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Soil physical and hydrological properties following logging and slash burning in the *Eucalyptus regnans* forest of southeastern Australia

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Abstract

Logging causes soil profile disturbance (mixing and/or removal of soil) and compaction. Regeneration slash fire causes burning of surface soils. This may change soil physical and hydrological properties, which may affect site productivity and catchment water quality. This study was undertaken to quantify the effect of logging and slash burning on areal distribution of soil profile disturbance, fire intensity class and physical and hydrological properties of the 0–100 mm surface soil in the Victorian Central Highlands, southeastern Australia. Following clearfelling logging and slash burning, four coupes were surveyed using a systematic grid sampling technique. Each coupe was classified into the following operation categories: snig tracks, log landings and general logging areas. Each coupe was also classified in terms of both level of soil profile disturbance: undisturbed, litter disturbed, topsoil disturbed and subsoil disturbed; and intensity of fire: unburned, low intensity, moderate intensity and high intensity. The soil physical and hydrological properties were measured in two of the four logging coupes. Measurements were made in the snig tracks (primary, secondary and tertiary tracks), log landings and general logging areas. Within the general logging areas, plots were located for two classes of soil profile disturbance: undisturbed and topsoil disturbed. Within each of the two classes of soil profile disturbance measurements were made for three levels of fire intensities: unburned, moderate intensity and high intensity burn.

Following logging and slash burning, on average 11% of the coupe area remained undisturbed, 11% litter disturbed, and 78% had mineral soil exposed. The snig tracks, log landings and disturbed general logging area occupied about 19%, 3% and 66% of the coupe area, respectively. On average, 52% of the coupe area remained unburned and 8% was affected by high intensity burn.

Soil profile disturbance significantly changed particle size and organic matter distribution, increased bulk density, decreased aeration porosity and saturated hydraulic conductivity in the unburned general logging area. Soil compaction significantly increased bulk density, water-filled porosity (< 30 μm) and available water, and decreased aeration porosity and saturated hydraulic conductivity in the primary snig tracks and log landings.

The high intensity slash burning significantly reduced clay and organic matter content in the undisturbed soil profile conditions but not for disturbed soil profile conditions. Implications for changes in these soil properties are discussed in terms of eucalypt establishment and growth and soil erosion potential.

Keywords: Timber harvesting; Clearfelling; Fire; Soil compaction; Soil disturbance; Soil erosion; Saturated hydraulic conductivity

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1. Introduction

In forestry systems, the use of fire to burn logging slash and facilitate seed-bed preparation is still a common practice around the world. Slash fires may affect the soil environment in a number of ways including partial burning of the litter layer to a complete burning of the litter layer. This may eliminate the beneficial effects of the organic layer on soil physical and hydrological properties. The heating of soil itself produces various degrees of burned areas ranging from low intensity to high intensity burned areas (completely oxidised ash-bed). The degree and extent of the slash burning effect on soil properties vary with duration and intensity of fire, temperature, type and amount of logging slash and vegetation, soil moisture content at the time of burning, soil organic matter and texture (Roberts, 1965; Humphreys and Lambert, 1965; Downer and Harter, 1979; Wells et al., 1979; Humphreys and Craig, 1981; Granger, 1984; Cass et al., 1984; Flinn et al., 1984).

The high intensity slash burning may reduce organic matter content (Austin and Baisinger, 1955; Raison, 1979, Raison, 1980), decrease bulk density (Clinnick and Willatt, 1981), increase aeration porosity (Tarrant, 1956) and decrease infiltration rates (Tarrant, 1956; Clinnick and Willatt, 1981; McNabb et al., 1989). The changes in soil properties may be detrimental in terms of increasing the risk of soil erosion (Flinn et al., 1984; Mackay et al., 1985) and detrimental or beneficial in terms of tree growth (King et al., 1993a, King et al., 1993b).

In the Victorian Central Highlands, eucalypt forests are logged using ground-based machinery under a clearfelling silvicultural system. Following clearfelling, the soil surface is littered with an accumulation of slash consisting of tops, branches and utilised wood. Broadcast slash burning is frequently used for preparation of the seed-bed in the regeneration of harvested areas. In some situations, the seed-bed is prepared by mechanically re-distributing logging slash and scarification of surface soils. The effect of logging and mechanical seed-bed preparation on soil profile disturbance, soil physical properties and regeneration and early growth of *Eucalyptus regnans* in the Victorian Central Highlands forest

Table 1
Summary of site characteristics, machinery configuration and logging records of four experimental coupes in the Victorian Central Highlands forest

Characteristics	Coupes			
	Top Regen	Research Spur	Simpsons Road	North Loch
Site characteristics				
Forest block	Tooronga	Rowleys	Rowleys	North Loch
Area (ha)	7.36	4.03	19.7	17.0
Elevation (m)	920–980	620–680	580–600	740–760
Dominant aspect	E	E	SE	S
Average slope (°)	15–20	15–20	10–20	10–20
Geology	Metamorphic	Granitic	Granitic	Metamorphic
Machinery configuration [a]				
Snigging	CAT 518 Cable	CAT D7G	CAT 518 Cable	FMC 210
Landing construction	CAT D7G	CAT D7G	CAT D7G	CAT D7G
Log debarking and loading	Rubber tyre loader	Rubber tyre loader	Excavator	Excavator
Logging records				
Harvesting season	Summer, 88–89	Late summer to early Autumn, 89	Winter, 88	Winter–Spring, 89
Slash burning period	6 April 89	6 April 89	4 April 89	14 Feb 90
Timber volume (m^3 ha^{-1})				
Sawlogs	198	151	190	244
Residual logs	333	243	381	364
Total	531	394	571	608

[a] CAT D7G, fixed track crawler tractor; CAT 518 Cable, rubber tyre skidder; FMC 210, flexible steel track skidder.

were investigated (see King, 1993; King et al., 1993a, King et al., 1993b; Rab, 1994; Rab et al., 1994). There is a dearth of information available on the effect of broadcast slash burning on physical and hydrological properties of soil in this forest. This information is necessary to provide a basis for developing guide-lines for the effective use of prescribed fire. This study was undertaken to measure the effect of logging and broadcast slash burning on particle size distribution, organic carbon and organic matter content, bulk density, pore-size distribution, available water and saturated hydraulic conductivity of soil in the Victorian Central Highlands forest, southeastern Australia.

2. Methods

2.1. Study area description

The study area is located 150 km east of Melbourne, near Tanjil Bren, in the Victorian Central Highlands (30°2′S, 146°15′E). Four clearfelled coupes (Top Regen, Research Spur, Simpsons Road and North Loch) were selected for this study. The size of the coupes varied from 4.03 ha to 19.7 ha (Table 1). The parent material of Top Regen and North Loch is metamorphic and Research Spur and Simpsons Road is granitic in origin. The landform is mainly steep hills to moderately steep rolling hills (McDonald et al., 1990). The major soil type of the area is red gradational with a small percentage of yellow brown gradational soil (Northcote et al., 1975). The average depth of the topsoil is 250 mm with up to 400 mm along drainage lines. The depth of subsoil varies between 650 mm and 1200 mm. The climate of the study area is cool temperature and average annual rainfall is approximately 1900 mm. Average monthly temperature ranges from 0°C in July to 20°C in February. Elevation ranges from 580 to 980 m (Table 1). The average slopes vary from 0 to 20°. The vegetation of the study area was predominantly 1939 regrowth Mountain Ash (*Eucalyptus regnans*), with occasional overmature and regrowth Mountain Grey Gum (*Eucalyptus cypellocarpa*). Stands were of moderate density (approximately 40 m^2 ha^{-1} basal area) with top heights of 50 m. The understorey comprised three distinct strata. The upper stratum was generally sparse and consisted of wattles (*Acacia dealbata* and *A. obiquinervia*) and occasional Myrtle Beech (*Nothofagus cunninghamii*) in damp locations. The middle stratum was dense and contained many shrubs and small trees including Blanket Leaf (*Bedfordia arborescens*), Musk Daisy Bush (*Olearia argophylla*), Hazen Pomaderris (*Pomaderris aspera*) and tree ferns (*Disksonia antarctica* and *Cyathea australis*). The ground stratum was generally sparse and consisted of various species of fern. The forest also contains many standing and fallen, fire-killed, overmature trees.

2.2. Logging and slash burning

Sawlogs and residual logs of 50-year-old Mountain Ash forests were logged using ground-based machinery under a clearfelling silvicultural system during 1988–89 (Table 1). Logging involved (i) construction of log landings, (ii) felling of trees, (iii) cutting of felled trees into log pieces, (iv) mechanical snigging of logs to landings and (v) debarking and loading of logs to trucks for transportation. Construction of log landings in all coupes was carried out using a D7G fixed track crawler tractor (Table 1). Trees were felled and cut into logs using a chainsaw. Logs were snigged to log landings using either a CAT 518 Cable rubber tyre skidder, a D7G fixed track crawler tractor, or a FMC 210 flexible steel track skidder. Logs were debarked at the landing and loaded using either a rubber tyre loader or excavator.

