
n1-hr*	1.0	1.64	0.14	0.68	0.26	0.24	16.5	1.4	6.8	2.6	2.4
n10-hr*	5.2	1.6	0.1	0.7	0.3	0.2	85.9	7.3	35.6	13.6	12.6
Total	**114.5**						**699.0**	**46.0**	**142.5**	**129.4**	**324.4**

* = refers to the mass of the needles found on the 1- and 10-hr branches in the 1- and 10-hr fuel classes.

5.4.1 Forest floor nutrient concentrations and pools

The N concentrations measured in this study, 0.76 ± 0.21, 1.03 ± 0.24 and 0.85 ± 0.22 % for the L, F and H layers respectively, are lower than in other studies (**Appendix 5.1**) in southern Africa (Carlson and Allan, 2001; Dames, 1996; Morris, 1986; Schutz, 1990). Morris (1986), reported concentrations of 1.29 and 1.32% for the L and F layers of *P. patula* FFs in Swaziland. Phosphorous, K, Ca, and Mg values recorded were similar to those recorded in other studies; however there are large variations in the concentrations of these nutrients in all the studies. The concentration of K in this study is at the high end of the range determined in the other studies (**Appendix 5.1**). Differences in the nutrient concentrations recorded in this study and those of other similar studies are due to the widely ranging locations, sampling differences and the degree to which the FF has been exposed to decomposition (Bird, 2001). The values in this study are comparable to those recorded by Freimond (1993) who found the N concentration of the litter to range between 0.50 and 0.75%, Bird (2001) who recorded N concentrations ranging between 0.98 ± 0.20 to 1.02 ± 0.14 for 16 to 17 year-old *P. patula* ST in the MPUH region. Lundgren (1978) also reported needle litter (L layer) and FF (F and H layer) values of 0.64 and 1.11% respectively for *P. patula* in Tanzania. Maggs (1988) found that the N concentration in the L and F layers was 0.33 and 0.44 % respectively for *P. elliottii*. Comparative values are from FF samples, from a range of stand ages and sites, and include very young to mature stands, while those in this study are from mature stands only (Ross and du Toit, 2004a). The total N (490.6 kg ha^{-1}) and P (28.1 kg ha^{-1}) nutrient contents contained in the FF determined in this study are comparable to the lower end of the nutrient content range reported by Morris (1986) for first rotation *P patula* stands in the Usutu forest in Swaziland (**Appendix 5.1)**. Large reserves of N (1442.0 kg ha^{-1}) and P (103.0 kg ha^{-1}) were recorded in the FF by Dames (1996) and 1045 to 2994 kg ha^{-1} of N were recorded by Schutz (1990) which are considerably higher estimates than observed in this study.

5.4.2 Harvest residue nutrient concentrations and pools

An analysis of the nutrients contained in different biomass components and the rate of uptake provide important information for understanding nutrient cycles, the impact of management practices on the site and for making the appropriate fuel management decision as this could ultimately determine the quantity of nutrients available for the following rotation (Carlson and Allan, 2001; Ovington, 1962 cited by Morris, 1986). Under current harvesting practices for pine in SA, only the stemwood and bark are removed from the site leaving the needles, secondary branches, main branches and dead branches on the site. The N concentrations measured in this study, for the 1-, 10-, 100- and 1000-hr fuel classes are comparable to other studies (**Appendix 5.1**) in southern Africa (Dames, 1996; Germishuizen, 1979; Morris, 1986). The 1-hr fuels generally had the highest concentration of all nutrients and **Table 5.2** shows the decrease of the concentration of all nutrients with increasing branch diameter (fuel class). The 10- and 100-hr fuel classes had almost identical concentrations for all nutrients. The 1000-hr fuels had the lowest Ca and K values of all the size classes but had similar or slightly higher N, P and Mg values to the 10- and 100-hr fuel classes. **Table 5.2** shows an initial increase in the mass of all the nutrients in the 10-hr and 100-hr fuel classes followed by a decrease in the 1000-hr fuel class for all nutrients except P, which, decreases in the 100-hr and 1000-hr classes. This increase is simply a function of the mass of the HR in these classes and the nutrient concentration. Although the concentrations of the nutrients decrease with increasing branch diameter, the mass of nutrients is most strongly affected by the mass of the HR on the site.

5.4.3 Total nutrient content contained in the fuel complex of an average PLP and ST stand

The total nutrient content contained in the fuel complex of an average PLP and ST stand are given in **Table 5.5** and **Table 5.6**. The FF accounts for the largest contribution of nutrients to the total nutrient pool of the fuel complex. A FF mass was predicted for an average PLP and ST using the model developed by Ross and du Toit (2004a) for two different altitude classes. The mass of the FF (and nutrients) increased with increasing altitude where age and MAP were held constant for both PLP and ST stands (**Table 5.4**) for all nutrients except for K, Mg and Ca in ST which decreased with increasing FF floor mass (**Table 5.6**). The large increase in FF mass is greater for ST when compared to PLP which can be explained by the difference in age between the ST (30) and PLP (17) sites as well as the slightly higher average altitude of the ST sites. The mass of the FF was found to increase with both age and altitude (Ross and du Toit, 2004a). The increase in the nutrient content of the fuel complex with increasing altitude is due to an increase in the concentration of nutrients contained in the F and H layers (**Figure 5.1**) as well as the increase of the mass of these layers with increasing altitude. The FF accumulates at high altitude through an imbalance between the rate of litter production and decomposition, and the mass of the F and H (duff) layers can be become increasingly large and account for a large proportion of the total FF mass (Dames, 1996; Ross and du Toit, 2004a). Although the concentrations of the nutrients do not increase greatly with increasing FF layer depth, except in the case of N and P, the mass of nutrients increases due to the greater mass of the FF layers. The increase in N concentration with increasing FF depth is due in part to an increase in the length of exposure to decomposers.

Table 5.6: Total mean nutrient mass (kg ha^{-1}) contained in the fuel load of a sawtimber stand at low (< 1600 m) (top half of table) and high altitude (> 1600 m) (bottom half of table).

