LOSS OF ORGANIC MATTER AND CARBON DURING SLASH BURNS IN NEW ZEALAND EXOTIC FORESTS

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ABSTRACT

The quantity of carbon lost to the atmosphere through volatilisation during burning of *Pinus radiata* D. Don and *Pinus contorta* Loudon forest logging slash was estimated from measurements made at four *P. radiata* sites and one *P. contorta* site in New Zealand. Pre- and post-burn fuel mass and carbon content were assessed at each site. On average 27 t C/ha, or 62% of carbon present before burning (excluding that contained in stumps, roots, and mineral soil), was lost to the atmosphere as a result of slash burns at the four *P. radiata* sites. At the *P. contorta* site 33 t C/ha, or 48% of carbon present before burning (excluding that contained in stumps, roots, and mineral soil), was lost to the atmosphere as a result of slash burning. Duff (F and H horizons), litter (L horizon), and sound woody material exceeding 7 cm in diameter were the components that contributed most to this loss. Total carbon loss in New Zealand due to burning of plantation forest logging slash was estimated to be 10 300 tonnes/year (s.e. = 1800) for *P. radiata* and 1600 tonnes/year (s.e. = 1160) for *P. contorta.*

Relationships between carbon loss from individual sites and the specific codes and indices of the Canadian Fire Weather Index System were examined. The best predictor of carbon loss was the Fire Weather Index itself. The development of a comprehensive system for modelling carbon losses from slash burns will require more information to develop a larger data set.

Keywords: biomass; carbon; slash burns.

INTRODUCTION

The United Nations Framework Convention on Climate Change (FCCC) calls for carbon dioxide emissions to be reduced to 1990 levels by the year 2000 and, as a signatory to the FCCC, New Zealand requires a system for assessing both the sources and sinks of greenhouse gases. Plantation forestry is an important component of New Zealand's plan to reduce net carbon dioxide (CO_2) emissions as trees absorb carbon during their growth. A combination of empirical data and modelling can be used to estimate the quantity of carbon that is sequestered by *P. radiata* plantations. The prototype module CARBON, which is to be incorporated into the stand modelling system STANDPAK (West 1993), is based on predictions of the effects of different silvicultural regimes on the annual partitioning of carbon into various forest organic matter components. Until now, models of carbon cycling have incorporated the assumption that all residues left in the forest after harvesting remain on the site and decay but little work has been done on the effect of site preparation techniques, such as burning, on carbon emissions to the atmosphere.

Prescribed fire is permitted under certain circumstances for land clearing and site preparation in New Zealand. Controlled burning reduces wildfire hazard and makes planting easier. It is a particularly useful technique on steep slopes where machinery cannot be used for land preparation (Balneaves *et al.* 1991). Blackened material can absorb heat and may raise the surface temperature sufficiently to avoid frost damage to newly planted seedlings which is important at higher altitude sites in the central North Island (Maclaren 1996). On the other hand, research also indicates that slash retention conserves soil moisture and nutrients, and may reduce weed germination (Flinn *et al.* 1979), and so slash retention rather than burning or windrowing after harvesting operations is now a common site management practice.

Combustion of organic matter leads to the release of carbon dioxide into the atmosphere. Mass and carbon have three potential fates in fires (Beorner 1982):

- Being lost to the atmosphere via volatilisation or ash convection;
- Being deposited on site as ash; or
- Remaining on site as unburnt material.

The objectives of this study were firstly to estimate, at the stand and forest estate levels, the amount of organic material and carbon lost to the atmosphere through volatilisation during the burning of logging slash, and secondly to relate carbon loss to the codes and indices of the Canadian Fire Weather Index System (Van Wagner 1987), which could form a useful basis for predicting the magnitude of loss under different conditions. If a significant amount of carbon is lost annually through slash burning, management practices relying on fire should be taken into account during consideration of carbon sequestration by plantation forests in New Zealand

METHOD

Survey

A questionnaire was sent through the Forest Owners' Association to all forest owners. Information was requested about the area of exotic forest burnt annually.

Study Areas

Five study sites were established. These were located at Glenbervie, Topuni (two sites), Kaingaroa, and Mawhera Forests (Fig. 1). Since *P. radiata* is the predominant forestry plantation species in New Zealand, four of the sites were in clearfelled *P. radiata* stands. The fifth site (Kaingaroa) was located in a clearfelled *P. contorta* stand because the harvesting of this species typically leaves a large amount of slash, and burning is a commonly-used technique for site rehabilitation.

Glenbervie Forest

Glenbervie Forest, owned by Rayonier New Zealand Ltd, had a mean annual rainfall of 1934 mm (New Zealand Meteorological Service 1983). The study area in Cpt 81 (34.5 ha) was characterised by steep terrain with slopes of 14° to 20°, and the soil was an Orthic brown

FIG. 1–Location of study areas.

soil (Rijkse & Hewitt 1995) classified as a Marua clay loam series. The site had been occupied by 27-year-old *P. radiata* (162 stems/ha) and undergrowth until harvested by hauler in August-September 1996. Hauler logging on steep terrain had resulted in the accumulation of logging slash on the lower slopes which makes re-planting difficult. No duff layer was present on site. Slash depth ranged from 0 (on higher slopes) to 1.5 m (gullies). The burn objective was reduction of slash on lower slopes to increase ease of planting. Pre-burn assessments were conducted in March 1997, burning took place on 2 April, and post-burn sampling was conducted shortly afterwards.

Mawhera Forest

This site was located in Cpt 223 of the Mawhera Forest of Timberlands West Coast Ltd. The area had a mean annual rainfall of 1892 mm (New Zealand Meteorological Service 1983). The area was characterised by steep terrain with slopes of 18° to 32°, and soils were poorly drained and dominated by Brown soils classified as the Wallaby steepland series (Hewitt 1995). The site had been occupied by 29-year-old *P. radiata* (186 stems/ha) and undergrowth prior to harvesting by hauler logger in December 1996. Litter and duff were present on this site. Slash depth ranged between 0.2 and 1.5 m. The burn objective was reduction of the slash load before re-planting. Pre-burn assessments were conducted in mid-February 1997, burning of 14.1 ha took place on 2 April, and post-burn sampling was conducted in early April 1997.