About 1 to 7 months after logging (Table 1), the seed-bed was prepared using broadcast slash burning.

2.3. Characterisation of soil profile disturbance and fire intensity

About 2 to 5 months after slash burning, the experimental coupes were surveyed using a systematic grid sampling for assessing type of operation category, level of soil profile disturbance and intensity of fire. The size of the grid was 20 m × 40 m. At each grid point a 1-m^2 quadrat was studied to identify the type of operation category, level of soil profile disturbance and intensity of fire. The operation categories were:

1. Snig tracks. Tracks created for towing or winching logs to the landing.
2. Log landings. Area where logs were snigged for debarking, sorting and loading.
3. General logging area. Areas where trees are felled (excluding the areas which were not used for snig tracks and log landings). This area also includes areas of retained forest or other vegetation within the coupe boundary.

The following soil profile disturbance categories were used:

1. Undisturbed. No machine or log passed. Litter on the surface and intact. O_1 horizon is predominant.
2. Litter disturbed. Machine or log has passed. Litter on the surface or partially removed. Some mineral soil may be visible in non-continuous patches. O_2 horizon is predominant. If O_2 is naturally thin, root mat still binds the surface A_1.
3. Topsoil disturbed. Machine or log has passed. Litter (O_1 and O_2) removed or mixed with topsoil. Topsoil partially removed or mixed with subsoil. Mineral topsoil (A horizon) is predominant. (Topsoil consists of A_1, A_2 and A_3 horizons except where A_2 is conspicuously bleached (McDonald et al., 1990), whereby A_2 and A_3 are regarded as subsoil.)
4. Subsoil disturbed. Machine or log has passed. Topsoil removed or mixed with subsoil. Subsoil removed or mixed with C horizon. Mineral subsoil (B horizon) or C horizon is predominant. Subsoil includes B_1 and B_2 horizons and conspicuously bleached A_2 horizon (and any other A horizon below A_2).

The intensity of fire was classified from the appearance of the litter and soil after burning, and referred into one of the following fire intensity classes.

1. Unburned. Litter, soil or vegetation unburned.
2. Low intensity. Partial burn of slash and litter of diameter up to 20 mm. Litter O_2 horizon, where present, predominantly unburned.
3. Moderate intensity. Near-complete burn of slash and litter of diameter up to 20 mm, partial burn of branches greater than 20 mm. Some soil oxidation present, but generally charcoal or ash-seed-bed.
4. High intensity. Near-complete burn of slash and litter of diameter up to 70 mm, partial burn of branches greater than 70 mm. Soil oxidation (orange ash-bed) predominant.

2.4. Measurements of soil physical and hydrological properties

2.4.1. Sampling strategy

Sampling for soil physical and hydrological measurements was carried out about 5 months after slash burning. To study the effect of fire intensity on soil physical and hydrological properties, plots were established within the general logging areas of two logging coupes (Top Regen and Simpsons Road). After characterising fire intensity and soil profile disturbance, the general logging areas of each coupe were stratified into three topographic positions: upper, middle and lower slopes. Within each topographic position, areas were located in the following six soil–fire disturbance categories:

1. Undisturbed–unburned
2. Undisturbed–moderate intensity burn
3. Undisturbed–high intensity burn
4. Topsoil disturbed–unburned
5. Topsoil disturbed–moderate intensity burn
6. Topsoil disturbed–high intensity burn

Within each topographic position, each disturbance category was represented by five 1-m^2 plots giving a total of 30 plots per topographic position. One of the five plots was selected randomly to measure soil physical and hydrological properties. For soil texture, organic carbon and organic matter determination, two samples were taken from each plot and measurements were made on bulked samples. Four measurements of bulk density, total porosity, aeration porosity and water-filled porosity and two measurements of saturated hydraulic conductivity were taken from each of the randomly selected plots and mean values were used for data analysis. The data were analysed using two-way analysis of variance (Payne et al., 1989). The least significant difference (LSD, $P < 0.05$) values were calculated using the appropriate residual from the analysis of variance. For a given level of fire intensity class, the mean values of a specific soil parameter for two soil disturbance categories (undisturbed and topsoil disturbed) were compared. For a given level of soil profile disturbance category, mean values of a specific soil parameter for three levels of fire intensity class were compared (Gomez and Gomez, 1984).

To study the effect of soil compaction on soil physical and hydrological properties, plots were established in the primary (tracks originated from log landing), secondary (tracks branched from primary tracks) and tertiary (tracks branched from secondary tracks) snig tracks and the log landing in one logging coupe (Top Regen). All snig track plots were unburned and classified as topsoil disturbed (litter layer completely and topsoil layer partially removed) and log landing plots were also unburned but classed as subsoil disturbed (topsoil layer completely and subsoil layer partially removed). The log landing and each class of snig track was replicated three times, each replication consisting of a cluster of five 1-m^2 plots. One of the five plots was selected randomly to measure soil properties. For a specific soil parameter, the same number of measurements as the fire intensity class (above) were taken from each plot and mean values were used for data analysis. The data were analysed using a one-way analysis of variance (Snedecor and Cochran, 1978). The least significant difference (LSD, $P < 0.05$) values were calculated using the appropriate residual from the analysis of variance, and the mean values of a specific soil parameter for the log landing, three classes of snig track and undisturbed areas were compared.

2.4.2. Particle size distribution

From each plot two disturbed soil samples were taken at 0–100 mm depth using an auger. The soil samples were bulked, air-dried and passed through a 2-mm sieve. Sieved samples were used to determine clay and silt content using the plummet balance method of McIntyre and Loveday (1974). Total sand content was determined using a decantation technique. Coarse and fine sand particles were separated using a 2-mm sieve. All results are reported on an oven-dried (105°C constant weight) basis. Soil texture was determined using an ISSS textural classification system (Leeper, 1967).

2.4.3. Organic carbon and organic matter

Organic carbon content was determined using the Walkley–Black procedure (Nelson and Sommers, 1989). Organic matter content was estimated as a percentage of loss on ignition of soil which was ignited to 450°C for 24 h. All results are reported on an oven-dried (105°C constant weight) basis.

2.4.4. Bulk density

Intact soil samples were taken at 0–100 mm depth using a brass core (63 mm long, 72 mm inside diameter). The cores were driven into the soil with a falling weight hand corer. Samples were trimmed and any small gaps in the samples were filled with sand, the volume of which was measured. (Samples with large gaps were discarded.) Samples were oven-dried at 105°C for 24 h and ground to determine gravel content. The volume of soil was determined by subtracting the volume of sand and gravel from the volume of a brass core. The mass of oven-dry soil was determined by subtracting the mass of gravel from the total mass of oven-dry soil and gravel. The bulk density of soil was determined by dividing the oven-dried mass of soil with the volume of soil.

2.4.5. Pore-size distribution and available water

The intact core samples, which were used for bulk density determination, were also used for determining total porosity, aeration porosity and water-filled porosity (pore diameter less than 30 μm). Intact core samples were saturated using vacuum suction desiccators and the volume of water content at saturation was determined. Saturated intact core samples were placed on a hanging column tension table and the volumetric water content at −10 kPa water potential was determined. Total porosity, the total volume of pore space as a percentage of total volume of soil and pore space, was obtained as volumetric water content at saturation. Water-filled porosity (pore diameter less than 30 μm) was obtained as volumetric water content at water potential of −10 kPa.

Aeration porosity was obtained as the difference between volumetric water content at saturation and at −10 kPa water potential.

Void ratio, e, was calculated as:

$$e = \left(\frac{\text{TPS}}{1 - \text{TPS}} \right)$$

where TPS is the total porosity.

Disturbed soil samples were used to determine the percentage of pore volume which was occupied by pores less than 0.2 μm in diameter. This was obtained by measuring volumetric water content at a water potential of −1500 kPa using a pressure plate.

Available water was determined as the difference between volumetric water content at −10 kPa and −1500 kPa water potential.

2.4.6. Saturated hydraulic conductivity, K_s

The K_s was measured in the field using a disc permeameter (Perroux and White, 1988) with a suction of 10 mm. Intact soil samples were taken at 0–100 mm depth using a brass core (73 mm long, 100 mm inside diameter). The cores were driven into the soil with a falling weight. One-dimensional vertical flow of water was determined on the intact core samples. The values of K_s were calculated using the following equation (Philip, 1957):

$$I = S\sqrt{t} + K_s t$$

where I is the cumulative flow (mm), S is the sorptivity (mm$\sqrt{\text{day}^{-1}}$), t is the elapsed time (days) and K_s is the saturated hydraulic conductivity (mm day^{-1}).