Fuel	Layer	N	P	K	Mg	Ca	N	P	K	Mg	Ca
	(t ha^{-1})						(kg ha^{-1})				
Low altitude sites (< 1600 m)											
FF	51.4	0.75	0.05	0.11	0.11	0.36	387.1	25.4	56.9	54.2	185.4
1-hr	2.7	0.44	0.04	0.19	0.14	0.20	12.0	1.1	5.2	3.8	5.5
10-hr	14.2	0.18	0.01	0.07	0.08	0.07	25.6	1.4	10.0	11.4	10.0
100-hr	18.6	0.16	0.01	0.07	0.07	0.07	29.8	1.9	13.0	13.0	13.0
1000-hr	13.3	0.19	0.01	0.06	0.12	0.03	25.3	1.3	8.0	16.0	4.0
n1-hr*	1.0	1.64	0.14	0.68	0.26	0.24	16.5	1.4	6.8	2.6	2.4
n10-hr*	5.2	1.64	0.14	0.68	0.26	0.24	85.9	7.3	35.6	13.6	12.6
Total	**106.5**						**582.2**	**39.9**	**135.5**	**114.6**	**232.8**
High altitude sites (> 1600 m)											
FF	83.9	1.07	0.06	0.04	0.03	0.13	898.6	47.1	36.1	23.6	107.0
1-hr	2.7	0.44	0.04	0.19	0.14	0.20	12.0	1.1	5.2	3.8	5.5
10-hr	14.2	0.18	0.01	0.07	0.08	0.07	25.6	1.4	10.0	11.4	10.0
100-hr	18.6	0.16	0.01	0.07	0.07	0.07	29.8	1.9	13.0	13.0	13.0
1000-hr	13.3	0.19	0.01	0.06	0.12	0.03	25.3	1.3	8.0	16.0	4.0
n1-hr*	1.0	1.64	0.14	0.68	0.26	0.24	16.5	1.4	6.8	2.6	2.4
n10-hr*	5.2	1.64	0.14	0.68	0.26	0.24	85.9	7.3	35.6	13.6	12.6
Total	**139.0**						**1093.7**	**61.6**	**114.7**	**84.0**	**154.4**

* = refers to the mass of the needles found on the 1- and 10-hr branches in the 1- and 10-hr fuel classes.

The mass of the HR fuel classes are less variable with age, altitude and product, and therefore, average fuel class loads and nutrient concentrations were calculated for *P. patula* across all ages, altitudes and products. Although nutrient concentration values contained in the HR fuel classes are much lower than those found in the FF, they still make a significant contribution to the total nutrient pool contained within the biomass. For this reason, they were added to the mass of the nutrients contained in the FF. The nutrient concentration of the needles retained on the 1- and 10-hr branches was not determined and average nutrient concentrations have been calculated from published data (**Appendix 5.3**). These concentrations were multiplied by the average mass of the 1- and 10-hr fuel loads across all ages, sites and products and added to the mass of the nutrients contained in the FF and HR to provide an estimate of the total nutrient pool contained in the fuel complex for an average ST and PLP stand at low and high altitude. The total content of nutrients contained in the fuel complex increases with altitude for both PLP and ST sites except for K, Mg and Ca in ST which decreases with increasing altitude. This increase of the total nutrient content contained in the fuel complex with altitude is due to the increase of the FF mass at high altitude.

5.4.4 Potential nutrient loss through burning

The effects of fire on the quantity of nutrients removed from the fuel complex are highly dependent on fire intensity and the residence time as well as the biomass present on the site, fuel composition, HR type, moisture content of the fuel, climatic conditions, the amount of fuel burnt, and existing nutrient budgets (Attiwill and Leeper, 1987; Bird, 2001; Fahey *et al*., 1991; Geldenhuys *et al*., 2004). The impact of a wildfire is in most cases severe as the protective duff layers are consumed (De Ronde, 1990). If the entire FF layer is consumed, the soil will be exposed and becomes water repellent and susceptible to drying-out, soil compaction and erosion. Large quantities of N and P can be lost from a site through high intensity burning and fire may also increase the concentrations of soluble Ca, Mg and K in soil which then become susceptible to leaching (Dyck *et al*., 1981). In stark contrast, with prescribed HR burns and under canopy fires some or all of the fuel load remains and the impact of these fires are less severe (De Ronde, 1988; 1990; Geldenhuys *et al*., 2004). Little *et al*. (1996) classified fire intensity in terms of low (cool), medium (moderate) and high (hot) fires. Low intensity prescribed burns remove only the 1-hr fuel, or part thereof, while high intensity wildfires may remove all the 1-and 10-hr fuels, and a large proportion of the 100- and 1000-hr fuels. No burning was conducted as part of this study and the potential mass of nutrients that could be lost through fires of different intensity has been summarised from published data and is given in **Table 5.7**. Cool burns generally involve the partial burning of litter and vegetation, which accumulate under a forest canopy or broadcast slash generated after clearfelling and they have been shown to have little effect on soil physical properties (Little *et al.*, 1996). De Ronde (1990) reported that light intensity fires produced no drastic changes in soil acidity, organic matter, carbon or chemical properties if the duff layer remained intact to protect the soil against heat. McKee (1982) states that cool, prescribed burns result in enhanced soil status of all major plant nutrients, including N. A moderate intensity fire consumes the majority of the litter and partial combustion of wood in the 1-, 10-, 100- and 1000-hr fuel classes that remain on the site after clearfelling. Changes in the soil, although minimal, are likely to accumulate over time with repeated burning (Little *et al.*, 1996). Hot fires result in the total combustion of all of the FF and most of the HR in the 1-, 10-, 100- and 1000-hr fuel classes. They usually occur under hot, dry and windy conditions, destroy large quantities of organic matter, expose bare soil and can lead to considerable damage to a forest ecosystem resulting in decreased survival and early growth of seedlings (Little *et al*., 1996).

Bird (2001) and Bird and Scholes (2002b) reported no effect on the soil physical characteristics of sites following burning. The highest loss of all nutrients in this study was recorded in plots subjected to high intensity fires, with N showing the greatest difference in amount lost between low and high intensity fires. The levels of nutrients decreased in the order N, Ca, K, Mg and P for all levels of fire intensity, high, medium and low, applied in the study (**Table 5.7)**. Nutrient concentrations in the ash-bed following under-canopy burning by Bird (2001) were higher than pre-burn nutrient concentrations for all nutrients measured in the study. In a study to determine the long-term effects of broadcast burning on the physical and chemical properties of forest soils, Kraemer *et al*. (1979), found no statistically significant differences between properties of burned and unburned soils. This suggests that broadcast burning (at the intensities applied in the study) does not have a lasting effect on chemical and physical properties of soils (Fisher and Binkley, 2000; McKee, 1982).

5.5 Conclusions and Recommendations

The effect of current management practices on future growth, productivity, the environment and economic viability needs to be considered and nutrients replaced accordingly (Dovey *et al*., 2004). Knowledge of the nutrient content of the FF and HR components is essential for the consideration of different management options that can result in the removal of nutrients from the site and in evaluating the potential cost of nutrient loss through prescribed burning or in the event of uncontrolled wildfires (Hendrickson, 1987). Knowledge of nutrient losses from prescribed burns of different intensities would allow for burns with minimal adverse impact on ecosystem nutrient status to be implemented (Feller, 1988). The determination of the nutrient pools contained in the forest floor layers and biomass components will also contribute to the calculation of a pINS index for this species. An index of nutritional stability (pINS), based on the negative logarithm of the ratio (net nutrient loss) / (nutrient pool) is being developed for pine in SA, where the nutrient pool can be the readily available soil pools or the (long term) potentially available system pools. This index is used to evaluate management intensity effects as well as the "buffer capacity" of the system (du Toit and Scholes, 2002).