Topuni Forest

Two sites were established at the Topuni Forest of Carter Holt Harvey Forests Ltd. Both were located in Cpt 10.2 where the mean annual rainfall was 1514 mm (New Zealand Meteorological Service 1983). The topography was almost flat (slopes of 0°–3°) and the soil was an Ultic soil classified as a mixture of Mahurangi fine sandy loam and Warkworth clay sandy loam (Rijkse & Hewitt 1995). A 28-year-old *P. radiata* stand grown at 270 stems/ha had been ground-based harvested in September 1996. Undergrowth was present, as were litter and duff. Slash depth ranged between 0 and 0.75 m. Site 1 was an untreated area of 2.6 ha. Site 2 (3.5 ha) had been sprayed with a desiccant 6 weeks before the burn took place. Burn objectives were the acquisition of data for this study and fire training for company personnel. Pre-burn assessments were carried out in March 1997, burning took place on 3 April, and post-burn sampling was completed by mid-April.

Kaingaroa Forest

This site, located in Cpt 302 of Kaingaroa Forest owned by Fletcher Challenge Forests Ltd, had a mean annual rainfall of 1379 mm (New Zealand Meteorological Service 1983). The topography was almost flat (slopes of 0°–3°) and the soil, identified as pumice, was classified as a combination of Kaingaroa sand and Taupo hill soils (Rijkse & Hewitt 1995). Prior to ground-based harvesting (November 1996) the site was occupied by 50-year-old *P. contorta* (1210 stems/ha). There was no undergrowth as it had been destroyed by harvesting but litter and duff were both present, and slash ranged between 0.2 and 1.0 m in depth. The burn objective was reduction of the heavy slash load and facilitation of planting. Pre-burn field work was conducted in February 1997, the burn (of 42.3 ha) took place on 18 March 1997, and post-burn organic matter sampling was completed in late March 1997.

Sampling

Pre- and post-burn sampling was used to describe and measure characteristics of the representative organic matter strata (logging slash, undergrowth, forest floor, and soil components). Sampling incorporated both line intersect (Warren & Olsen 1964; Van Wagner 1968; Brown & Roussopoulos 1974; McRae *et al.* 1979) and destructive (Catchpole & Wheeler 1992) methods. Weight estimates for the wood and needle components of logging slash and the larger woody components (>7 cm diameter) of undergrowth species were derived from line intersect data. The weight of organic material in other undergrowth components and in the upper soil horizons was determined by destructive sampling.

Estimation of the weight of woody slash material using the line intercept method

Two to five equilateral triangles with 30-m sides (transect lines) were marked out in randomly located positions at each burn site. Woody slash components less than 7.0 cm in diameter that were intercepted by the lines were measured before and after burning. Tree stumps were not included in the sampling. Sampling was stratified by restricting measurements to a specified length of each line that was related to diameter class (Fig. 2). During the pre-burn assessment, all pieces exceeding 7.0 cm in diameter (intercepted by 30-m transect lines) were marked with a nail hammered into the wood at the point of measurement so that the post-burn assessment could be made at the same point. Ground slope (%) below each transect was measured with a clinometer. The mean weight of pieces in each diameter class per site was calculated from the transect line data.

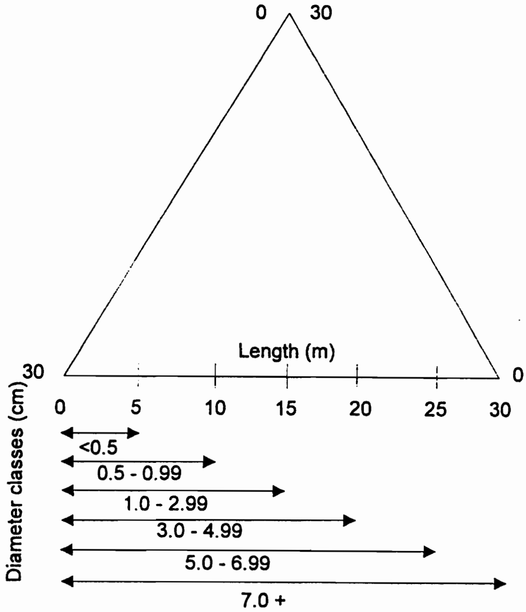

FIG. 2–Line intercept triangle, and the line lengths required for representative sampling of woody slash components in each diameter class.

Weight of woody slash was calculated from two equations (after Van Wagner 1968; Brown 1971; Brown & Roussopoulus 1974; McRae *et al.* 1979):

$$W = \frac{\frac{\pi^2}{8} \times n \times QMD^2 \times s \times a \times c}{L} \qquad \text{Eq. 1}$$

or

$$W = \frac{\frac{\pi^2}{8} \times (\Sigma d^2) \times s \times a \times c}{L} \qquad \text{Eq. 2}$$

where W = weight of woody slash material (t/ha)
n = number of intersections
QMD = quadratic mean diameter (cm)
d = diameter (cm)
s = density (g/cm^3)
a = angle correction factor
c = slope correction factor
L = length of line (m)

No quadratic mean diameter (QMD) or density information for material in diameter classes less than 7 cm is available for either *P. radiata* or *P. contorta*. Data for *P. radiata* were derived from laboratory measurements (Table 1) and were means of at least 30 branches in each diameter class from each site. QMD and density determinations were made on each branch. QMD values for *P. contorta* were assumed to equal the overall mean values for *P. radiata*.

TABLE 1–Quadratic mean diameter for species and diameter classes.

Species	Site	Diameter class (cm)					Source
		0–0.49	0.5–0.99	1.0–2.99	3.0–4.99	5.0–6.99	
P. contorta	Kaingaroa	0.32	0.75	2.06	4.19	6.02	Average of *P. radiata* measurements
P. radiata	Glenbervie	0.33	0.72	2.07	4.28	5.76	Laboratory measurement
P. radiata	Topuni 1 and Topuni 2	0.31	0.79	2.06	4.21	6.18	Laboratory measurement
P. radiata	Mawhera	0.31	0.74	2.04	4.08	6.11	Laboratory measurement

For QMD, diameter measurements were made at each end of each branch in the 0.0- to 0.99-cm classes. Branches in the 1.0- to 6.99-cm classes were measured at the mid point, two diameter measurements being made at right angles to each other. QMD was calculated as follows:

$$QMD = \sqrt{\frac{\sum d^2}{n}} \text{ (Van Wagner 1982)} \qquad \text{Eq. 3}$$

where d = mean diameter measurement
n = number of branches measured.