3. Results

3.1. Distribution of disturbed areas

Logging and slash burning disturbed the soil profile of 82% to 95% of the coupe area (see Table 2). The most common type of disturbance was topsoil disturbance which accounted for 60% to 80% of the coupe area. The majority of the disturbance occurred within the general logging area. The disturbed general logging area varied from 58% to 76% of the coupe area. Snig tracks occupied 10% to 29% and log landings occupied 3% to 4% of the coupe area.

Following logging and slash burning, 42% to 72% of the coupe area remained unburned (see Table 3). Most of the burned areas were found within the general logging areas. More than 71% of the snig tracks escaped fire. The intensity of fire varied considerably between coupes. The low intensity burned areas occupied 12% to 22%, moderate intensity burned areas 11% to 26% and high intensity burned areas 5% to 13% of the coupe area.

Table 2
Distribution of area by operation categories and level of soil profile disturbance following logging and slash burning

Coupes/operation categories	Level of soil profile disturbance (as percent of total coupe area)				Total disturbed
	Undisturbed	Litter disturbed	Topsoil disturbed	Subsoil disturbed	
Top Regen					
General logging	18	14	40	4	58
Snig tracks	0	0	20	1	21
Log landings	0	0	0	3	3
Total	18	14	60	8	82
Research Spur					
General logging	5	5	50	8	63
Snig tracks	0	0	25	4	29
Log landings	0	0	0	3	3
Total	5	5	75	15	95
Simpsons Road					
General logging	12	3	62	1	66
Snig tracks	0	0	16	2	18
Log landings	0	0	2	2	4
Total	12	3	80	5	88
North Loch					
General logging	11	21	52	3	76
Snig tracks	0	0	10	0	10
Log landings	0	0	1	2	3
Total	11	21	63	5	89

Table 3
Distribution of area by operation categories and level of fire intensity following logging and slash burning

Coupes/operation categories	Fire intensity class (as percent of total coupe area)				Total burned
	Unburned	Low intensity	Moderate intensity	High intensity	
Top Regen					
General logging	24	19	21	12	52
Snig tracks	15	3	2	1	6
Log landings	3	0	0	0	0
Total	42	22	23	13	58
Research Spur					
General logging	45	10	10	3	23
Snig tracks	24	2	1	2	5
Log landings	3	0	0	0	0
Total	72	12	11	5	28
Simpsons Road					
General logging	27	20	25	6	51
Snig tracks	15	1	1	1	3
Log landings	3	1	0	0	1
Total	45	22	26	7	55
North Loch					
General logging	41	17	21	8	46
Snig tracks	8	2	0	0	2
Log landings	1	1	0	1	2
Total	50	20	21	9	50

Table 4
Effect of soil profile disturbance and fire intensity on particle size distribution and texture of 0–100 mm soil depth (mean ± SE) in the general logging areas of the two coupes

Sampling site	Particle size distribution					Soil texture description
	Coarse sand (%)	Fine sand (%)	Total sand (%)	Silt (%)	Clay (%)	
Top Regen						
Undisturbed soil profile						
Unburned	11 ± 2	35 ± 2	46 ± 1	22 ± 1	32 ± 1	Clay loam
Moderate intensity	8 ± 2	39 ± 1	47 ± 1	23 ± 1	30 ± 1	Clay loam
High intensity	6 ± 1	37 ± 1	43 ± 1	30 ± 1	27 ± 1	Silty clay loam
Topsoil disturbed profile						
Unburned	6 ± 1	40 ± 2	46 ± 3	38 ± 1	16 ± 2	Silty loam
Moderate intensity	8 ± 1	33 ± 1	41 ± 1	30 ± 1	29 ± 2	Silty clay loam
High intensity	7 ± 1	37 ± 1	44 ± 1	29 ± 2	27 ± 1	Silty clay loam
Simpsons Road						
Undisturbed soil profile						
Unburned	6 ± 1	36 ± 2	42 ± 2	25 ± 2	33 ± 5	Silty clay loam
Moderate intensity	7 ± 2	38 ± 2	45 ± 2	25 ± 2	30 ± 5	Silty clay loam
High intensity	5 ± 1	38 ± 3	43 ± 3	27 ± 2	30 ± 2	Silty clay loam
Topsoil disturbed profile						
Unburned	4 ± 1	41 ± 2	45 ± 3	23 ± 3	32 ± 1	Clay loam
Moderate intensity	6 ± 1	35 ± 3	41 ± 3	26 ± 1	33 ± 3	Silty clay loam
High intensity	4 ± 0	37 ± 2	41 ± 2	26 ± 1	33 ± 1	Silty clay loam

Table 5
Particle size distribution and texture of 0–100 mm soil depth (mean ± SE) in snig tracks and log landings of the Top Regen

Sampling site	Particle size distribution					Soil texture description
	Coarse sand (%)	Fine sand (%)	Total sand (%)	Silt (%)	Clay (%)	
Undisturbed areas	11 ± 2	35 ± 2	46 ± 1	22 ± 1	32 ± 1	Clay loam
Primary snig tracks	5 ± 1	38 ± 1	43 ± 1	37 ± 1	20 ± 1	Silty loam
Secondary snig tracks	4 ± 1	38 ± 2	42 ± 2	36 ± 1	22 ± 2	Silty loam
Tertiary snig tracks	9 ± 2	34 ± 1	43 ± 1	34 ± 3	23 ± 2	Silty loam
Log landings	5 ± 1	45 ± 3	50 ± 3	34 ± 2	16 ± 1	Silty loam

3.2. Effect of soil profile disturbance and fire intensity on soil properties

3.2.1. Particle size distribution

In the undisturbed–unburned areas of Top Regen and Simpsons Road, soil texture was clay loam and silty clay loam, respectively (Table 4). Soil profile disturbance changed particle size distribution in the unburned areas of both logging coupes. In contrast, in the burned areas, no differences in particle size distribution and soil texture were found between undisturbed and topsoil disturbed profile sites.

The effect of slash burning on particle size distribution and soil texture was variable. In the undisturbed soil profile areas of Top Regen, clay and sand content was lower and silt content was higher in the high intensity burned areas compared with unburned areas. In contrast, no significant difference in soil texture was found for moderate intensity burned areas compared to unburned areas. Within topsoil disturbed profile areas, no difference in soil texture was found for three levels of fire intensity. In Simp-

Table 6
Effect of soil profile disturbance and fire intensity on organic carbon and organic matter content of 0–100 mm soil depth (mean ± SE) within general logging areas of the two coupes

Sampling site	Organic carbon (%)	Organic matter (%)
Top Regen		
Undisturbed soil profile		
Unburned	15.4 ± 0.9	32.4 ± 1.8
Moderate intensity	13.3 ± 0.1	32.1 ± 1.2
High intensity	10.7 ± 1	26.1 ± 1.5
Topsoil disturbed profile		
Unburned	8.7 ± 0.9	22.9 ± 2.3
Moderate intensity	11.5 ± 1.0	28.6 ± 2.5
High intensity	10.2 ± 1.9	24.4 ± 4.5
Simpsons Road		
Undisturbed soil profile		
Unburned	5.2 ± 0.6	17.6 ± 0.6
Moderate intensity	6.3 ± 1.7	17.5 ± 4.5
High intensity	5.8 ± 0.5	14.0 ± 1.9
Topsoil disturbed profile		
Unburned	5.3 ± 0.3	13.8 ± 0.7
Moderate intensity	5.4 ± 0.6	14.1 ± 1.3
High intensity	5.0 ± 0.6	13.1 ± 1.3

sons Road, no difference in soil texture was found for three levels of fire intensity except for topsoil disturbed profile conditions.

Soil texture in the snig tracks and log landings of Top Regen were also different compared with undisturbed areas (Table 5).

3.2.2. *Soil organic carbon and organic matter*

Both organic carbon and organic matter content were lower in Simpsons Road compared with those in Top Regen (Table 6). In Top Regen, for undisturbed soil profile conditions, both organic carbon and organic matter content were significantly ($P > 0.05$) lower in the high intensity burned areas but no significant difference was observed for moderate intensity burned areas compared to those in unburned areas. In contrast, for topsoil disturbed profiles, no significant differences in both organic carbon and organic matter were found between three levels of fire intensity. For undisturbed soil profile conditions, organic carbon and organic matter content decreased by about 31% and 19% in high intensity burned areas, respectively, compared with unburned areas.

In the unburned areas, significant differences for both organic carbon and organic matter content were found between undisturbed and topsoil disturbed profiles. In contrast, in the burned areas, no significant differences for both organic carbon and organic matter content were found between undisturbed and topsoil disturbed soil profiles. In the topsoil disturbed–unburned areas, organic carbon and organic matter content were 44% and 29% lower, respectively, than undisturbed–unburned areas.