An analysis of the nutrients contained in different biomass components, and the rate of uptake, provide important information for understanding nutrient cycles, and the impact of management practices. The FF and HR form large nutrient pools on a site and the management thereof can have long-term impacts on site productivity. Large amounts of nutrients accumulate in the FF (particularly N), and these amounts become much larger than the available nutrients in the topsoil as the litter accumulates on the FF. The greatest proportion of all nutrients and cations is contained in the F layer of the FF followed by the H and L layers respectively for all nutrients. Burning constitutes a rapid release of nutrients back into the system with some associated loss depending on the intensity of the fire. Prescribed under canopy burning was found to be an inexpensive, reliable method for managing FF fuel loads without significantly affecting tree growth and nutrient cycling (Bird, 2001; Bird and Scholes, 2002b) provided that various conditions are met and precautions taken to ensure a safe and successful burn.

Table 5.7: Effect of the type and resulting intensity of fires on the nutrient loss (kg ha^{-1}) from the site in a number of studies covering a range of species.

Fire type	Species	Fuel load (t ha^{-1})	Intensity	Nutrient losses (kg/ha)					Author
				N	P	Ca	Mg	K	
Prescribed under-canopy	*P. patula*	14.8 ± 8.1	Low	15.3 ± 5.0	0.7 ± 0.2	4.9 ± 1.7	1.2 ± 0.4	1.8 ± 0.6	Bird (2001)
	P. patula	12.0 ± 5.5	Medium	23.3 ± 7.4	1.3 ± 0.4	10.2 ± 3.7	2.1 ± 0.7	2.7 ± 0.9	Bird (2001)
	P. patula	14.0 ± 9.2	High	53.4 ± 17.6	2.4 ± 0.8	22.4 ± 7.2	5.0 ± 1.5	6.3 ± 2.0	Bird (2001)
Prescribed post-harvest	*P. patula*	87.5	High	1183	86	73	68	48	Morris (1986)
	P. radiata	80		220	8	123	13	21	Flinn *et al*. (1979)
	P. radiata	59		139					Hall (1984)
Prescribed	*P. taeda*			10-40					Richter *et al*. (1982)
Slash fire	*T. heterophylla*		High	980	16	154	29	37	Feller (1983)
Slash fire	*T. heterophylla*		Medium	490	9	87	7	17	Feller (1983)
Slash fire	*Eucalyptus*			75-100	2-3	19-30	5-10	12-21	Raison *et al*. (1985)
Slash fire	Mixed forest	630			10	100	37	51	Harwood & Jackson (1975)
Wildfire	*P. menziesii*		High	855		75	33	82	Grier (1975)
Slash fire	Tropical moist forest			800-1600	5-20				Kauffman *et al*. (1995)

6. PHOTO SERIES FOR QUANTIFYING *Pinus patula* FUEL

6.1 Introduction

A photo series of typical fuel loads can be useful for visual fuel status evaluation and also in prescribed burning applications. They are particularly useful if computer based and can be used for natural fuels such as fynbos and grassland, as well as plantations (De Ronde *et al*., 2004). As a result, prescribed burning has focussed on the climatic and topographic factors affecting fire with little emphasis being placed on fuels and fuel loads, and their effect on fire behaviour. The major objectives in developing a photo series are to provide an array of fuel loads that will allow foresters to make logical comparative estimates of fuel loads by size class in similar stands and to enable management to quantify desirable fuel loads (Maxwell and Ward, 1980). A photo-series is designed to provide a reliable, easy-to-use tool for quantifying HR and can be used to make a fast, easy and inexpensive quantification of fuel loads that are adequate for most management needs. Photographs display different fuel load levels, by size class, for areas of similar harvesting systems and fuel management treatment. Information accompanying each photo includes measured masses, volumes, structure, depth and other residue data, additional information about the compartment and harvesting and thinning operations, and fuel ratings and fire behaviour information (De Ronde *et al*., 2004). Fuel loads in different fuel classes; average fuel depth and the percentage of the ground area covered by the fuel are all characteristics that can be seen in the photographs. Managers can estimate any of these characteristics in a compartment by comparing them with the photos.

6.2 Materials and Methods

Sites photographed for this series (discussed in **Paragraph 3.2.1**) were selected to show representative, typical fuel load variations resulting from commonly applied harvesting and fuel management practices over a wide geographical and altitudinal range in SA (De Ronde *et al*., 2004). Photographs were taken before re-planting operations in order to minimise disturbance of the spatial distribution of the fuel. Compartment information is presented in **Appendix 3.1**. The marker in these photos is 30 cm square, and the pole is painted in contrasting colours at 10 cm intervals to provide perspective and an accurate means of estimating fuel depth. Stumps are not included in residue quantities.

The material in the photo area was sampled by making use of the methods described by Maxwell and Ward (1980) and Brown (1974) which is discussed in detail in **Chapter 4**. A data sheet listing fuel classes with measured weights and volumes, other relevant fuel measurements and stand characteristics accompanies each photo (Wade *et al*., 1993). Information on the data sheets (**Table 6.1, Table 6.2** and **Table 6.3**) was calculated using a combination of the FF measurements (**Chapter 3**) and information calculated from the line intersect (LIS) method (**Chapter 4**). Stand characteristics were obtained from the landowner or company managing the site. Fuel loads were predicted along with available compartment data provided by the company that owned the plantation on which the site was located. These inventory data provide information regarding the number of stems per hectare, the average dbh, basal area per hectare and total and utilisable volume. Information provided in the tables can be input into BehavePlus for the prediction of fire behaviour. There is no set number of loading levels needed to develop a photo series. De Ronde *et al*. (2004) suggest that a single set of 20-40 plots/photographs should be sufficient for one region. The photos presented in this study are by no means a complete photo series and describe a limited range of fuel conditions. A complete photo series should describe the complete range of fuel conditions across a range of ages and sites for a particular species.

6.3 Results

This study has focussed on a single species within a very limited range of ages and sites in order to restrict the fuel models, developed in **Paragraph 4.3.2**, to the period just prior to, and directly following clearfelling. A complete photo series should ideally cover the full range of ages and sites, within a given region, for a particular species, or genera, if there are significant differences in the fuel loads generated by two different species within the same genera. The limited range of this study did not provide the range in fuel load situations for the development of a single photo series for *P. patula* in the summer rainfall region of SA. The tables accompanying the photographs provide fuel data that can be used as input variables in fire behaviour prediction programmes like BehavePlus. Three fuel load scenarios, undercanopy (**Photograph 6.1**), a PLP site (**Photograph 6.3**) and a ST (**Photograph 6.4**) site, after clearfelling, are provided. Each photograph is representative of the fuel situations encountered before and after clearfelling *P. patula*. **Photograph 6.1** corresponds with **Model 1**, **Photograph 6.3** with **Model 3** and **Photograph 6.4** with **Model 4** developed in **Chapter 4**. **Photograph 6.2** shows a profile of the the FF showing the L and F layers.