Density of sound *P. radiata* wood was determined by destructive sampling techniques (Treloar & Lausberg 1997). For *P. contorta* wood, specific gravity was substituted for density, the value being taken from Belanger *et al.* (1984). Data of Bambur & Burley (1983) were used for rotten *P. radiata* wood. Density of *Dicksonia squarrosa* (Forst. f.) Swartz wood in the >7.0 cm diameter class was estimated as for *P. radiata* branches in the 1.0- to 6.99-cm classes. Indigenous hardwood data were derived from the work of Clifton (1990), the mean density of species most common at each site being used as a representative value. At Glenbervie these species were *Knightia excelsa* R. Br. and *Beilschmiedia tawa* (A. Cunn.) Kirk; at Mawhera *Elaeocarpus dentatus* (J.R. et G.Forst.) Vahl, *Prumnopitys ferruginea* (D.Don) de Laub., and *Dacrydium cupressinum* Lamb. There were no indigenous hardwoods at Topuni or Kaingaroa. Densities and specific gravities used in Equations 1 and 2 are shown in Table 2.

The angle correction factor *a* was used to adjust weight estimates because all woody particles do not lie horizontally as assumed in the line intercept theory. Brown & Roussopoulus (1974) have shown that woody slash weight may be under-estimated by 8–39% if no correction is made. The angle correction factors used in Equations 1 and 2 are shown in Table 3 (Brown 1974).

The slope correction factor *c* (McRae *et al.* 1979) was used to convert estimates made from a sloping transect to a horizontal basis and was calculated using the following formula:

TABLE 2–Density or specific gravity values used in Equations 1 and 2.

Component	Diameter class	Wood density *P. radiata* (g/m^3)			Specific gravity *P. contorta* (g/m^3)
		Glenbervie	Topuni	Mawhera	Kaingaroa
Sound *P. radiata* and *P. contorta*	0–0.49	0.56	0.51	0.57	0.48
	0.5–0.99	0.55	0.53	0.53	0.48
	1.0–2.99	0.42	0.47	0.47	0.48
	3.0–4.99	0.37	0.35	0.43	0.52
	5.0–6.99	0.39	0.37	0.44	0.52
	>7.0	0.41	0.41	0.41	0.38
Rotten	>7.0	0.3	0.3	0.3	0.36
Hardwood	>7.0	0.73		0.642	
Ponga	>7.0	0.22		0.22	

TABLE 3–Angle correction factors used in Equations 1 and 2.

Diameter class	0–0.49	0.5–0.99	1.0–2.99	3.0–4.99	5.0–6.99	7.0+
Angle correction factor	1.14	1.13	1.13	1.1	1.1	1

$$c = \sqrt{1 + \left(\frac{slope(\%)}{100}\right)^2} \quad \text{(McRae } et\ al. \text{ 1979)} \qquad \text{Eq. 4}$$

Values for percentage slope were derived from clinometer readings made for each transect line.

Equation 1 was used to calculate the weight of slash less than 7.0 cm in diameter and Equation 2 for the slash greater than 7.0 cm.

Estimation of needle weight

Needle weight (*NW*) estimates were made from data for foliage retention (*F*), the needle-to-branch weight ratio (*NBR*), and the weight of woody slash material less than 3.0 cm in diameter (*SW*). Needle weight was calculated using the following equation:

$$NW = F \times SW \times NBR \quad \text{(McRae } et\ al. \text{ 1979)} \qquad \text{Eq. 5}$$

Canadian researchers have reported that foliage retention in logging slash less than 8 months old is 100% (McRae *et al.* 1979). This has been confirmed for *P. radiata* in New Zealand although NBR's vary with nutrient availability, stocking, and age (P.N.Beets, New Zealand Forest Research Institute, pers. comm.). Webber & Madgwick (1983) and Madgwick *et al.* (1977) reported estimates of 0.29 and 0.21 for 22- and 29-year-old stands respectively. The *P. radiata* stands in this study were 26, 29, and 28 years old at Glenbervie, Mawhera, and Topuni respectively, and values for Equation 5 were obtained by simple linear interpolation. Values for *P. contorta* were obtained from Johnstone (1968). NBR data are presented in Table 4.

TABLE 4–Needle to branch weight ratio estimates used in Equation 5.

Glenbervie	Mawhera	Topuni 1	Topuni 2	Kaingaroa
0.26	0.21	0.23	0.23	0.64

Estimation of the weight of undergrowth and forest floor material by destructive sampling

Before and after burning, all above-ground material was collected from each of eight to 10 randomly-located 1 × 1-m plots, using a vertical projection of the plot boundary to define the sample. Material was sorted into diameter classes (<0.5 cm; 0.5–1.0 cm; 1.1–3.0 cm; >3.0 cm) and dead and live material in each class was oven-dried and weighed separately.

Litter and duff were collected from a 0.3 × 0.3-m area located at random within each plot. At Mawhera, where the duff was more than 20 cm deep, large post-burn sampling errors were avoided by estimating weight loss due to burning from pre-burn sample weight, sample depth, and depth-of-burn measurements. Values were expressed as means for all subplots at each site.

Calculation of Carbon Content of Slash and Undergrowth Material

Carbon content of all potential fuel (organic matter) components was assumed to be 50% of fuel weight (Matthews 1993).

Estimation of Soil Carbon Content

Prior to burning, 10 samples of mineral soil (A horizon; 0–10 cm) were collected from the area within each set of transect lines and bulked. Sample positions and depths were marked to ensure that post-burn sampling would represent the same layer. Two additional soil samples were taken from each triangular area for bulk density determination. Samples for carbon analysis were air-dried and sieved. Carbon content of the <2 mm fraction was determined using LECO CNS-2000 Carbon, Nitrogen, and Sulphur Analyser and the LECO method as outlined by Bremnar (1996). Carbon in the >2 mm fraction was estimated by loss on ignition.

Samples from Mawhera contained duff material and were not analysed. It was found that little or no heat reached a depth of 10 cm in the duff layer during the burn, and it was assumed that burning had a negligible effect on the carbon content of the mineral soil at this site.

Fire Impact Assessment

Depth of burn

Two depth-of-burn pins were located at each corner of each transect triangle. These were used to provide a vertical measurement of loss of material from the litter and duff horizons.