In Simpsons Road, no significant differences for both organic carbon and organic matter content were found between three levels of fire intensity and two levels of soil profile disturbance.

Table 7
Organic carbon and organic matter content of 0–100 mm soil depth (mean ± SE) in snig tracks and log landings of Top Regen

Sampling site	Organic carbon (%)	Organic matter (%)
Undisturbed area	15.4 ± 0.9	32.4 ± 1.8
Primary snig tracks	9.3 ± 0.1	23.9 ± 0.4
Secondary snig tracks	8.7 ± 0.4	22.4 ± 1.0
Tertiary snig tracks	12.3 ± 1.9	30.5 ± 3.2
Log landings	3.4 ± 1.2	8.1 ± 0.4

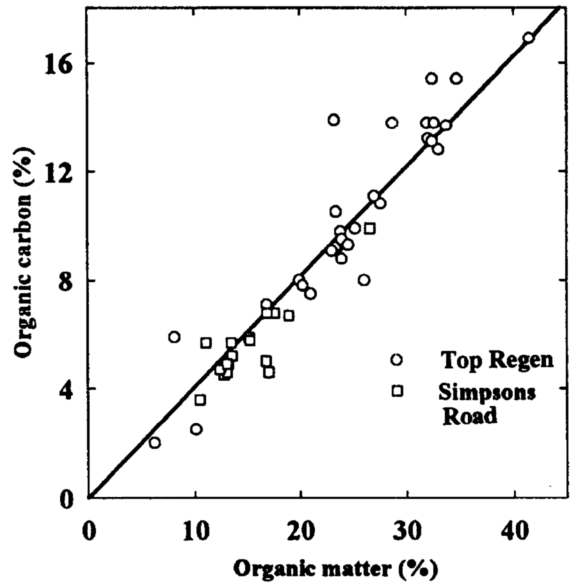

Fig. 1. Relationship between organic carbon and organic matter content in two logging coupes.

Organic carbon and organic matter content in the primary and secondary snig tracks and log landings of Top Regen were significantly lower than those of undisturbed areas (Table 7). In contrast, organic carbon and organic matter content in the tertiary snig tracks were not significantly different from those in undisturbed areas.

Organic carbon content decreased by about 40%, 44% and 78% in the primary and secondary snig tracks and log landings, respectively, compared with undisturbed areas. Organic matter content decreased by about 26%, 31% and 75% in the primary and secondary snig tracks and log landings, respectively, compared with undisturbed areas.

The relationship between organic matter and organic carbon is presented in Fig. 1. The average ratio of organic carbon to organic matter was found to be 0.406.

3.2.3. *Bulk density*

For all disturbance categories, mean bulk density in Top Regen was lower compared with that in

Table 8
Effect of soil profile disturbance and fire intensity on bulk density (Mg m^{-3}) of 0–100 mm soil depth (mean ± SE) within general logging areas of the two coupes

Sampling site	Coupes	
	Top Regen	Simpsons Road
Undisturbed soil profile		
Unburned	0.53 ± 0.07	0.91 ± 0.03
Moderate intensity	0.45 ± 0.07	0.86 ± 0.03
High intensity	0.64 ± 0.08	0.88 ± 0.09
Topsoil disturbed profile		
Unburned	0.73 ± 0.03	1.11 ± 0.03
Moderate intensity	0.60 ± 0.04	0.91 ± 0.08
High intensity	0.80 ± 0.11	0.89 ± 0.11

Simpsons Road (Table 8). In both logging coupes no significant differences in bulk densities were found between three levels of fire intensity.

In the unburned areas of both logging coupes, significant differences in bulk density were found between undisturbed and topsoil disturbed soil profiles. In contrast, in the burned areas, no significant differences in bulk density were found between undisturbed and topsoil disturbed soil profiles.

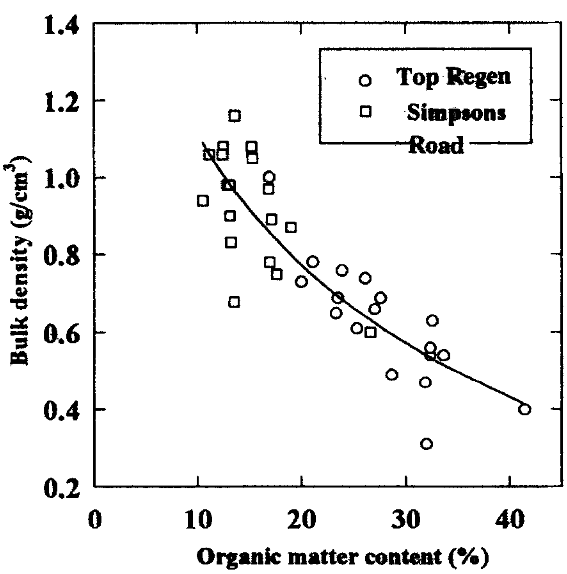

Fig. 2. Relationship between bulk density and organic matter content in two logging coupes.

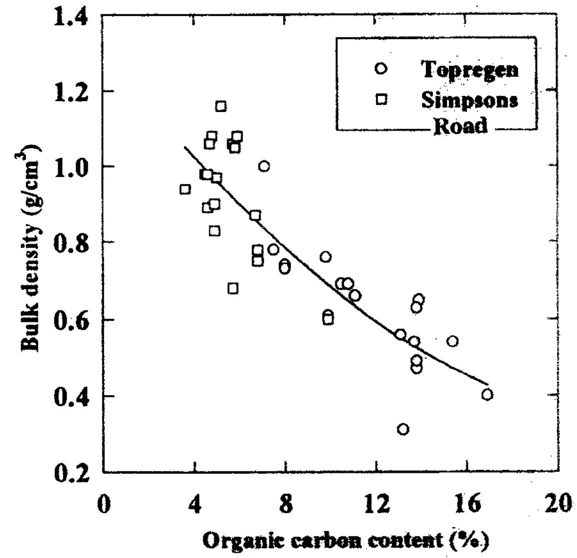

Fig. 3. Relationship between bulk density and organic carbon content in two logging coupes.

Bulk density in the topsoil disturbed–unburned areas in Top Regen and Simpsons Road were 38% and 22% higher, respectively, compared with undisturbed–unburned areas.

The relationship between bulk density and organic matter for uncompacted areas in two logging coupes (excluding data from snig tracks and log landings) is presented in Fig. 2. Bulk density decreased exponentially with increasing organic matter content. The relationship between bulk density and organic matter was found to be:

$$BD = 1.525 - 0.0825(\ln(OM))^2$$

($n = 36$; $R^2 = 0.77$; SE = 0.105; $F = 111$) where BD is the bulk density (Mg m^{-3}) and OM is the organic matter content (%). The regression coefficient 0.0825 was significant at the 1% level.

The relationship between bulk density and organic carbon content for uncompacted areas in two logging coupes (excluding data from snig tracks and log landings) is presented in Fig. 3. Bulk density decreased exponentially with increasing organic carbon content. The relationship between bulk density and organic carbon was found to be:

$$BD = 1.222 - 0.1009(\ln(OC))^2$$

($n = 36$; $R^2 = 0.76$; SE = 0.108; $F = 104$) where BD is the bulk density (Mg m^{-3}) and OC is the organic

Table 9
Effect of soil profile disturbance and fire intensity on pore-size distribution, available water and saturated hydraulic conductivity, K_s, of 0–100 mm soil depth (mean ± SE) within general logging areas of the two coupes

