Amelioration of adverse snig-track soil properties and revegetation as influenced by forest-site characteristics and time since harvesting

J.R. Williamson[1] and W.A. Neilsen[2]*
[1]Environment Protection Authority
43 Williamson St, Bendigo 3550
[2]Forestry Tasmania, GPO Box 207, Hobart 7001

Abstract

Compaction and soil displacement during harvesting were studied on eight harvested areas of various ages covering three forest sites. Under a dry eucalypt forest site, compaction of the most severely disturbed (primary) snig tracks persisted 12 years after harvesting. Increased soil strength also persisted. Regeneration of Eucalyptus sieberi *was as good on primary snig tracks as on undisturbed areas, despite topsoil displacement. Under two wet forest sites with very high rainfall there was generally amelioration of compaction within one year of harvesting, when comparing equivalent soil horizons. However, displacement of surface soil from primary snig tracks on wet forest sites resulted in poor conditions for regeneration, and trees generally failed to survive or at best remained stunted. The exposed subsoil had attained little of the characteristics of undisturbed topsoil, and soil strength generally persisted at elevated levels. Understorey species tolerant of poorly aerated soil were the most prominent early colonisers on primary snig tracks on all sites, while other species dominated undisturbed areas.*

* Corresponding author
e-mail: bill.neilsen@forestrytas.com.au

Introduction

Reduced growth and stocking of trees on snig tracks in harvested areas have been measured in a number of studies (Young *et al.* 1967; Moehring and Rawls 1970; Wert and Thomas 1981). Poor growth on snig tracks has been related to soil compaction which inhibited root growth by mechanical impedance and creation of conditions of poor aeration, waterlogging or water-deficit conditions (Greacen and Sands 1980). Compaction and topsoil displacement or removal created areas of low productivity (Reinhart 1964; Greacen and Sands 1980). Soil organic matter (OM) removal and disturbance of surface soil were associated with poor regeneration on snig tracks (Calais and Kirkpatrick 1983; Wronski 1985).

Productivity of snig tracks is dependent on the severity of soil damage and the rate of amelioration following disturbance. The rate of amelioration of compacted soils is dependent on soil type, wetting / drying cycles, freeze / thaw cycles, biological activity and the initial level of compaction (Webb 1983). The effects of compaction can persist for many years after a harvesting operation. On a krasnozem soil in south-eastern Australia, compaction was still detectable in the surface 30 cm, 32 years after harvesting (Jakobsen 1983). Soil organic matter levels were slow to recover following removal of surface soil from skid-trails, with recovery dependent on revegetation and root growth, climate, OM build-up and the rate of parent material weathering (Froehlich *et al.* 1985).

A study in Tasmania showed a similar extent of compaction due to harvesting traffic to that found by Froehlich *et al.* (1985), averaging 0.17 g/cm^3 increase in soil bulk density (BD) for six field sites investigated (Williamson and Neilsen 2000). The environment under which soils had formed played a major role in determining the BD of the undisturbed soil, with soils on low rainfall sites under dry forest having the lowest OM contents and highest BDs, and soils on very high rainfall sites under wet forest having highest OM contents and lowest BDs. On the wettest soils, machine forces displaced topsoils rather than causing compaction *in situ*. The loss of topsoil and other forms of profile disturbance would be likely to result in reduced tree establishment and growth.

The present study was undertaken to examine revegetation of snig tracks, soil physical properties and amelioration of soil compaction. A range of soils and years since harvesting was covered to measure temporal changes.

Methods

Sites

Three soils were selected, based on a previous study of compaction and soil damage. The soils covered a wide range of forest vegetation in Tasmania (Williamson and Neilsen 2000). One soil, a gravelly clay loam (Hapludult), was formed on Devonian granite under dry forest at Goulds Country (148°07’E, 41°07’S) (< 1100 mm / annum). The other two were under wet forest with very high rainfall (> 1800 mm / annum): one was a silty loam (Hapludalf) formed on Jurassic dolerite at Picton (146°40’E, 43°02’S) and the other was a sandy loam (Endoaquept) formed on sedimentary parent materials derived from Precambrian mudstone at Sumac (145°04’E, 41°17’S). The sites covered a range of age classes, degree of soil damage and soil depth.