Burn temperature

Burn temperature was assessed using Thermindex temperature-indicating paints spread on to 0.55-mm aluminium flashing. The paints were dried and the flashing was folded in half to prevent scorching. The paints indicate whether temperatures of 80, 115, 295, 310, or 515°C had been exceeded. Choice of paints was related to temperatures at which organic material breaks down. These were (Moore *et al.* 1995):

60°C: denaturation of proteins; hydrated cell death;
100°C: boiling point of water; thermal arrest; desiccation of tissues;
300°C: ignition; decomposition of plant materials; charring of tissues;
500°C: mineralisation of organic matter.

Fuel moisture content (%)

The moisture status of organic matter on a site determines fuel availability and ease of ignition. It is influenced by current and past weather conditions, and the size, arrangement and distribution of individual components. Representative samples of material above the soil A horizon were collected prior to burning and placed in sealed plastic bags. Wet weight (*WW*) and oven-dry weight at 100°C (*ODW*) were determined. Fuel moisture content (*FMC*) of each component was calculated, using the following equation :

$$FMC = \frac{WW - ODW}{ODW} \times 100 \qquad \text{Eq. 6}$$

Fire Weather Index System and weather measurements

The Canadian Fire Weather Index System, considered to be compatible with New Zealand conditions, has been developed as a means of predicting potential fire danger. From current and recent weather data, a set of codes and indices is generated (Fig. 3; Table 5). Output provides ratings for the potential flammability and availability of fuels, and the potential rate of spread and intensity of head fire, and amalgamates these into an overall index of fire hazard. It is important to note that high values for Moisture Codes indicate a low moisture content.

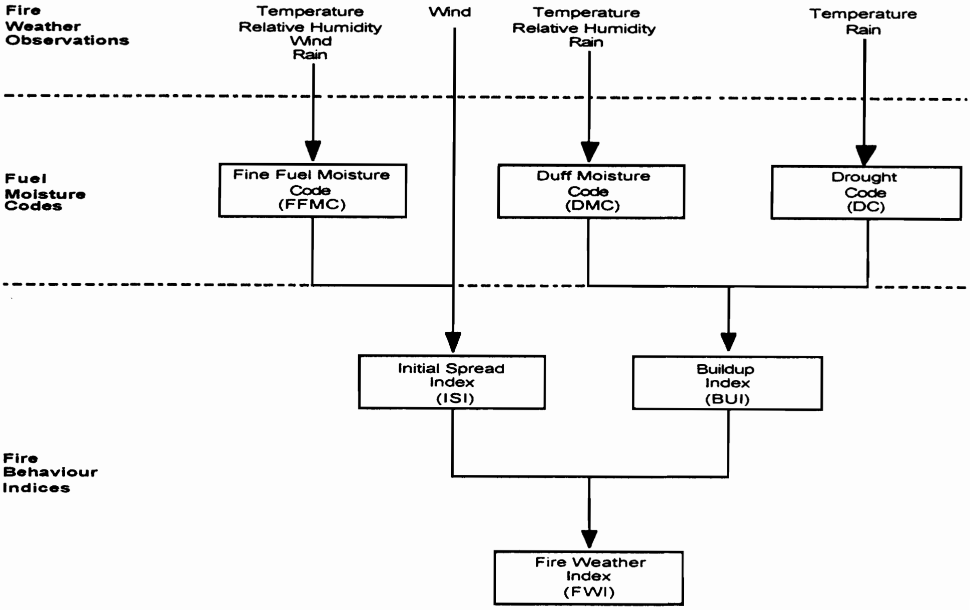

FIG. 3–Structure of the Canadian Fire Weather Index System (Van Wagner 1987).

For each site in the current study, values of the six indices listed in Table 5 were determined from standard information available from the nearest weather station. Distances between weather stations and sites varied from 5 to 17 km. Additional rainfall data were obtained from locations 5 km from the Glenbervie site and 2 km from the Topuni sites. An automatic weather station was set up at each site on the day of the burn to record temperature, relative humidity, wind speed, and rainfall.

TABLE 5–Definitions of the Canadian FWI System components (after Van Wagner 1987).

Component	Definition
Fine Fuel Moisture Code (FFMC)	A numerical rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel. A value of 86 indicates a 100% chance of ignition.
Duff Moisture Code (DMC)	A numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-size woody material. A value of 20 indicates that duff will be involved in the fire.
Drought Code (DC)	A numerical rating of the average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels, soil dryness, the amount of smouldering in deep duff layers and large logs. A value of 200 indicates deep duff layers will be involved in the fire, and that substantial resources, time, and money will be required to completely extinguish the fire.
Initial Spread Index (ISI)	A numerical rating of the expected rate of fire spread. It combines the effects of wind and FFMC on rate of spread without the influence of variable quantities of fuel.
Buildup Index (BUI)	A numerical rating of the total amount of fuel available for combustion that combines DMC and DC.
Fire Weather Index (FWI)	A numerical rating of fire intensity that combines ISI and BUI. It is suitable as a general index of fire danger throughout the forested and rural areas of New Zealand.

Fire danger conditions were estimated based on weather data and the S-1 jack or lodgepole pine slash fuel type in the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992).

Ignition, burning, and fire behaviour conditions

Glenbervie, Mawhera, and Kaingaroa burns were started using gelled accelerant dispensed from an aerial drip torch suspended below a helicopter. Slash at the two sites at Topuni was lit along one edge of the site using a hand-held gas torch.

RESULTS

Survey

The Glenbervie trial site was not included in the returns. From the return sample, it was estimated that an average of 386 ha of harvested exotic forest had been burnt annually in New Zealand over the last 4 years. This represents 0.0002% of the total exotic forest estate and is likely to be a minimum value.

Description of Organic Material Above the Mineral Soil

Before burning

Recently-harvested logging slash (needles and woody material) at *P. radiata* sites contributed an average of 60 t/ha (range 43–77 t/ha) (Table 6) to the total weight of above-

TABLE 6–Total weight and carbon content of organic matter in logging slash, undergrowth, and forest floor material at the five study sites (excluding stumps, roots, and mineral soil).