Sampling site	Total porosity (%)	Void ratio (%)	Aeration porosity (> 30 μm) (%)	Water-filled porosity		Available water (%)	K_s (mm day^{-1})
				(< 30 μm) (%)	(< 0.2 μm) (%)		
Top Regen							
Undisturbed soil profile							
Unburned	70.6 ± 0.9	2.4 ± 0.1	23.1 ± 1.0	47.5 ± 1.0	18.8 ± 1.6	28.7 ± 1.8	758
Moderate intensity	75.3 ± 2.0	3.1 ± 0.3	25.7 ± 0.2	49.7 ± 2.2	16.4 ± 1.6	33.3 ± 2.7	818
High intensity	72.0 ± 3.0	2.7 ± 0.4	21.3 ± 1.8	50.7 ± 3.3	14.7 ± 1.9	36.0 ± 2.8	843
Topsoil disturbed profile							
Unburned	73.7 ± 3.0	2.8 ± 0.2	17.6 ± 1.6	56.1 ± 3.1	22.1 ± 1.6	34.0 ± 3.4	474
Moderate intensity	69.0 ± 1.7	2.2 ± 0.1	20.4 ± 1.5	48.6 ± 2.3	16.6 ± 2.2	32.0 ± 3.2	705
High intensity	68.1 ± 3.3	2.2 ± 0.2	8.2 ± 0.9	59.9 ± 2.8	19.7 ± 1.7	40.2 ± 3.3	531
Simpsons Road							
Undisturbed soil profile							
Unburned	62.0 ± 1.9	1.6 ± 0.1	13.1 ± 1.2	48.9 ± 3.0	19.4 ± 0.6	29.5 ± 3.1	461
Moderate intensity	61.5 ± 4.1	1.7 ± 0.3	16.0 ± 3.2	45.2 ± 0.9	18.3 ± 1.7	26.9 ± 1.9	450
High intensity	58.1 ± 7.5	1.5 ± 0.4	19.7 ± 3.6	38.4 ± 4.2	15.7 ± 2.2	22.7 ± 4.7	598
Topsoil disturbed profile							
Unburned	57.8 ± 1.2	1.4 ± 0.1	5.0 ± 1.3	52.8 ± 0.2	20.9 ± 0.5	31.9 ± 0.5	249
Moderate intensity	66.6 ± 0.8	2.0 ± 0.1	12.5 ± 1.1	54.1 ± 1.9	21.1 ± 0.7	33.0 ± 2.0	445
High intensity	64.0 ± 3.6	1.8 ± 0.3	14.2 ± 4.5	49.9 ± 1.8	18.0 ± 1.9	31.9 ± 2.6	704

carbon content (%). The regression coefficient 0.1009 was significant at the 1% level.

3.2.4. Pore-size distribution and available water

In both logging coupes, no significant differences in total porosity were found between two levels of soil profile disturbance and three levels of fire intensity (Table 9).

Aeration porosity in the topsoil disturbed areas was significantly lower than that in the undisturbed areas (Table 9). In contrast, no significant difference in aeration porosity was found between three levels of fire intensity except for topsoil disturbed–high intensity burned areas.

In both logging coupes for a given level of fire intensity class, no significant differences in water-filled porosity were found between two levels of soil profile disturbance except for moderate intensity burned areas in Simpsons Road (Table 9). No significant differences in water-filled porosity were found between three levels of fire intensity.

No significant differences in available water were

Table 10
Effect of soil compaction on bulk density, pore-size distribution, available water and saturated hydraulic conductivity, K_s, of 0–100 mm soil depth (mean ± SE) in snig tracks and log landing of Top Regen

Sampling site	Bulk density (Mg m^{-3})	Total porosity (%)	Void ratio (%)	Aeration porosity (> 30 μm) (%)	Water-filled porosity		Available water (%)	K_s (mm day^{-1})
					(< 30 μm) (%)	(< 0.2 μm) (%)		
Undisturbed area	0.53 ± 0.07	70.6 ± 0.9	2.4 ± 0.1	23.1 ± 1.0	47.5 ± 1.0	18.8 ± 1.6	28.7 ± 1.9	758
Primary snig tracks	0.81 ± 0.02	72.4 ± 2.9	2.7 ± 0.4	14.5 ± 2.4	57.9 ± 1.0	22.2 ± 1.4	35.7 ± 1.7	286
Secondary snig tracks	0.77 ± 0.02	68.4 ± 1.3	2.2 ± 0.1	12.1 ± 0.9	56.3 ± 1.1	20.9 ± 1.6	35.4 ± 1.9	390
Tertiary snig tracks	0.64 ± 0.08	71.8 ± 0.8	2.6 ± 0.1	16.3 ± 2.8	55.5 ± 2.2	18.3 ± 1.6	37.2 ± 2.7	678
Log landings	1.38 ± 0.16	54.7 ± 4.8	1.3 ± 0.2	10.3 ± 2.8	44.4 ± 4.8	18.0 ± 5	26.4 ± 6.6	68

found between two levels of soil profile disturbance and three levels of fire intensity.

3.2.5. Saturated hydraulic conductivity, K_s

In both logging coupes, no significant differences in K_s were found between three levels of fire intensity (Table 9). In the unburned areas, significant differences in K_s were found between undisturbed and topsoil disturbed profile areas. In contrast, in the burned areas no significant differences in K_s were found between undisturbed and topsoil disturbed profile areas.

3.3. Effect of compaction on soil properties

3.3.1. Bulk density

Bulk densities in the secondary and tertiary snig tracks of Top Regen were not significantly different from that of undisturbed areas. In contrast, bulk densities in the primary snig tracks and the log landing areas were significantly greater than that of undisturbed areas (Table 10). Bulk densities in the primary snig tracks and the log landing areas increased by about 53% and 160%, respectively, compared with undisturbed areas.

3.3.2. Pore-size distribution and available water

Total porosity in all three types of snig track was not significantly different from that of undisturbed soil profile areas (Table 10). In contrast, total porosity was significantly lower in log landing compared with undisturbed areas.

Aeration porosity was significantly lower in all three types of snig track and the landing area compared with undisturbed areas (Table 10).

Water-filled porosity ($< 30 \mu m$ in diameter) in the snig tracks was significantly higher compared with undisturbed areas (Table 10). In contrast, water-filled porosity in the log landing area was significantly lower compared with undisturbed areas.

Available water in the snig tracks was higher compared with undisturbed areas (Table 10). In contrast, it was lower in the log landing compared with undisturbed areas.

3.3.3. Saturated hydraulic conductivity, K_s

Soil compaction significantly decreased K_s in the primary snig tracks and the log landing area compared with undisturbed areas (Table 10). In contrast, in the secondary and tertiary snig tracks K_s values were not significantly different from those of undisturbed areas. In the primary snig tracks and log landings K_s decreased by about 62% and 92%, respectively, compared with undisturbed areas.

4. Discussion

4.1. Distribution of disturbed areas

The exposure of mineral soil has been used by many authors as an index of soil erosion potential (e.g. Bockheim et al., 1975). In this study, the proportion of the coupe area where mineral soil was exposed was calculated by adding the topsoil and subsoil disturbed areas shown in Table 2. This shows that logging of Mountain ash in the Victorian Central Highlands forests using ground-based machinery exposed mineral soil on 68% to 90% of the coupe area, averaging about 78%. This falls within the range for logging using ground-based machinery reported elsewhere by Klock (1975), 74%, and Bockheim et al. (1975), 69%.

On average, 18% of the coupe area was disturbed by snig tracks. This is comparable to that found by Rab et al. (1994), 22%, in this forest; and Raison et al. (1991), 24%, lowland mixed species forest of East Gippsland, southeastern Australia. This is lower than that reported by Krag et al. (1986) who found that 27% of the coupe is disturbed by snig tracks (skid roads) in southeast British Columbia. These differences can be attributed to design of the snig track layout, type of snigging machinery and the slope of the terrain.

One of the objectives of the slash burning was to produce a receptive seed-bed. About 42% to 72% of the coupe area remained unburned following slash burning. Some areas were not burned because logging has removed all fuel including surface litter particularly in the snig tracks and log landings. Others may have too small an amount of litter to carry fire. Local weather conditions may also stop fire spread.

About 48% of the coupe area was burned. This is lower than that reported by King (1993), 67%, for the same forest type. This difference may be associated with differences in amount and type of fuel available and local weather conditions at the time of slash burning.

4.2. *Effect of soil profile disturbance and fire intensity on soil properties*

4.2.1. *Particle size distribution*

Slash burning had no effect on particle size distribution in Simpsons Road. In Top Regen, for the undisturbed soil profile conditions, high intensity slash burning reduced the amount of clay content and increased silt content. This agrees with Dyrness and Youngberg (1957) who found a reduction in clay content due to high intensity slash burning of Douglas-fir in the Pacific Northwest forest, while a decrease in silt and clay content and an increase in sand content was found by Giovannini et al. (1988) following laboratory heating of soil above 220°C. These differences may be associated with differences in soil texture, organic matter content, moisture content and duration and intensity of fire between these studies.

The soil profile disturbance changed particle size distribution in the snig tracks and the log landing. The positive correlation between site index and topsoil thickness has been found for a number of tree species (Colie and Schumacher, 1953; Cockroft and Hughan, 1964). The changes in particle size distribution found here reflect a movement/loss of topsoil that may reduce site quality.

4.2.2. *Organic carbon and organic matter*

Soil profile disturbance due to logging reduced organic matter in the topsoil disturbed general logging area, primary and secondary snig tracks and the log landing. This reduction in organic matter can be attributed to removal of mineral soil from snig tracks, the log landing and disturbed general logging areas. Changes in forest floor organic matter following clearfelling logging was also reported for other forest and soil types (Sands et al., 1979; Covington, 1981; Ole-Meiludie and Njau, 1989; Ryan et al., 1992; Rab, 1994).