6.4 Discussion

A desired fuel load would be the amount of fuel that can and should be retained on a site to meet environmental and management goals and objectives. Some of these goals and objectives would include the nutritional sustainability of the site, the long-term site stability, and reduced fire risk and reduced management costs. A photo series can provide managers with a means of recognising the appearance of different quantities and distributions of fuel in a compartment. From this, decisions, based on quantitative data, can be taken regarding the amount of fuel that should remain to meet the above objectives. The primary purpose of a photo series is to provide a reliable, easy-to-use tool for quantifying fuel. An inventory of the fuel on a site can be made using the photo series by comparing the observable fuel characteristics with the photos as follows:

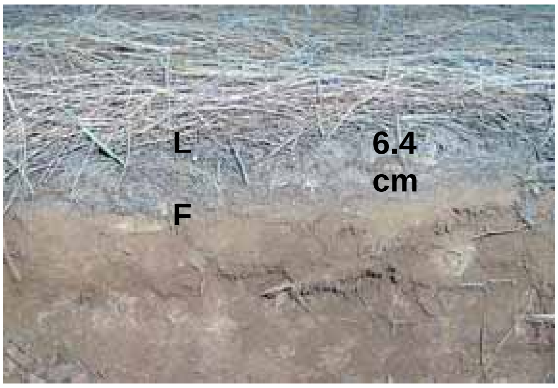
1. Each characteristic of the fuel is first observed on the ground, i.e. the size, arrangement and depth of the fuel;
2. A photo that nearly matches the observed characteristic, or alternatively, two photos that describe the fuel is selected from the series;
3. Quantitative values for the characteristics being estimated are obtained from the data sheet accompanying the selected photo, or are interpolated between the two photos;
4. The above steps are repeated for each characteristic for fuels in the 0- to 7.6-cm diameter range. Steps two and three are used for fuels 7.6 cm and greater in diameter;
5. Once the quantitative values have been determined for each size class, the values can be put into BehavePlus, along with all relevant topographic and climatic information, to generate an estimate of the fire behaviour that could be expected from the particular fuel situations.

If the compartment being inventoried has areas of obvious differences in fuel loading, separate determinations can be made for each area, which can then be weighed and cumulated for the entire compartment. Fine fuel (1-hr) ranging from 0.0 - 0.6 cm in diameter is difficult to view in the photos. The 0.6 - 2.5-cm fuels should be estimated first, and then the corresponding zero to 0.6-cm values from the data sheet assigned for the same photo (or for the interpolation between two photos).

The amount of fuel produced on a particular site is affected by a number of factors such as the condition of the stand, topography, harvesting system and specifications and therefore, the photo series provides for only a limited number of possible combinations. A photo series can also be used to provide an estimate of the amount of fuel that will be realised from clearfelling. This can be done by comparing the site and stand information provided in the photo series with the existing compartment information. This will provide the user with a visual picture of what the slash could look like, as well as quantitative fuel load data that can be used in BehavePlus, to estimate possible fire behaviour scenarios. To predict the expected fuel load after harvesting, cruise volume and size data are compared with the information provided on the data sheet of the photo series. A fuel load level, with similar stand characteristics, is selected for the photo series, noting those factors, which differ from the photo series situation and the expected fuel load, estimated.

Comrie A26

Photograph 6.1: Forest floor under a mature *P. patula* PLP stand, KZN.



Photograph 6.2: Profile showing the L and F layers of the forest floor. In this compartmrnt the H layer was insignificant.

Table 6.1: Site and stand data for fuel model 1.

DATA SHEET	
FUEL LOADING	
Size class (cm)	**Weight (t ha^{-1})**
1	3.16
10	0.6
100	0.0
Total	3.76
COMPARTMENT INFORMATION	
Stand age (years)	20
Altitude (m)	1209
MAP (mm)	865
Average dbh (cm)	25.5
Stems ha^{-1}	690
Standing volume (m^{3} ha^{-1})	261.7
Average slash depth (cm)	20.1
Average litter depth (cm)	6.4
Average litter load (t ha^{-1})	21.7

Linwood C16

Photograph 6.3: Harvest residue load generated after clearfelling a mature PLP stand, KZN.

Table 6.2: Site and stand data for fuel model 3.

DATA SHEET	
FUEL LOADING	
Size class (cm)	**Weight (t ha^{-1})**
1	8.82
10	16.01
100	12.63
Total	37.46
COMPARTMENT INFORMATION	
Stand age (years)	14
Altitude (m)	1297
MAP (mm)	928
Average dbh (cm)	23.3
Stems ha^{-1}	723
Standing volume (m^3 ha^{-1})	249.5
Average slash depth (cm)	30.3
Average litter depth (cm)	9.5
Average litter load (t ha^{-1})	41.8

Dargle B1

Photograph 6.4: Harvest residue load generated after clearfelling a mature ST stand, KZN.

Table 6.3: Site and stand data for fuel model 4.

DATA SHEET	
FUEL LOADING	
Size class (cm)	**Weight (t ha^{-1})**
1	9.46
10	17.15
100	15.17
Total	41.78
COMPARTMENT INFORMATION	
Stand age (years)	22
Altitude (m)	1222
MAP (mm)	902
Average dbh (cm)	30.1
Stems ha^{-1}	406
Standing volume (m^3 ha^{-1})	312
Average slash depth (cm)	25
Average litter depth (cm)	10.8
Average litter load (t ha^{-1})	62

6.5 Conclusions

Photo series offer a basic aid for predicting the expected quantity of residue as this is affected by numerous complex factors. Expected fuel loads can be predicted by comparing volume and size information from cruise data with the information provided in the photo series. This photo series is by no means complete but, the study has laid the foundation for the development of a complete photo series for *P. patula* that should cover the full range of age classes, sites and fuel load scenarios across the planted region for this species in SA to provide a practical aid for fuel management to foresters and mangers. Photo series must be developed for all the major commercial species planted in SA as they are critical to our understanding of fire behaviour, prediction fire risk and assessing and implementing fuel management strategies that will not only reduce the risk of catastrophic wildfires but ensure the maximum and continued productivity of the available plantation area in SA.

7. SUMMARY AND CONCLUSIONS

7.1 Is forest floor accumulation still a major problem in South African *P. patula* plantations?

The primary factors driving forest productivity are energy, water and nutrient supply. The rate of breakdown of the FF material is influenced by the physical and chemical nature of the litter, the aeration, temperature and moisture conditions of the FF and the kinds and numbers of the flora and fauna present. These physiological and biological factors drive needle production, which affects litterfall and subsequent forest floor accumulation. This study has served to confirm that forest floor accumulation occurs in and is limited to; mature sawtimber stands of *P. patula* at high altitude and is linked to the drivers mentioned above. The FF was quantified, by layer, and models were developed to predict the forest floor load based on a direct relationship with FF depth and site and stand factors namely, age, altitude and MAP. Nutrient pools were calculated for anverage sawtimber and pulpwood stand at both low and high altitude. The models and nutrient pools determined in this study represent a combination of ST and PLP *P. patula* sites from across the planted area for this species in SA.