Site	Weight of organic matter			Weight of carbon*			Dry matter or carbon loss
	Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)	Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)	(%)
P. radiata							
Glenbervie	90.7	43.7	47	45.4	21.6	23.7	52.2
Mawhera	89.5	32.6	56.9	44.8	16.3	28.8	64.3
Topuni 1	77.6	29.2	48.4	38.8	14.6	24.2	62.4
Topuni 2	89.5	27.7	61.8	44.7	13.8	30.9	69.1
Average	86.8	33.3	53.5	43.4	16.6	26.9	62.0
s.e.	3.1	3.6	3.5	1.5	1.8	1.8	3.6
P. contorta							
Kaingaroa	136.6	70.7	65.9	68.3	35.4	32.9	48.2

* Carbon content is assumed to be 50% of organic matter oven-dry weight.

ground material. Undergrowth, duff, and litter contributed 27 t/ha (range 13–43 t/ha). Depth of burn in the organic soil horizons ranged between 0.6 and 8.0 cm.

At the *P. contorta* site, where there was no undergrowth component, logging slash contributed 79 t/ha to the total weight of above-ground organic material. Litter and duff layers contributed 58 t/ha.

Effect of burning

At *P. radiata* sites, 52–70% (mean 59%) of the total weight of organic material and its carbon content was lost to the atmosphere during burning (Table 6). At the *P. contorta* site 48% of the total weight (and carbon) was lost.

No consistent relationship was detected between carbon loss and pre-burn weight of logging slash components or between carbon loss and pre-burn weight of all above-ground organic material.

At *P. radiata* sites the largest above-ground losses (greater than 80%) were recorded in the duff and woody material >0.99 cm components (Table 7). Losses at the *P. contorta* site (Table 8) exceeded 80% in the needles and woody material <2.99 cm components. The proportion of each category lost was not related to the relative category contributions to overall weight (or carbon) loss. Litter/ash and sound slash >7.0 cm at *P. radiata* sites, and duff at *P. contorta* sites were the only components that contributed more than 15% to the total loss. There was some indication that pre-burn weight of an individual category might be related to the contribution of that category to the total loss, but more data would be required to confirm this. Results from each site are presented in Appendix 1.

Effect of Burning on Soil Carbon Content

Data from the four sites examined did not provide convincing evidence of carbon loss or gain from the upper soil layers after burning (Table 9). Post-burn values at Glenbervie and Kaingaroa were not significantly different from pre-burn values. The significance of larger

TABLE 7–*Pinus radiata* sites. Effect of burning on the contribution of individual categories to the total weight and carbon loss of organic material above the mineral soil (excluding stumps, roots, and mineral soil).

Component	Diameter class (cm)	Weight of organic matter Pre-burn (t/ha)	Weight of organic matter Post-burn (t/ha)	Weight of organic matter Loss (t/ha)	Weight of carbon* Pre-burn (t/ha)	Weight of carbon* Post-burn (t/ha)	Weight of carbon* Loss (t/ha)	Dry matter or carbon loss (%)	Contribution to total C loss (%)
Duff		11.1	6.6	4.5	5.6	3.3	2.3	20.4	8.2
Litter/Ash		14.2	2.0	12.2	7.1	1.0	6.1	86.1	22.8
Undergrowth	0.0–7.0	1.8	0.4	1.4	0.9	0.2	0.7	64.9	2.7
Needles		3.4	1.0	2.4	1.7	0.5	1.2	72.9	4.6
Sound woody material	0.0–0.49	1.2	0.2	1.0	0.6	0.1	0.5	87.4	2.0
	0.5–0.99	3.0	0.5	2.4	1.5	0.3	1.2	81.7	4.5
	1.0–2.99	10.4	3.4	6.9	5.2	1.7	3.5	68.4	13.1
	3.0–4.99	9.2	4.1	5.1	4.6	2.1	2.5	56.3	9.4
	5.0–6.99	7.9	3.8	4.0	3.9	1.9	2.0	54.1	7.4
	>7.0	20.5	10.2	10.4	10.3	5.1	5.2	50.6	19.3
Rotten woody material	>7.0	2.7	0.4	2.3	1.4	0.2	1.1	66.4	4.4
Hardwood	>7.0	0.4	0.0	0.3	0.2	0.0	0.2	30.2	0.6
Punga	>7.0	1.0	0.4	0.6	0.5	0.2	0.3	29.4	1.1
Total woody material		59.7	24.2	35.5	29.9	12.1	17.8	61.4	66.3
Total		86.8	33.2	53.7	43.4	16.6	26.8	61.8	100.0

* Carbon content is assumed to be 50% of organic matter oven-dry weight.

differences recorded at Topuni could not be assessed, and there is reason to suspect sampling error at Topuni Site 1 (ash included in the soil sample).

Fire Impact Assessment

Ignition

Due to dense green scrub growth and non-continuous slash, the fire at Glenbervie did not travel between slash heaps. Several helicopter passes with the aerial drip torch were required before ignition occurred at this site and flaming combustion in heaps was sustained for less than 10 minutes after light up. At Mawhera and Topuni Sites 1 and 2, fire spread rapidly between slash heaps. Smouldering combustion continued for about 30 minutes at both the Topuni sites. At Kaingaroa the fire did not always travel between slash heaps but it was easier to light up than at Glenbervie.

Depth of burn and burn temperature

Depth of duff burn ranged from 1 mm (Mawhera) to 8 mm (Kaingaroa) while depth of litter burn ranged from 5 mm (Mawhera) to 60 mm (Topuni site 1). A layer of moss/lichen included in the duff samples from Kaingaroa may explain the large depth of burn values recorded there.

TABLE 8—*Pinus contorta* site. Effect of burning on the contribution of individual categories to the total weight and carbon loss of organic material above the mineral soil (excluding stumps, roots, and mineral soil).