Organic carbon decreased by about 44%, 40% and 78%, respectively, in the topsoil disturbed general logging area, primary snig tracks and log landings, respectively. These values are greater than those found for the topsoil disturbed general logging area (29–36%), lower than primary snig tracks (53%) and greater than log landings (42%), respectively, in this forest (Rab, 1994).

These values are greater than those of Anderson et al. (1992) who found that organic carbon decreased by 7%, 33% and 39%, respectively, in the general logging area, primary snig tracks and log landings in the dry sclerophyll forest, eastern Victoria, southeastern Australia. These differences may be associated with differences in level of mixing and removal of litter and mineral topsoil in the snig tracks, log landings and general logging areas.

The slash burning had no significant effect on organic matter and organic carbon content in both logging coupes except in the high intensity burned areas of Top Regen. Simpsons Road had a lower amount of organic matter content than Top Regen. The low amount of organic matter in Simpsons Road may have influenced the degree of burning and as a consequence the reduction in organic matter.

High intensity slash burning in Top Regen significantly reduced organic matter and organic carbon. The temperature resulting during moderate intensity burning is not sufficiently high or prolonged to oxidise organic matter. Reduction in organic matter content due to high intensity slash burning was also reported for other forest and soil types (Dyrness and Youngberg, 1957; Alban, 1977; Raison, 1979, Raison, 1980; Clinnick and Willatt, 1981). Other researchers (Ahlgren, 1963; Ralston and Hatchell, 1971; Knighton, 1977) found no detectable change in organic matter due to slash burning.

Organic matter was decreased by about 19% following high intensity burning. This is lower than that found by Austin and Baisinger (1955), 75.5%, and Dyrness and Youngberg (1957), 61%. The differences in the level of decrease in organic matter between the above studies may be associated with differences in intensity and duration of burning and amount of organic matter present at the time of slash burning.

Since organic matter is important in promoting favourable soil aggregation, its loss is of special importance from a soil erodibility viewpoint (Dyrness and Youngberg, 1957; Giovannini et al., 1988). The removal of organic matter not only results in the breakdown of aggregates but it also precludes the further formation of aggregates by means of organic matter cementation. The loss of this cementing agent is especially serious in view of the fact that organic matter is conducive to the formation of relatively large stable aggregates of the type which are resistant to erosion (Dyrness and Youngberg, 1957).

Therefore, reduction in organic matter and organic carbon in the primary and secondary snig tracks, the log landing and general logging areas (topsoil disturbed and high intensity burned areas) may decrease the aggregate stability and consequently may increase the potential for soil erosion.

Organic matter also provides a source of nitrogen, phosphorus and sulphur (Koorevaar et al., 1983). Therefore, the reduction in organic matter and organic carbon due to soil profile disturbance and high intensity slash burning may affect soil fertility in this site.

4.2.3. Bulk density

The soil profile disturbance due to logging increased bulk density in the topsoil disturbed general logging areas. Similar results were also reported by others (Anderson et al., 1992; Rab, 1994). The increase in bulk density due to topsoil disturbance was about 38% and 22% in Top Regen and Simpsons Road, respectively. This difference in change in bulk density may be associated with differences in soil texture, organic matter content and degree of soil profile disturbance between these coupes.

It appears that high intensity slash burning increased bulk density in Top Regen but not in Simpsons Road. However, the increase was not statistically significant. A small increase in bulk density due to burning was also found by Boyer and Miller (1994) for a coastal plain longleaf pine site, southwest Alabama.

4.2.4. Pore-size distribution and available water

Aeration porosity, water-filled porosity and available water was not affected by slash burning in this site. These findings do not agree with Austin and Baisinger (1955) and Boyer and Miller (1994) who found a reduction in water holding capacity due to slash burning. For a prescribed fire of moderate intensity, Tarrant (1956) found that burning increased the volume of macropores and decreased the volume of micropores, yet overall did not affect total porosity.

4.2.5. Saturated hydraulic conductivity, K_s

The slash burning did not affected K_s in this site. This agrees with Craig (1968) who found that high intensity slash fires did not adversely affect water-transmission properties of well-structured clay loam. The finding of this study does not agree with Beaton (1959) who found a decrease in infiltration rate due to burning.

4.3. Effect of compaction on soil properties

4.3.1. Bulk density

Logging significantly increased bulk density in the primary snig tracks and log landings in this site. Similar results were found for other forest soils (Gent et al., 1984; Incerti et al., 1987; Ole-Meiludie and Njau, 1989; Malmer and Grip, 1990; Aust et al., 1993; Rab, 1994; Aust et al., 1995). In the present study, increase in bulk density in the primary snig tracks was associated with increase in compaction while increase in bulk density in the log landing was associated with soil compaction as well as exposure of dense subsoil.

Bulk density in the primary snig tracks and log landings increased by about 53% and 160%, respectively, compared with undisturbed areas. These values are greater than those found by Incerti et al. (1987) who reported that clearfelling of *E. regnans* forest using a crawler tractor in the Otway Ranges of southwestern Victoria, southeastern Australia, increased bulk density of the top 0–6 cm of soil by 27.1% and 38.5%, respectively, in the primary snig tracks and log landings. The increase in bulk density values found in this study are lower than those found by Anderson et al. (1992) who reported that clearfelling harvesting of sawlogs in eastern Victoria, southeastern Australia, increased bulk density of 0–100 mm soil depth by 54% and 62% in the primary snig tracks and log landings, respectively. The differences in the level of increase in bulk density between the above studies may be associated with differences in type of soil, amount of timber removed, number of machinery passes, type of machinery and soil moisture content at the time of logging.

The reduction in tree growth in compacted snig tracks has been reported for many forest species (Hatchell et al., 1970; Froehlich, 1979; Jakobsen, 1983; Froehlich et al., 1986; Anderson et al., 1992). Jakobsen (1983) found a significantly lower concentration of roots of naturally regenerated *E. delegatensis* below snig tracks compared with adjacent undisturbed soil. Anderson et al. (1992) found lower root concentrations under naturally regenerated sclerophyll forest in the snig tracks and log landings compared with those in the undisturbed areas. They also reported that the eucalyptus height growth was poor and density was less in the primary snig tracks and log landings compared with undisturbed areas. Therefore, the resulting increase in bulk density in the primary snig tracks and log landings in this site may affect seedling establishment and growth and consequently site productivity (Perry, 1964; Wert and Thomas, 1981; Lockaby and Vidrine, 1984; King et al., 1993a, King et al., 1993b).

Various researchers determined the critical bulk density at which seedling growth will be limited (Greacen and Sands, 1980; Mitchell et al., 1982; Rab, 1992). However, the values of critical bulk density are dependent on soil texture and plant species (Daddow and Warrington, 1984). Duffy and McClurkins (1974) reported that loblolly pine (*Pinus taeda L.*) growth was affected when bulk density exceeds 1.45 Mg m^{-3}. Williamson (1990), using a glasshouse experiment, showed that eucalyptus seedling weight decreased by 18% when bulk density increased from 0.7 to 0.9 Mg m^{-3}. Froehlich (1979) reported a reduction in *Pinus* seedling growth due to an increase in bulk density of 10% from 0.84 Mg m^{-3}. Foil and Ralston (1967) reported a 50% reduction in shoot length for 1-year-old loblolly pine when bulk density exceeds 1.3 Mg m^{-3}. In an earlier study in this forest, the relationships between bulk density and height and bulk density and diameter of field grown *E. regnans* were developed for clay loam soil. It was reported that 50% reductions in height and diameter growth will occur at bulk density values of 0.91 and 0.96 Mg m^{-3}, respectively (Rab, 1994). In the present study for silty loam soil, the values of bulk density in the primary snig tracks and log landings were found to be 0.81 and 1.38 Mg m^{-3}, respectively. The reduction in *E. regnans* seedlings height and diameter growth in the primary snig tracks and log landings in this site was found by King et al. (1993a) and King et al. (1993b). These suggest that for silty loam soil, bulk density values of less than 0.81 Mg m^{-3} need to be maintained if significant growth reduction of *E. regnans* seedlings following logging is to be minimised. For a silty clay loam soil, in the topsoil disturbed–unburned areas of Simpsons Road, bulk density was found to be 1.11 Mg m^{-3}. Further investigation is required to determine the critical values of bulk density for this soil.

It may take 5–100 years for soils to recover from compaction depending on the degree of compaction, depth of compaction, soil type, vegetation and climate (Froehlich, 1979; Greacen and Sands, 1980; Froehlich et al., 1985; Rab, 1992). The results presented by Anderson et al. (1992) for dry sclerophyll forest and Jakobsen (1983) for *E. regnans* forest showed that bulk density was significantly greater in the snig tracks compared with undisturbed areas even 25 to 32 years after logging. The effect of compaction on bulk density in the primary snig tracks and log landings could last one-third of an 80-year harvesting cycle in this forest.