The results from this study indicate that FF loads found under *P. patula* stands in the summer rainfall region, given current silvicultural management regimes, are not as thick as those reported previously in the literature. FF depth has a greater range under ST stands than under PLP stands, due largely to the age differences and the effect of pruning and thinning operations. Forest floor accumulation is not a problem in pulpwood stands. Although there is variation in the total FF depth and load between sites and products, the mass of the L layer remains fairly constant across both. Any soil contamination of the sample as a result of the sampling process can be removed by conducting a loss on ignition process on sub-samples of the FF. This provides a better fit between depth and ash-free mass allowing for the more accurate prediction of fuel available for consumption within the compartment. Ash-free mass can also be predicted accurately by using site and stand variables such as age, altitude and MAP.

A good relationship exists between FF depth and ash-free mass for *P. patula* across the region and a single model has been developed and can be used to predict ash-free mass with an accuracy of approximately 10 t ha^{-1}. A model to predict the ash-free mass of the pre-burn duff layer of the FF has also been presented. This model for the prediction of ash-free duff mass will play a role in determining the amount of duff present on the site, how much could be consumed in a fire and ultimately, the effect of fire on the nutrient pools present on the site. The level of accuracy required for management purposes will determine the method to be used to predict the FF fuel load as part of fuel load and fire management.

7.2 How much fuel is present on a site after clearfelling *P. patula* and what are the fire risk implications?

The effect of silvicultural regime i.e. ST versus PLP, has been summerised and HR loads remaining on the site after clearfelling have been quantified in terms of fuel load properties for the development of fuel models to predict fire behaviour. The nutrient contents of the various HR components have also been calculated and presented. The fuel models developed in this study were used in BehavePlus to predict the FLI that could be expected in mature ST and PLP *P. patula* stands after clearfelling. A number of photographs were taken at each site for the inclusion into a photo series for the quantification of *P. patula* HR in SA.

This study has provided constants that can be utilised when using the LIS method for assessing HR and fuel loads, and fire behaviour assessment and planning on *P. patula* sites. The LIS method has been successfully implemented to measure the quantity of HR resulting from clearfelling *P. patula* ST and PLP compartments. It is a non-destructive method and avoids the time-consuming and costly task of collecting and weighing large quantities of HR and loads obtained from this method are comparable to loads obtained in other SA studies where the HR was destructively sampled. The LIS method was found to be applicable to all broadcast HR situations and is adequate for assessing HR on both skidder and cable yarder harvested areas. This method is not suitable where fuel has been piled in windrows and other methods are required for the accurate determination of fuel loads in windrows.

Regime influences the size and distribution of HR across the site. The 1- and 10-hr fuels were heavier in PLP compartments and 100- and 1000-hr fuels loads were heavier in ST compartments. Although the 100- and 1000-hr fuel loads were not significantly different on a product basis, stands that contain a higher proportion of 1- and 10-hr fuel when compared to those with more 100- and 1000-hr fuel have deeper, less compact HR. This has extremely important implications for fire behaviour. Fire intensity will be higher in the former due to the greater amount of loosely packed 1- and 10-hr fuels. Fire intensity in the latter will be lower but if there is sufficient fine fuel (1- and 10-hr) present, 100- and 1000-hr fuels could ignite and burn for a greater length of time.

There are a limited number of fuel models that have been published for fire behaviour prediction in industrial plantations in SA. The models presented in this study provide a means of estimating fire behaviour on a broad geographical scale across the summer rainfall region and provide managers with a means of quantifying post-harvest fuel loads and possible prescribed scenarios, and provide a means for determining the expected fire behaviour and risk for standing and clearfelled stands of *P. patula*. These models form the basis of fire risk assessment, fuel management planning and prescribed burning operations both prior to and following clearfelling. The fuel models can be used when assessing the potential fire risk to a site, different fuel management options and whether these are required at all.

This study has laid the foundation for the development of a complete photo series for *P. patula* that would cover the full range of age classes, sites and fuel load scenarios across the planted region for this species in SA. The methods presented in this study can and should be expanded to other genera and species. Fuel models and photo series need to be developed for all the major commercial species planted in SA as they are critical to our understanding of fire behaviour, prediction fire risk and assessing and implementing fuel management strategies that will not only reduce the risk of catastrophic wildfires but ensure the maximum and continued productivity of the available plantation area in SA.

7.3 What nutrient pools exist within the fuel complex on a *P. patula* clearfell site?

Plantation management can influence the long-term sustainability of a site. The FF and HR form large nutrient pools on a site and the management thereof can have long-term impacts on site productivity. Large amounts of nutrients (particularly N) accumulate in the FF. The greatest proportion of all nutrients are contained in the F layer of the FF followed by the H and L layers respectively for all nutrients.

The effect of current management practices on future growth, productivity, the environment and economic viability needs to be considered and nutrients replaced accordingly. Knowledge of the nutrient content of the FF and HR components is essential for the consideration of different management options that can result in the removal of nutrients from the site and in evaluating the potential cost of nutrient loss through prescribed burning or in the event of uncontrolled wildfires. Knowing the potential nutrient losses from prescribed burns of different intensities would allow for burns with minimal adverse impact on ecosystem nutrient status to be implemented. The determination of the nutrient pools contained in the forest floor layers and biomass components will also contribute to the calculation of the degree of site resilience to nutrient loss. An analysis of the nutrients contained in different biomass components, and the rate of uptake, provide important information for understanding nutrient cycles, and the impact of management practices.

7.4 Recommendations for future research

There is lack of understanding of the moisture dynamics in standing *P. patula* plantations in SA, particularly where thick L and duff layers accumulate, and knowledge of the moisture profile drying rates is urgently required. Information regarding the FF is absolutely necessary in evaluating the effects of fire, either wildfire or prescribed burning. The FF load is directly related to the moisture dynamics of the fuel complex and it is the FFMC that is the most critical factor affecting FLI and fire behaviour. Thick, moist FFs will carry fires of lower intensity and are more stable than thin FFs whose moisture content fluctuates widely. There are currently no suitable FFMC (L and duff layer) data available in SA to accurately predict fire behaviour and risk. Future research on fire risk and behaviour in commercial plantations in SA would require the measurement and monitoring of the FFMC over both time and space. An index of fire risk based on the depth of the L and duff layers and on the moisture content of these layers needs to be developed. This would improve fire risk analysis and fire behaviour prediction within the SA context. Forest floor MC needs to be modelled across the range of FF depths to determine the effects that it has on fire behaviour and risk.

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APPENDICES

Appendix 3.1: Compartment information including product, random forest floor depth, weighed forest floor mass, ash-free forest floor mass, age, and altitude, MAP and MAT, and site index.