Component	Diameter class (cm)	Weight of organic matter			Weight of carbon*			Dry matter or carbon loss (%)	Contribution to total C loss (%)
		Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)	Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)		
Duff		45.5	16.7	28.9	22.8	8.3	14.4	63.4	43.8
Litter/Ash		12.2	4.3	7.8	6.1	2.2	3.9	64.4	11.9
Undergrowth	0.0–7.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0
Needles		4.6	0.7	3.9	2.3	0.3	2.0	85.8	6.0
Sound woody material	0.0–0.49	0.9	0.0	0.8	0.4	0.0	0.4	95.0	1.2
	0.5–0.99	2.6	0.1	2.5	1.3	0.1	1.3	95.7	3.8
	1.0–2.99	11.8	2.2	9.6	5.9	1.1	4.8	81.5	14.6
	3.0–4.99	5.2	4.1	1.0	2.6	2.1	0.5	20.2	1.6
	5.0–6.99	5.6	4.5	1.0	2.8	2.3	0.5	18.5	1.6
	>7.0	45.6	37.8	7.8	22.8	18.9	3.9	17.2	11.9
Rotten woody material	>7.0	2.6	0.3	2.4	1.3	0.1	1.2	89.6	3.6
Hardwood	>7.0	0.0	0	0	0.0	0.0	0.0	0.0	0.0
Punga	>7.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0
Total wood material		78.8	49.7	29.2	39.4	24.8	14.6	37.0	44.3
Total		136.6	70.7	65.9	68.3	35.4	32.9	48.2	100.0

*Carbon content is assumed to be 50% of organic matter oven-dry weight.

TABLE 9—Effect of burning on soil carbon content.

Site	Pre-burn (t/ha)	s.e.	Post-burn (t/ha)	s.e.
Glenbervie	34.6	3.0	34.2	3.7
Mawhera — not sampled				
Topuni 1	25.6	ND	37.8*	ND
Topuni 2	27.8	ND	29.7	ND
Kaingaroa	34.4	3.1	33.4	4.0

ND = Not determined (two samples only).
* Sampling error suspected

Fuel moisture content, weather, and FWI System values

Duff at Mawhera was very damp, with fuel moisture content varying between 276% and 342% (Appendix 2) and a low Drought Code (Table 10). Duff moisture content ranged between 84% (Topuni Site 1) and 342 % (Mawhera) and litter moisture content ranged from 10% (Topuni Site 2) to 65% (Kaingaroa). The Fine Fuel Moisture Code (FFMC) ranged from 83 to 86 at Glenbervie and Topuni respectively, indicating that ignition should have been easy at all sites (an FFMC value of 74 indicates a 50% chance of ignition while 86 indicates

TABLE 10–Weather and FWI values on the day of the burn.

Site	Glenbervie	Mawhera	Topuni 1	Topuni 2	Kaingaroa
Temp (°C)	16.4	17.4	20.0	20.0	16.2
R.H.(%)	69	65	56	56	57
Wind speed (km/h)	12.6	13.7	9.3	9.3	16.6
Days since rain (>0.6 mm)	4	11	8	8	6
FFMC*	83.4	86.0	86.2	86.2	85.1
DMC	14.7	17.5	21.3	21.3	7.7
DC	95.0	56.8	126.2	126.2	135.2
ISI	3.2	4.8	3.9	3.9	4.9
BUI	21.2	19.8	30.0	30.0	13.5
FWI	5.4	7.6	8.1	8.1	6.3
Fire danger conditions	Very high	Extreme	Extreme	Extreme	Very high

* See Table 5 for explanation of abbreviations

a 100% chance). The Duff Moisture Code (DMC) indicted duff involvement at the two Topuni sites as values exceeded 20. The Initial Spread Index (ISI) indicated a slow rate of spread at all sites. All burns were conducted in very high or extreme fire danger conditions (Table 10).

Carbon Loss and the Fire Weather Index System

The best predictor of total organic matter and carbon losses was the Fire Weather Index ($r^2 = 0.66$) (Fig. 4). At this stage carbon loss due to burning cannot be modelled as only five experimental slash fires under similar FWI system conditions have been conducted.

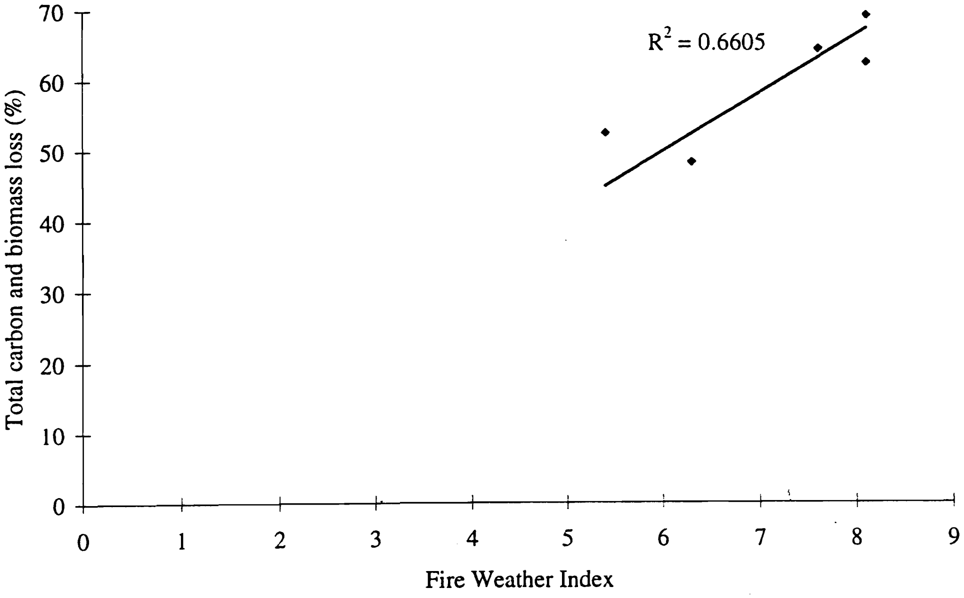

FIG. 4–Relationship between carbon loss during burning and the Fire Weather Index.

DISCUSSION

On average, 27 t C/ha (s.e. = 1.8) or 62% (s.e. = 3.6) of carbon present before burning (excluding that contained in stumps, roots, and mineral soil) was lost to the atmosphere as a result of slash burns at the four *P. radiata* sites selected for this investigation. For the *P. contorta* site 33 t C/ha or 48% of carbon present before burning (excluding that contained in stumps, roots, and mineral soil) was lost to the atmosphere as a result of slash burning. No previous studies on carbon loss from slash burns have been conducted in New Zealand. The *P. radiata* estimate reported here is slightly higher than the 49–58% calculated by Vose & Swank (1993) for pine-hardwood stands in North Carolina, or the 8–54% reported by Feller (1989) for conifers in British Columbia under a range of FWI System conditions. The *P. contorta* estimate reported here falls within the range of results from both studies.