4.3.2. Pore-size distribution and available water

In all three types of snig track, soil compaction due to logging decreased aeration porosity and increased water-filled porosity (< 30 μm in diameter) which resulted in no net change in total porosity. In contrast in the log landing, both aeration porosity and water-filled porosity (< 30 μm in diameter) decreased which resulted in a net decrease in total porosity.

Reduction in aeration porosity due to compaction has been found for other forest soils (Gent et al., 1984; Incerti et al., 1987; Aust et al., 1993, Aust et al., 1995). Soil compaction may reduce aeration porosity to the extent that root growth is limited by oxygen availability (Greacen and Sands, 1980; Rab, 1992). Aeration porosity below 10% is generally considered too restrictive for root proliferation (Greenwood, 1975; Koorevaar et al., 1983). In the present study, values of aeration porosity were above the critical level (10%) and therefore may not restrict root growth of *E. regnans*.

In the snig tracks, water-filled porosity (> 30μm) was increased due to soil compaction and, as a consequence, available water was increased, while in log landings water-filled porosity (> 30μm) decreased due to soil compaction and exposure of poor structure subsoil which consequently decreased available water.

4.3.3. Saturated hydraulic conductivity, K_s

Soil compaction due to logging usually reduces K_s (Greacen and Sands, 1980; Gent et al., 1984; Incerti et al., 1987; Malmer and Grip, 1990; Aust et al., 1993; Rab, 1994; Aust et al., 1995). The results from the present study show that logging significantly reduced K_s in the primary snig tracks and log landings. K_s determines the rate at which water can move into, or through, the soil system. On steep sites, a decrease in K_s may increase overland flow, after heavy rain, thus increasing the potential for soil erosion.

The effect of K_s on plant growth is not clear because little work has been done to determine a critical value of K_s for adequate or acceptable plant growth (Gent et al., 1984). However, K_s is closely related to aeration porosity and much work has been done to determine values of aeration porosity that are critical to plant growth (Greenwood, 1975; Koorevaar et al., 1983).

5. Conclusions

This study has shown that the logging and slash burning in the Victorian Central Highlands forest of southeastern Australia has a measurable impact on the physical and hydrological properties of the top 100 mm of soil. This may have consequences for next rotation tree regeneration, establishment and growth and the hydrological effects on stream flow.

A significant increase in bulk density and decrease in organic matter content, aeration porosity and saturated hydraulic conductivity were found in the primary snig tracks, landings and disturbed general logging area (topsoil disturbed). Slash burning significantly reduced organic matter in the general logging area (undisturbed–high intensity burned area). To minimise the impact of compaction, forest managers should aim to minimise the area of primary snig tracks and landings, degree of compaction on snig tracks and landings and they should also rehabilitate primary snig tracks and landings. To minimise the adverse effects of slash burning, forest managers should aim to use moderate intensity burning for preparing seed-beds.

The results of this study and a similar study (Rab, 1994) carried out in the Central Highlands provided some quantitative information on the impact of clearfelling logging and mechanical and slash burning seed-bed preparation on the physical and hydrological properties of a forest soil. For this information to be of greater value in forestry operations, studies of this nature need to be performed over a wide range of soil and forest types. In addition, long-term impact of the changes in soil properties on tree growth need to be monitored.

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References

Ahlgren, C.E., 1963. Some basic ecological factors in prescribed burning in northern Minnesota. In: Proceedings 2nd Annual Tall Timbers Fire Ecology Conf., Tall Timbers Research Sta., Tallahassee, FL. pp. 143–161.

Alban, D.H., 1977. Influence on soil properties of prescribed burning under mature red pine. Res. Pap., NC-139, North Centre Forest Experiment Station, USDA Forest Service, St. Paul, MN.

Anderson, H., Boddington, D. and Van Rees, H., 1992. The long-term effects of sawlog-only harvesting on some soil physical and chemical properties in East Gippsland. Department of Conservation and Environment, Victoria, Australia (unpubl.) 29 pp.

Aust, W.M., Reisinger, T.W., Burger, J.A. and Stokes, B.J., 1993. Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders. SJAF, 17: 22–25.

Aust, W.M., Tippett, M.D., Burger, J.A. and McKee, W.H., Jr., 1995. Compaction and rutting during harvesting affect better drained soils more than poorly drained soils on wet pine flats. SJAF, 19: 72–77.

Austin, R.C. and Baisinger, D.H., 1955. Some effects of burning on forest soils of western Oregon and Washington. J. For., 53: 275–280.

Beaton, J.D., 1959. The influence of burning on the soil in the timber range area of Lac le Jeune, British Columbia. I. Physical properties. Can. J. Soil Sci., 39: 1–11.

Bockheim, J.G., Ballard, T.M. and Willington, R.P., 1975. Soil disturbance associated with logging in southwest British Columbia. Can. J. For. Res., 5: 285–290.

Boyer, W.D. and Miller, J.H., 1994. Effects of burning and brush treatments on nutrient and soil physical properties in young longleaf pine stands. For. Ecol. Manage., 70: 311–318.

Cass, A., Savage, M.J. and Wallis, F.M., 1984. The effect of fire on soil and microclimate. In: P.D.V. Booysen and N.M. Tainton (Editors), Ecological Effects of Fire in South African Ecosystems. Springer-Verlag, New York, pp. 312–325.

Clinnick, P.F. and Willatt, S.T., 1981. Soil physical and chemical properties measured in an ashbed following windrow burning. Aust. For., 44: 185–189.

Cockroft, B. and Hughan, D.A., 1964. Peach soil management trial, Tatura, 1948–57. Sta. Rep. No. 2, Department Agriculture, Victoria, Australia, 85 pp.

Colie, T.S. and Schumacher, F.X., 1953. Relation of soil properties to site index of loblolly and shortleaf pines in the Piedmont region of the Carolinas, Georgia, and Alabama. J. For., 51: 739–744.

Covington, W.W., 1981. Changes in forest floor organic matter and nutrient content following clear cutting in Northern Hardwoods. Ecology, 62: 41–48.

Craig, F.G., 1968. Effects of fire and heat on the physical properties of soils. Ph.D. thesis, University of Melbourne, Victoria, Australia.

Daddow, R.L. and Warrington, G.E., 1984. The influence of soil texture on growth-limiting bulk densities. In: New Forests for a Changing World. Proceedings of the 1983 Convention of the Society of American Foresters, Portland, OR. pp. 252–256.

Downer, P.S. and Harter, R.D., 1979. Effects of fire on forest soil and nutrient cycling: An annotated bibliography. Sta. Bulletin 514, New Hampshire Agric. Expt. Sta., University of New Hampshire, Durham, NH, 21 pp.

Duffy, P.D. and McClurkins, D.C., 1974. Difficult eroded planting sites in north Mississippi evaluated by discriminant analysis. Soil Sci. Soc. Am. J., 38: 676–678.

Dyrness, C.T. and Youngberg, C.T., 1957. The effect of logging and slash-burning on soil structure. Soil Sci. Soc. Proc., 21: 444–447.

Flinn, D.W., Farrell, P.W., Stewart, H.T.L., Leitch, C.J. and Hopmans, P., 1984. The effects of fire in eucalyptus forests on soils, nutrient cycling, tree growth and catchment hydrology: A review with particular reference to fuel-reduction burning. Res. Bran. Rep. No. 256, Forests Commission Victoria, 44 pp.

Foil, R.R. and Ralston, C.W., 1967. The establishment and growth of loblolly pine seedlings on compacted soils. Soil Sci. Soc. Am. Proc., 31: 565–568.

Froehlich, H.A., 1979. Soil compaction from logging equipment: Effects on growth of young ponderosa pine. J. Soil Water Conserv., 34: 276–278.

Froehlich, H.A., Miles, D.W.R. and Robbins, R.W., 1985. Soil bulk density recovery on compacted skid trails in Central Idaho. Soil Sci. Soc. Am. J., 49: 1015–1017.

Froehlich, H.A., Miles, D.W.R. and Robbins, R.W., 1986. Growth of young *Pinus ponderosa* and *Pinus contorta* on compacted soil in Central Washington. For. Ecol. Manage., 15: 285–294.

Gent, J.A., Ballard, R., Jr., Hassan, A.E. and Cassel, D.K., 1984. Impact of harvesting and site preparation on physical properties of Piedmont forest soils. Soil Sci. Soc. Am. J., 48: 173–177.

Giovannini, G., Lucchesi, S. and Giachetti, M., 1988. Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Sci., 146: 225–261.

Gomez, K.A. and Gomez, A.A., 1984. Statistical Procedures for Agricultural Research. John Wiley, New York, 679 pp.

Granger, J.E., 1984. Fire in forest. In: P.D.V. Booysen and N.M. Tainton (Editors), Ecological Effects of Fire in South African Ecosystems. Springer-Verlag, New York, pp. 179–197.