Plantation	Compt #	Prod	LD (mm)	LMw (t ha^{-1})	LMloi (t ha^{-1})	Age (yrs)	Alt (m)	MAP (mm)	MAT (°C)	Site Index
Demagtenberg	B54	PLP	70.1	33.1	30.2	19	1184	1032	16.3	21.2
Goodhope	E10	PLP	74.5	49.8	36.6	11	1372	903	15.7	24.0
Comrie	A26	PLP	78.6	42.6	21.7	20	1209	865	15.8	22.2
Witklip	E4	ST	82.5	21.8	14.6	24	1015	936	18.2	33.1
Sneezewood	D43	ST	84.9	44.5	27.7	34	1303	836	15.3	29.6
Linwood	C17	PLP	85.2	48.3	41.8	14	1297	928	15.7	23.6
Dargle	B4	ST	85.35	42.1	33.5	22	1222	902	16.3	22.6
Sarnia	A41	ST	85.6	55.0	33.7	27	1302	850	15.7	25.0
Linwood	C16	PLP	86.4	39.5	28.5	13	1600	-	-	20.3
Willowmere	E12	PLP	89.3	72.8	45.6	13	1703	914	13.6	21.2
Donnybrook	D18	PLP	90.4	41.1	43.4	17	1368	836	15.9	28.2
Demagtenberg	D12	PLP	91.9	45.5	39.7	19	1120	1155	16.8	21.9
Dargle	B2	ST	95.1	61.6	44.5	22	1222	902	16,3	25.6
Peak	A21	PLP	95.3	27.2	32.6	11	1618	929	13.9	-
Willowmere	E14	PLP	95.6	72.8	19.5	14	1677	922	13.7	21.2
Clairmont	A12	PLP	95.8	39.5	52.8	22	1552	1182	14.8	24.1
Spitskop	D16A	ST	96.0	37.9	24.2	27	1329	1075	16.6	27.1
Ingwe	A117A	PLP	97.8	61.0	37.0	20	1243	982	16.3	-
Linwood	C10	PLP	100.1	47.7	25.4	14	1175	999	16.3	24.6
Goodhope	E08	PLP	100.4	60.8	33.3	13	1298	909	15.8	20.9
Lothair	F9	PLP	107.9	66.5	34.3	25	1496	843	15.3	19.8
Langewacht	A11	ST	109.0	168.4	29.5	27	1549	732	15.7	22.3
Renosterhoek	E09A	ST	109.1	85.6	70.7	35	1304	954	17.4	22.6
Donnybrook	A07	PLP	126.8	54.1	51.4	17	1321	860	15.9	23.0
Jessivale	E29A	ST	137.3	57.8	48.0	34	1682	881	14.4	30.9
Jessivale	B19	ST	151.0	114.4	45.1	22	1699	879	14.2	20.0
Morgenzon	A18A	ST	175.3	82.9	106.0	29	1820	823	14.1	26.0
Morgenzon	D18	ST	182.7	63.7	72.7	33	1890	820	14.0	26.4
Tweefontein	X24C	ST	189.7	145.4	103.8	27	1738	1166	14.6	21,1
Ceylon	X6B2	ST	196.2	106.6	137.9	37	1625	1215	15.3	21.5
Ceylon	X6B	ST	227.2	151.9	133.4	37	1625	1215	15.3	21.5

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Appendix 3.2: Published models for the prediction of forest floor mass from forest floor depth and site and stand variables.

Considerable research has been conducted on biomass production, decomposition and accumulation in *P. patula* in order to develop methods for predicting FF depths and fuel loads. Much of this work has been done in SA (Carlson and Allan, 2001; Dames, 1996; De Ronde, 1984, 1992a; Schutz, 1990; Schutz *et al.*, 1983) and Swaziland (Evans, 1974, 1975; Morris, 1986, 1993), but also in Tanzania (Lundgren, 1978) and India (Singh, 1982). These studies have focussed primarily on mature, thinned stands, with the exception of the studies conducted in Swaziland (Evans, 1974, 1975; Morris, 1986) and in KwaZulu-Natal (KZN) (De Ronde, 1997).

Model to predict FF mass from FF depth for *P. patula* ST stands in the MPUE region, SA (Schutz *et al.*, 1983).

$$\log LM = 0.69 + 2.95 * \log\left(\frac{LD}{10}\right) - 0.77 \log^2\left(\frac{LD}{10}\right)$$

Where: LM = Forest floor mass (g 0.10 m^{-2})
LD = Forest floor depth (mm)
Log = common logarithm

Model to predict FF mass from FF depth for *P. patula* PLP stands in the Usutu Forest, Swaziland (Morris, 1986).

$$LM = 11.20(LD) - 17.60$$

Where: LM = Forest floor mass (t ha^{-1})
LD = Forest floor depth (cm)

Model to predict ash-free FF mass from FF depth for *P. patula* ST stands in the MPUE region (Dames, 1996).

$$LM = 0.65(LD) + 2.83$$

Where: LM = Forest floor mass (t ha^{-1})
LD = Forest floor depth (cm)

Model to predict FF mass using age and altitude for *P. patula* PLP stands in the Usutu forest, Swaziland (Morris, 1986).

$$LM = 244.60 - 20.14A - 0.18E + 0.02(A * E)$$

Where: LM = Forest floor mass (t ha^{-1})
A = stand age (yrs)
E = elevation (m)

Model to predict ash-free FF mass using age and altitude for *P. patula* ST stands in the MPUE region (Dames *et al*. 1998).

$$LM_{ash-free} = 0.98(Age) + 0.03(Alt) - 10.66$$

Where: $LM_{ash\text{-}free}$ = Ash-free **FF** mass (t ha^{-1})
Age = stand age (yrs)
Alt = elevation (m)

Model to predict ash-free duff layer mass from FF depth (mm) for *P. patula* ST and PLP stands in the summer rainfall region of SA (this study).

$$DM = 0.64(LD) - 25.73$$

Where: DM = Ash-free duff layer mass (t ha^{-1})
LD = Forest floor depth (mm)

Appendix 3.3: Modelled output to demonstrate the interaction between the forest floor fuel load and its moisture content on fire behaviour.