The Fire Weather Index System conditions under which the slash burns in this study were conducted are probably typical of the range of slash-burning conditions throughout New Zealand. It is likely Glenbervie represented the lower end of this range, because ignition was difficult. The two sites at Topuni are thought to represent the upper limit because duff was involved, and the site required extended surveillance and mop up. More trials would be required to ascertain whether carbon loss from the five selected sites is representative of carbon loss from all burns around New Zealand.

From the survey data and the results of the field study, the current best estimates of annual carbon loss due to burning of logging slash in New Zealand are 10 300 tonnes (s.e. = 1800) for *P. radiata* and 1600 tonnes (s.e. = 1160) for *P. contorta* sites. It has been calculated that the plantation forest estate in New Zealand contained 143 Mt C in the year ending 31 March 1995, and 4.0 Mt C were sequestered in that year (Ministry for the Environment 1997). Carbon loss from slash burns is therefore unlikely to be a significant component of total loss at the national level. In spite of this, carbon losses at the forest level could be considerable if burning, as a site-preparation technique, is more widespread than the survey suggested.

Carbon loss from exotic forest slash burning may be significant at the stand level as a 27 t/ha carbon loss represents 12–14 % of the carbon in an "normal stand at harvesting" (Maclaren 1995). If tradeable carbon certificates were to become a reality in New Zealand, forest or land owners might be required to surrender certificates at the time trees were felled or forest/scrubland was cleared (Ministry for the Environment 1996). When an exotic forest stand is harvested, over half the pre-harvest carbon content remains on site. Depending on the criteria used, further carbon reduction due to burning could increase justification for the immediate surrender of carbon certificates. Estimates of carbon loss due to slash burning, based on Fire Weather Index, could be used to calculate the value of the carbon certificates to be surrendered at the time of burning.

The best predictor of total organic matter and carbon losses was the Fire Weather Index. More work is required under a wide range of FWI conditions if a comprehensive system for modelling carbon loss from slashburns is to be developed.

The prototype CARBON module includes carbon loss from burning in calculations of the total amount of carbon sequestered by *P. radiata* plantations. Currently carbon loss from burning is included in the CARBON module as a user-defined input of percentage carbon loss. In future the Fire Weather Index could be used to provide an estimate of percentage carbon loss. Application to total forest stand data (supplied by STANDPAK) would provide an estimate of total carbon loss due to burning.

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APPENDIX 1

WEIGHT OF ORGANIC MATTER AND CARBON CONTENT AT EACH SITE. RESULTS ARE AVERAGE VALUES FOR THE NUMBER OF TRIANGULAR TRANSECTS.

Component	Diameter class (cm)	Weight of organic matter			Weight of carbon				Dry matter or carbon loss (%)	Contribution to total C loss (%)
		Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)	Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)	s.e.		
(a) Glenbervie organic matter and carbon content (*P. radiata*, n=4)										
Duff		N/P*								
Litter/Ash		14.5	2.0	12.5	7.2	0.7	6.5	2.6	67.8	30.4
Undergrowth	0.0–7.0	4.0	1.6	2.4	2.0	0.8	1.2	0.7	80.7	4.7
Needles		4.7	3.3	1.3	2.3	1.7	0.7	0.4	30.6	2.8
Sound woody material	0.0–0.49	2.0	0.6	1.4	1.0	0.3	0.7	0.3	73.7	3.3
	0.5–0.99	2.8	1.0	1.7	1.4	0.5	0.9	0.3	65.8	4.0
	1.0–2.99	13.2	6.3	6.8	6.6	3.2	3.4	1.4	54.4	16.0
	3.0–4.99	11.3	6.9	4.4	5.7	3.5	2.2	0.8	43.1	10.1
	5.0–6.99	7.7	6.0	1.6	3.8	3.0	0.8	0.4	22.2	3.6
	>7.0	22.5	14.4	8.1	11.2	7.2	4.1	2.4	33.4	15.9
Rotten woody material	>7.0	5.8	1.2	4.5	2.9	0.6	2.3	2.3	29.7	7.7
Hardwood	>7.0	0.2	0.2	0.1	0.1	0.1	0.0	0.0	6.9	0.1
Punga	>7.0	2.1	1.3	0.8	1.1	0.7	0.4	0.4	12.6	1.4
Total woody material		72.2	41.4	30.8	36.1	20.7	15.4	6.3	43.3	64.9
Total		90.7	45.0	45.7	45.4	22.2	23.1	8.3	53.1	100.0
(b) Mawhera organic matter and carbon content (*P. radiata*, n=5)										
Duff							0.3	0.1	0.0	1.4
Litter/Ash		12.9	2.9	10.0	6.4	1.4	5.0	1.8	69.4	18.9
Undergrowth	0.0–7.0	N/P								
Needles		2.9	0.5	2.3	1.4	0.3	1.2	0.2	80.3	4.5
Sound woody material	0.0–0.49	1.3	0.1	1.2	0.6	0.0	0.6	0.1	89.2	2.1
	0.5–0.99	3.0	0.4	2.6	1.5	0.2	1.3	0.2	86.1	5.2
	1.0–2.99	9.4	2.2	7.2	4.7	1.1	3.6	0.5	76.0	13.8
	3.0–4.99	9.1	4.8	4.2	4.5	2.4	2.1	0.7	44.3	8.6
	5.0–6.99	10.6	6.2	4.4	5.3	3.1	2.2	0.6	39.3	8.0
	>7.0	33.7	14.6	19.0	16.8	7.3	9.5	4.9	50.0	27.7
Rotten woody material	>7.0	3.5	0.5	3.0	1.8	0.2	1.5	0.9	73.1	4.9
Hardwood	>7.0	1.2	0.0	1.2	0.6	0.0	0.6	0.3	60.2	1.9
Punga	>7.0	1.9	0.4	1.5	1.0	0.2	0.8	0.2	67.2	3.1
Total woody material		76.6	29.7	46.9	38.3	14.9	23.5	5.9	58.6	79.8
Total		89.5	32.6	56.9	44.8	16.3	28.8	6.0	62.2	100.0

APPENDIX 1 cont.