Greacen, E.L. and Sands, R., 1980. A review of compaction of forest soils. Aust. J. Soil Res., 18: 163–189.

Greenwood, D.J., 1975. Measurement of soil aeration. In: Soil Physical Conditions and Crop Production. Tech. Bull. 29, Ministry of Agriculture, Fisheries and Food, HMSO, London, pp. 261–272.

Hatchell, G.E., Ralston, C.W. and Foil, R.R., 1970. Soil disturbances in logging: Effects on soil characteristics and growth of loblolly pine in the Atlantic Coastal Plain. J. For., 68: 772–775.

Humphreys, F.R. and Craig, F.G., 1981. Effects of fire on soil chemical, structural and hydrological properties. In: A.M. Gill, R.H. Groves and I.R. Noble (Editors), Fire and the Australian Biota. Australian Academy of Science, Canberra, pp. 178–200.

Humphreys, F.R. and Lambert, M.J., 1965. An examination of forest site which has exhibited the ashbed effect. Aust. J. Soil Res., 3: 81–94.

Incerti, M., Clinnick, P.F. and Willatt, S.T., 1987. Changes in the physical properties of a forest soil following logging. Aust. For. Res., 17: 91–108.

Jakobsen, B.F., 1983. Persistence of compaction effects in a forest Kraznozem. Aust. For. Res., 13: 305–308.

King, M., 1993. The regeneration of *Eucalyptus Regnans* under alternative silvicultural systems: 6. Seedbed conditions. VSP Intern. Rep. No. 25, Department of Conservation and Natural Resources, Victoria, Australia, 24 pp.

King, M., Hookey, P., Baker, T. and Rab, M.A., 1993a. The regeneration of *Eucalyptus Regnans* under alternative silvicultural systems: 4. Effect of seedbed on seedling establishment. VSP Intern. Rep. No. 16, Department of Conservation and Natural Resources, Victoria, Australia, 30 pp.

King, M., Rab, M.A. and Baker, T., 1993b. The regeneration of *Eucalyptus Regnans* under alternative silvicultural systems. 5. Effect of seedbed on seedling growth. VSP Intern. Rep. No. 24, Department of Conservation and Natural Resources, Victoria, Australia, 24 pp.

Klock, G.O., 1975. Impacts of five post-fire salvage logging systems on soils and vegetation. J. Soil Water Conserv., 30: 78–81.

Knighton, M.D., 1977. Hydrologic response and nutrient concentrations following spring burns in an oak–hickory forest. Soil Sci. Soc. Am. J., 41: 627–631.

Koorevaar, P., Menelik, G. and Dirksen, C., 1983. Elements of Soil Physics. Elsevier, Amsterdam, 228 pp.

Krag, R., Higgingbotham, K. and Rothwell, R., 1986. Logging and soil disturbance in southeast British Columbia. Can. For. Res., 16: 1345–1354.

Leeper, G.W., 1967. Introduction to Soil Science. 4th edn., Melbourne University Press, Australia, 250 pp.

Lockaby, B.G. and Vidrine, C.G., 1984. Effect of logging equipment traffic on soil density and growth and survival of young loblolly pine. South J. Appl. For., 8: 109–112.

Mackay, S.M., Long, A.C. and Chambers, R.W., 1985. Erosion pin estimates of soil movement after intensive logging and wildfire. In: R.J. Loughran (Editor), Drainage Basin Erosion and Sedimentation. University of Newcastle, UK.

Malmer, A. and Grip, H., 1990. Soil disturbance and loss of infiltrability caused by mechanized and manual extraction of tropical rainforest in Sabah, Malaysia. For. Ecol. Manage., 38: 1–12.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S., 1990. Australian Soil and Land Survey Field Handbook. 2nd edn., Inkata Press, Melbourne, 160 pp.

McIntyre, D.S. and Loveday, J., 1974. Bulk density. In: J. Loveday (Editor), Methods for Analysis of Irrigated Soils. Tech. Commun. No. 54, Bureau of Soils, South Australia, pp. 38–42.

McNabb, D.H., Gaweda, F. and Froehlich, H.A., 1989. Infiltration, water repellency, and soil moisture content after broadcast burning a forest site in southwest Oregon. J. Soil Water Conserv., 44: 87–90.

Mitchell, M.L., Hassan, A.E., Davey, C.B. and Gregory, J.D., 1982. Loblolly pine growth in compacted greenhouse soils. Trans. ASAE, 25: 304–307, 312.

Nelson, D.W. and Sommers, L.E., 1989. Total carbon, organic carbon, and organic matter. In: A.L. Page, R.H. Miller and D.R. Keeney (Editors), Methods of Soil Analysis: Part-2: Chemical and Microbiological Properties. 2nd edn., American Society of Agronomy, Madison, WI, pp. 539–579.

Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, G.H. and Bettenay, E., 1975. A Description of Australian Soils. CSIRO, Australia, 170 pp.

Ole-Meiludie, R.E.L. and Njau, W.L.M., 1989. Impact of logging equipment on water infiltration capacity at Olmotonyi, Tanzania. For. Ecol. Manage., 26: 207–213.

Payne, R.W., Lane, P.W., Ainsley, A.E., Bicknell, K.E., Digby, P.G.N., Harding, S.A., Leech, P.K., Simpsons, H.R., Todd, A.D., Verrier, P.J. and White, R.P., 1989. Genstat 5 Reference Manual. Clarendon Press, Oxford, 749 pp.

Perroux, K.M. and White, I., 1988. Designs for disc permeameters. Soil Sci. Soc. Am. J., 52: 1205–1215.

Perry, T.O., 1964. Soil compaction and loblolly pine growth. Tree Plant. Notes, US Forest Service, pp. 67–69.

Philip, J.R., 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil Sci., 84: 257–264.

Rab, M.A., 1992. Impact of logging on soil disturbance and compaction with reference to residual log harvesting in East Gippsland, Victoria – a review. VSP Tech. Rep. No. 13, Native Forest Research, Department of Conservation and Environment, Victoria, Australia, 18 pp.

Rab, M.A., 1994. Changes in physical properties of a soil associated with logging of *Eucalyptus regnans* forest in southeastern Australia. For. Ecol. Manage., 70: 215–229.

Rab, M.A., Baker, T.G. and King, M., 1994. Quantification of the degree and extent of soil disturbance on clearfelled coupes of mountain ash in the Victorian Central Highlands. VSP Intern. Rep. No. 27, Department of Conservation and Natural Resources, Victoria, Australia, 22 pp.

Raison, R.J., 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review. Plant Soil, 51: 73–108.

Raison, R.J., 1980. Possible forest site deterioration associated with slash-burning. Search, 11: 68–72.

Raison, R.J., Jacobsen, K.L., Connell, M.J., Khanna, P.K., Bauhus, J., Kalkiner, R.A., Smith, S.J., Piotrowski, P. and Keith, P., 1991. Nutrient cycling and tree nutrition. In: An interim report by the CSIRO Division of Forestry, Collaborative silvicultural systems research in East Gippsland between CSIRO and the Victorian Department of Conservation and Environment. pp. 5–63.

Ralston, G.W. and Hatchell, G.E., 1971. Effects of prescribed burning on physical properties of soil. In: Proceedings Prescribed Burning Symp., USDA Forest Service, Southeast For. Exp. Sta., Asheville, NC. pp. 68–85.

Roberts, W.B., 1965. Soil temperature under a pile of burning logs. Aust For. Res., 1: 21–25.

Ryan, D., Huntington, T.G. and Martin, W., 1992. Redistribution of soil nitrogen, carbon, and organic matter by mechanical disturbance during whole-tree harvesting in northern hardwoods. For. Ecol. Manage., 49: 87–90.

Sands, R., Greacen, E.L. and Gerard, C.J., 1979. Compaction of sandy soils in radiata pine forests. I. A penetrometer study. Aust. J. Soil Res., 17: 101–13.

Snedecor, G.W. and Cochran, W.G., 1978. Statistical Methods. 6th edn., Iowa State University Press, Ames, 593 pp.

Tarrant, R.F., 1956. Effects of slash burning on some soils of the Douglas-fir region. Soil Sci. Soc. Proc., 20: 408–411.

Wells, C.G., Campbell, R.E., Debano, L.F., Lewis, C.E., Fredriksen, R.L., Franklin, E.C., Froehlich, R.C. and Dunn, P.H., 1979. Effects of fire on soil: A state of knowledge review. General Tech. Rep. No. WO-7, US Department of Agriculture and Forest Service, 34 pp.

Wert, S. and Thomas, B.R., 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J., 45: 629–632.

Williamson, J.R., 1990. The effects of mechanised forest harvesting operations on soil properties and site productivity. Res. Rep. No. 5, Tasmanian Forest Research Council, Tasmania, 214 pp.