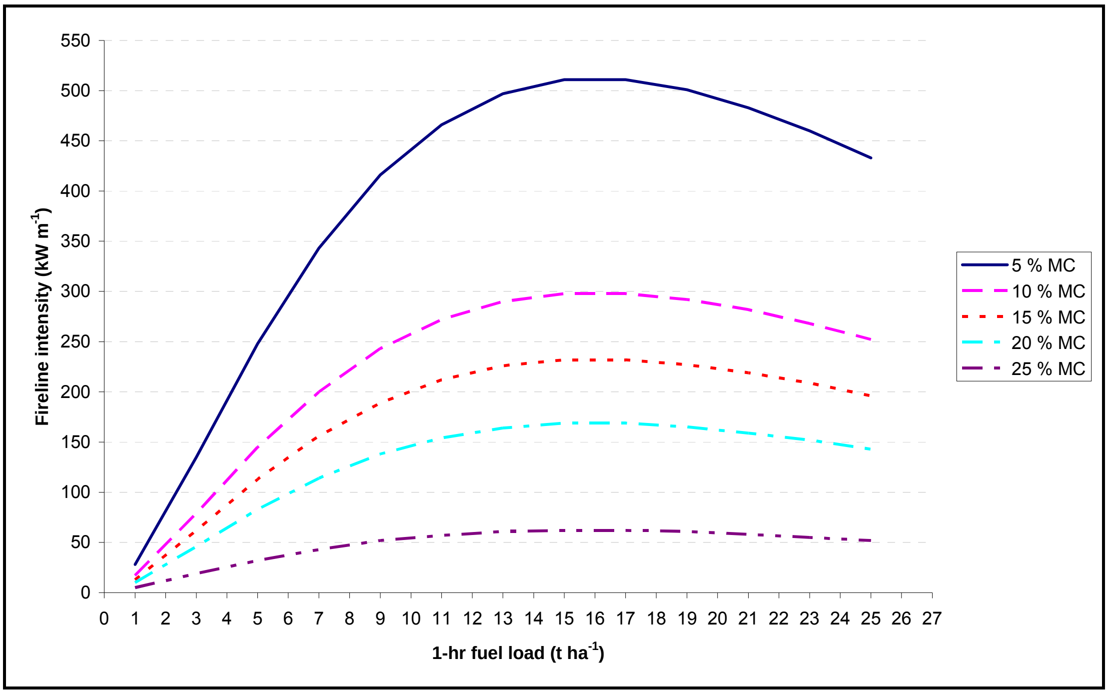
The effect of increasing fuel load (with constant fuel bed depth) and moisture content of the FF, and its indirect effect on FLI was examined using the BehavePlus (Andrews, 1986; www.fire.org) fire behaviour prediction programme. Additional fuel model information was obtained from fuel model number 20 developed by De Ronde (1996) (Trollope *et al*., 2004).

Fuel model developed for 15-18 year-old even-aged P. elliottii and *P. patula* stands with closed crown canopy in Mpumalanga (De Ronde, 1996).

Description of fuel characteristics	Fuel Model 20
1- hr fuel load (t ha^{-1})	28.22
10- hr fuel load (t ha^{-1})	1.01
100- hr fuel load (t ha^{-1})	0.40
Live herb fuel load (t ha^{-1})	0.02
Live woody fuel load (t ha^{-1})	0.00
Fuel depth (m)	0.14

Available FF loads (L layer) between 1 and 25 t ha^{-1} were selected, and the effect of these loads with increasing moisture content on the FLI was tested (**Appendix 3.4**). Fireline intensity reached a peak at a fuel load of approximately 15 t ha^{-1} at all moisture content values and was considerably higher at lower moisture content values. Fireline intensity values approached zero as the fuel load approached approximately 50 t ha^{-1}. When the moisture content of the 1-hr fuels is between 5% and 10%, the risk of ignition is high, combustion is rapid, FLI is high and occasional crown fires may be experienced (Harrington, 1986). Below a moisture content value of 5%, ignition occurs very easily, burning conditions are critical and spotting is common (Harrington, 1986). Above a moisture content of 30%, the FLI approached zero. The effect of increasing fuel load and fuel bed depth on the FLI was also tested for three fixed FF moisture content values (5, 15 and 25%) in BehavePlus. Fireline intensity decreased with increasing fuel load and fuel bed depth for all three moisture content values and for all fuel loads as the moisture content was increased from 5 to 15% and again from 15 to 25%.

Appendix 3.4: Fire line intensity with increasing 1-hr fuel load and fuel moisture.



Appendix 4.1: Constants determined for *P. patula* in South Africa for use in the line-intersect sampling method.

This study involved the determination of the average diameter and density values for each fuel class, non-horizontal correction factors and slope correction factors to calculate the HR load by fuel class, and the HR depth using the LIS technique.

Slope correction factors for converting t ha^{-1} on a slope basis to a horizontal basis (Brown, 1974).

Slope Percent	Correction factor C	Slope Percent	Correction factor C
0	1.00	60	1.17
10	1.00	70	1.22
20	1.02	80	1.28
30	1.04	90	1.35
40	1.08	100	1.41
50	1.12	110	1.49

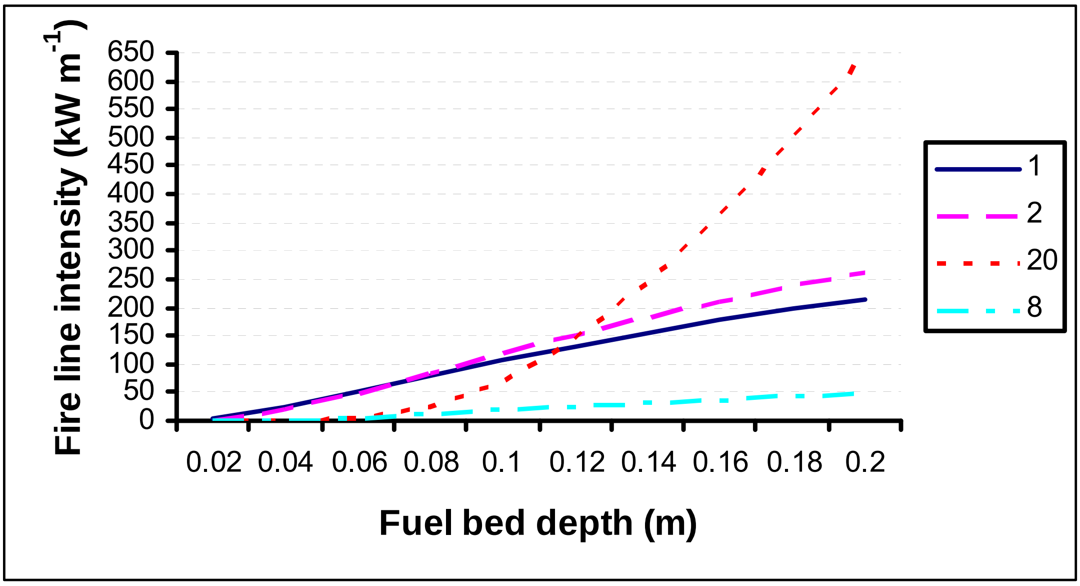
The squared average quadratic mean diameters (d2) and average density values (s) for each size class for *P. patula* in South Africa and non-horizontal correction factors (a) from Brown (1974).