Component	Diameter class (cm)	Weight of organic matter			Weight of carbon				Dry matter or carbon loss (%)	Contribution to total C loss (%)
		Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)	Pre-burn (t/ha)	Post-burn (t/ha)	Loss (t/ha)	s.e.		
(c) Topuni, site 1 organic matter and carbon content (*P. radiata*, n=2)										
Duff		22.2	14.4	7.8	11.1	7.2	3.9	0.5	35.0	16.6
Litter/Ash		10.5	1.1	9.4	5.3	0.5	4.7	1.0	88.4	20.3
Undergrowth	0.0–7.0	1.9	0.0	1.9	1.0	0.0	1.0	0.4	100.0	3.8
Needles		3.0	0.8	2.2	1.5	0.4	1.1	0.3	71.7	4.5
Sound woody material	0.0–0.49	0.7	0.0	0.6	0.3	0.0	0.3	0.1	94.2	1.3
	0.5–0.99	2.8	0.4	2.4	1.4	0.2	1.2	0.4	83.6	4.8
	1.0–2.99	9.6	3.0	6.6	4.8	1.5	3.3	0.7	67.0	13.3
	3.0–4.99	7.3	2.9	4.4	3.6	1.4	2.2	1.3	45.5	8.4
	5.0–6.99	6.8	1.8	5.0	3.4	0.9	2.5	0.8	69.7	9.9
	>7.0	12.9	5.0	8.0	6.5	2.5	4.0	0.9	59.7	17.2
Rotten woody material	>7.0	N/P								
Hardwood	>7.0	N/P								
Punga	>7.0	N/P								
Total woody material		43.0	13.8	29.2	21.5	6.9	14.6	2.6	66.6	59.3
Total		77.6	29.2	48.4	38.8	14.6	24.2	1.5	62.3	100.0
(d) Topuni, site 2 organic matter and carbon content (*P. radiata*, n=2)										
Duff		22.4	12.1	10.4	11.2	6.0	5.2	3.3	36.2	15.9
Litter/Ash		19.0	2.4	16.6	9.5	1.2	8.3	1.9	87.0	27.5
Undergrowth	0.0–7.0	1.1	0.0	1.1	0.6	0.0	0.6	0.0	100.0	1.8
Needles		3.1	0.6	2.5	1.6	0.3	1.3	0.0	80.5	4.1
Sound woody material	0.0–0.49	1.0	0.1	0.9	0.5	0.0	0.5	0.1	92.2	1.5
	0.5–0.99	3.3	0.3	2.9	1.6	0.2	1.5	0.0	89.9	4.8
	1.0–2.99	9.3	2.2	7.1	4.7	1.1	3.5	0.0	76.1	11.5
	3.0–4.99	9.3	2.0	7.3	4.6	1.0	3.6	0.3	78.8	11.9
	5.0–6.99	6.4	1.3	5.1	3.2	0.6	2.6	0.1	80.0	8.3
	>7.0	13.1	6.7	6.3	6.5	3.4	3.2	0.3	49.5	10.2
Rotten woody material	>7.0	1.6	0.0	1.6	0.8	0.0	0.8	0.1	100.0	2.6
Hardwood	>7.0	N/P								
Punga	>7.0	N/P								
Total woody material		47.0	13.3	33.8	23.5	6.6	16.9	0.3	72.0	54.9
Total		89.5	27.7	61.8	44.7	13.8	30.9	1.1	69.4	100.0

APPENDIX 1 cont.

Component	Diameter class (cm)	Weight of organic matter Pre-burn (t/ha)	Weight of organic matter Post-burn (t/ha)	Weight of organic matter Loss (t/ha)	Weight of carbon Pre-burn (t/ha)	Weight of carbon Post-burn (t/ha)	Weight of carbon Loss (t/ha)	s.e.	Dry matter or carbon loss (%)	Contribution to total C loss (%)
(e) Kaingaroa organic matter and carbon content (*P. contorta*, n = 5)										
Duff		45.5	16.7	28.9	22.8	8.3	14.4	2.6	62.1	47.2
Litter/Ash		12.2	4.3	7.8	6.1	2.2	3.9	0.9	63.4	13.7
Undergrowth	0.0–7.0	N/P								
Needles		4.6	0.7	3.9	2.3	0.3	2.0	0.3	84.9	7.1
Sound woody material	0.0–0.49	1.5	0.1	1.4	0.7	0.0	0.7	0.2	91.6	2.6
	0.5–0.99	0.7	0.0	0.7	0.4	0.0	0.4	0.0	95.2	1.3
	1.0–2.99	5.0	0.9	4.1	2.5	0.5	2.0	0.2	81.0	7.2
	3.0–4.99	6.6	5.3	1.3	3.3	2.6	0.7	0.4	17.9	2.5
	5.0–6.99	3.5	2.8	0.6	1.7	1.4	0.3	0.2	15.5	1.3
	>7.0	45.6	37.8	7.8	22.8	18.9	3.9	1.0	16.5	13.5
Rotten woody material	>7.0	2.6	0.3	2.4	1.3	0.1	1.2	0.9	71.1	3.6
Hardwood	>7.0	N/P								
Punga	>7.0	N/P								
Total woody material		70.2	47.9	22.3	35.1	23.9	11.2	1.3	31.4	39.1
Total		127.9	68.9	59.0	63.9	34.4	29.5	3.3	45.5	100.0

* N/P = not present

APPENDIX 2

AVERAGE FUEL MOISTURE CONTENT (%) OF VARIOUS ORGANIC MATTER COMPONENTS

	Glenbervie	Mawhera	Topuni 1	Topuni 2	Kaingaroa
Duff (covered)	N/P	342.31	102.76	210.08	136.12
Duff (open)	N/P	276.19	84.4	149.35	107.99
Litter (covered)	42.38	31.79	20.35	24.99	64.55
Litter (open)	24.03	21.72	10.7	10.14	14.55
Undergrowth	510.63	N/P	296.04	17.81	N/P
Slash <0.5 cm (elevated)	16.87	17.58	14.91	16.04	14.81
Slash <3 cm (covered)	109.77	N/A	17.95	21.08	19.00
Slash <3 cm (open)	28.89	13.88	16.43	18.48	N/A
Slash <7 cm (covered)	27.18	31.21	23.71	19.19	N/A
Slash <7 cm (open)	55.33	N/A	17.23	16.2	28.96
Rotten slash	240.12	N/A	N/A	N/A	N/A

N/P = not present
N/A = not available