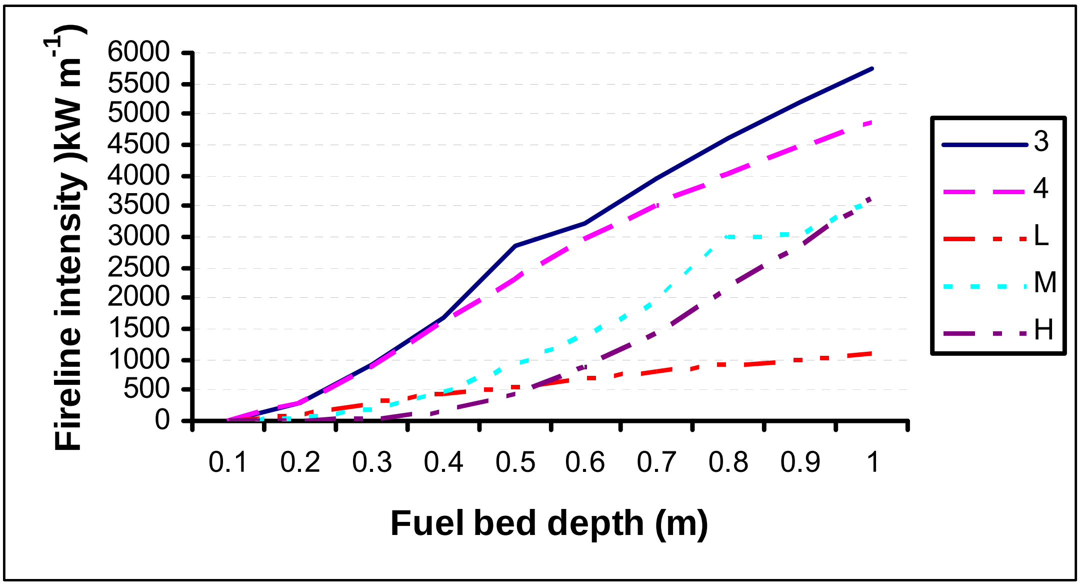
Size class (cm)	Average d^2 (cm)	a	s (g/cm^3)
0 – 0.6	0.58	1.40	0.58
0.6 – 2.5	3.20	1.13	0.52
2.5 – 7.6	15.00	1.10	0.55
> 7.6	178.80	1.00	0.50

Appendix 4.2: Description of fuel models presented in Table 3.

	Fuel Model	**Model Description**
This study	**1**	11-37 year-old even-aged *P. patula* stands with closed crown canopy Light FF
	2	11-37 year-old even-aged *P. patula* stands with closed crown canopy Heavy FF
	3	17-37 year-old even-aged *P. patula* ST stands with closed crown canopy Light HR
	4	17-37 year-old even-aged *P. patula* ST stands with closed crown canopy Heavy HR
	5	11-25 year-old even-aged *P. patula* PLP stands with closed crown canopy Light HR
	6	11-25 year-old even-aged *P. patula* PLP stands with closed crown canopy Heavy HR
Behave Plus	**8**	Closed timber litter
De Ronde (1996)	**Model**	15-18 year old even-aged *Pinus elliottii* and *Pinus patula* stands with closed crown canopy in Mpumalanga
Behave Plus custom fuel models	**Light**	Light HR
	Medium	Medium HR
	Heavy	Heavy HR

Appendix 4.3: Fire line intensity with increasing fuel bed depth.





Appendix 5.1: The mean and standard deviation of the nutrient concentrations of the litter.

Prod	N	P	Ca	Mg	K	Na	Layer	Author
ST	1.00	0.068	0.345	0.058	0.113	0.010	mean	Bird (2001)
ST	1.135	0.045	0.074	0.046	0.059	0.012	mean	Carlson and Allan (2001)
	0.149	0.009	0.039	0.019	0.025	0.004	std	
PLP	1.29	0.07	0.32	0.15	0.1	not determined	L Layer	Morris (1986)
PLP	1.32	0.07	0.15	0.08	0.07		F Layer	
ST	1.28	0.16	0.28	0.08	0.1	0.06	mean	Schutz (1990)
	0.16	0.14	0.22	0.05	0.05	0.01	std	
ST	1.64	0.08	not determined				mean	Dames (1996)
ST	0.64	0.03	0.81	0.24	0.14		Needle litter	Lundgren (1978)
	1.11	0.1	1.42	0.21	0.21		Forest floor	
ST	0.57						Litter	Freimond (1993)

Estimated nutrient content (kg ha-1) of forest floor under first rotation P patula stands at age 10 and 17 years for high (1450 m) and low (1150 m) elevation sites (Morris, 1986).

Age	Site	N	P	K	Ca	Mg	Author
10	all	498	27	30	72	34	Morris (1986)
17	low	557	30	34	81	38	
17	high	1036	55	63	150	71	

Appendix 5.2: Concentrations as % of oven-dry weight, of N, P, K, Ca and Mg in live and dead branches (all growth rates) (Miller *et al.*, 1985).

Species		**Element**					**Author**
		N	**P**	**K**	**Ca**	**Mg**	
P. nigra		0.2	0.018	0.05	0.285	0.055	Miller *et al*, 1985
P. patula		0.13	0.003	0.006	0.09	0.018	Germishuizen, 1979
P. patula	mean	0.175	0.017	0.012	0.143	0.04	Morris, 1986; 1992
	std	0.065	0.005	0.003	0.035	0.007	
P. nigra		0.22-0.34	0.029-0.034	0.170-0.203	0.370-0.295	0.058-0.064	Miller *et al*, 1985
P. patula	mean	0.05	0.02	0.28	0.05	0.34	Dames, 1996
	std						
P. patula	mean	0.28	0.04	0.25	0.14	0.07	Morris, 1986; 1992
	std	0.053	0.016	0.094	0.053	0.032	

Appendix 5.3: Foliar nutrient concentrations from a number of studies carried out on *P. patula* in South Africa.

Nutrient	N	P	Ca	Mg	K	Na	Author
	%						
mean	1.715	0.143	0.241	0.11	0.45	0.011	Carlson and Allan (2001)
std	0.224	0.019	0.053	0.044	0.088	0.005	
mean	2.15	0.18	0.26	0.17	0.87	0.03	Schutz (1990) [Tree had mean age of 38 years, n=147]
std	0.16	0.02	0.11	0.43	0.17	0.03	
mean	1.649	0.15	0.211	0.122	0.516		Carlson and Soko (2001) [Tree age of 8 years, n=240]
std	0.14	0.03	0.06	0.02	0.14		
mean	1.55	0.135	0.295	0.179	0.829		Morris (1992) [Age of trees range from 1 to 21, n=33]
std	0.19	0.17	0.137	0.03	0.108		
mean	1.67	0.15	0.21	1.06	0.84		Dames (1996) [Tree age of 42 years, n=10]
std	0.37	0.02	0.19	0.09	0.17		
mean	1.239-1.785	0.125--0.170	0.174-0.248	0.098-0.113	0.500-0.756	0.022-0.030	Louw and Scholes (2002) [Age of trees from 6-10 years, thinned stands] [Values given for dormant and growth season
std	0.17-0.33	0.03-0.03	0.06-0.48	0.02-0.02	0.17-0.22	0.01-0.02	
mean	1.37	0.103	0.3	0.208	0.705		Germishuizen (1979)