Layout and sampling

On each soil type, areas from two age classes which had been harvested under similar conditions were selected. Age classes were selected from available areas and varied between the soil types. Soil damage classes were based on the three-class visual assessment of Wronski (1984) (Williamson and Neilsen 2000). The damage classes of primary (the most severe damage) and secondary were identified where present for each site, and the pre-harvesting 30 cm soil depth was determined for each soil (Table 1). Primary snig tracks on all sites had lost the original 0–10 cm layer through displacement during the harvesting operation. Sumac areas had a gravel hardpan at 20 cm on the harvested area aged seven years and at 30 cm on the harvested area aged one year. On primary snig tracks, the surface 10 cm and 20 cm had been displaced on the harvested areas aged seven years and one year respectively. On the Picton areas, soil was displaced to a depth of 10 cm on the harvested area aged four years and to a depth of 20 cm on the harvested area aged nine years. Secondary snig tracks still retained the 0–10 cm layer intact but were compacted. Tertiary snig tracks could not be distinguished from undisturbed country on any soil type on the basis of surface deformation or vegetation differences.

On each area and damage class, two lengths of snig track were randomly selected and four paired plots were randomly laid out on each length of snig track. The paired plots consisted of one 3 m x 5 m plot located on the snig track and the other on an adjacent area that had been harvested but was undisturbed by machinery. The area was burnt following harvesting to prepare a seed bed for regeneration. On the snig track, subplots of ruts and the middle of the snig track were separately sampled. Thus, three treatments were identified: ruts, middle and undisturbed, the size being 5 m^2, 10 m^2 and 15 m^2 respectively.

Soil cores for bulk density determination

In each plot, three intact soil cores making a core set were taken at 0–10 cm, 10–20 cm and 20–30 cm for BD determination. Where soil displacement had occurred on snig tracks, cores were taken to what was estimated to be the original 30 cm depth, and compared with equivalent horizons in the undisturbed site. Intact soil samples were removed using steel cores that were 10 cm high with an internal diameter of 7.5 cm (417 cm^3) and a wall thickness of 1.6 mm. The cores were driven into the soil using a falling-weight hand corer. BD and gravimetric moisture content were determined from the cores (Blake 1965). Four core sets were taken on ruts and undisturbed plots and two core sets were taken on plots located on the middle of the snig track.

Soil strength and soil organic matter determinations

Soil strength measurements were taken at 10 cm intervals using a falling-weight penetrometer (Williamson and Neilsen 2000). Twenty measurements were taken on each of the ruts and undisturbed plots, and 15 on plots located in the middle of the snig track. Soil moisture levels of the related sites were checked for comparability. A 50 g soil sample from the surface 10 cm was taken adjacent to each BD core set hole for OM estimation by loss on ignition (LOI) (Williamson and Neilsen 2000).

Vegetation assessment

Vegetation was assessed at two levels, eucalypts and other species. Eucalypt height and stocking were measured on each plot. Height was divided into five classes: < 0.5 m, 0.5–2.0 m, 2.0–5.0 m, 5.0–10.0 m and > 10.0 m. Other species were assigned a Braun-Blanquet cover / abundance rating (Mueller-Dombois and Ellenberg 1974). In this study, the Braun-Blanquet rating was modified to a six-class system based on percentage cover / abundance: + = < 1%; 1 = 1–5%; 2 = 5–25%; 3 = 25–50%; 4 = 50–75%; 5 = 75–100%. Only species rooted in the plots were included in the survey and fungi, lichens and bryophytes were excluded. To simplify data presentation for other species, dominant species were selected according to a greater than 50% constancy across the plot replicates (Mueller-Dombois and Ellenberg 1974). The number of understorey species present was also assessed, whether dominant or not.

Analysis

Data were analysed using GENSTAT® for analysis of variance to determine differences within site and age classes. Overall effects were compared using site as a covariate. The mean of the replicates from each plot was used for calculating the statistics.

Results

Bulk density

With all cases of primary damage, the surface 10 cm of soil was not present and comparisons were made with equivalent layers in the undisturbed areas. Under dry forest at Goulds Country, there was a small but significant difference in BD between undisturbed and ruts four and 12 years after disturbance for primary damage, averaging 0.095 g / cm^3 (Figures 1A, 1B). There was no significant residual compaction for secondary damage (Figure 1C). On the wet forest site with very high rainfall at Picton, no differences in BD persisted nine years and four years after harvesting (Figures 1D, 1E). Results varied on the wet forest site with very high rainfall at Sumac, with no difference on one sample area one year after harvesting, while large increases in BD persisted from primary damage seven years

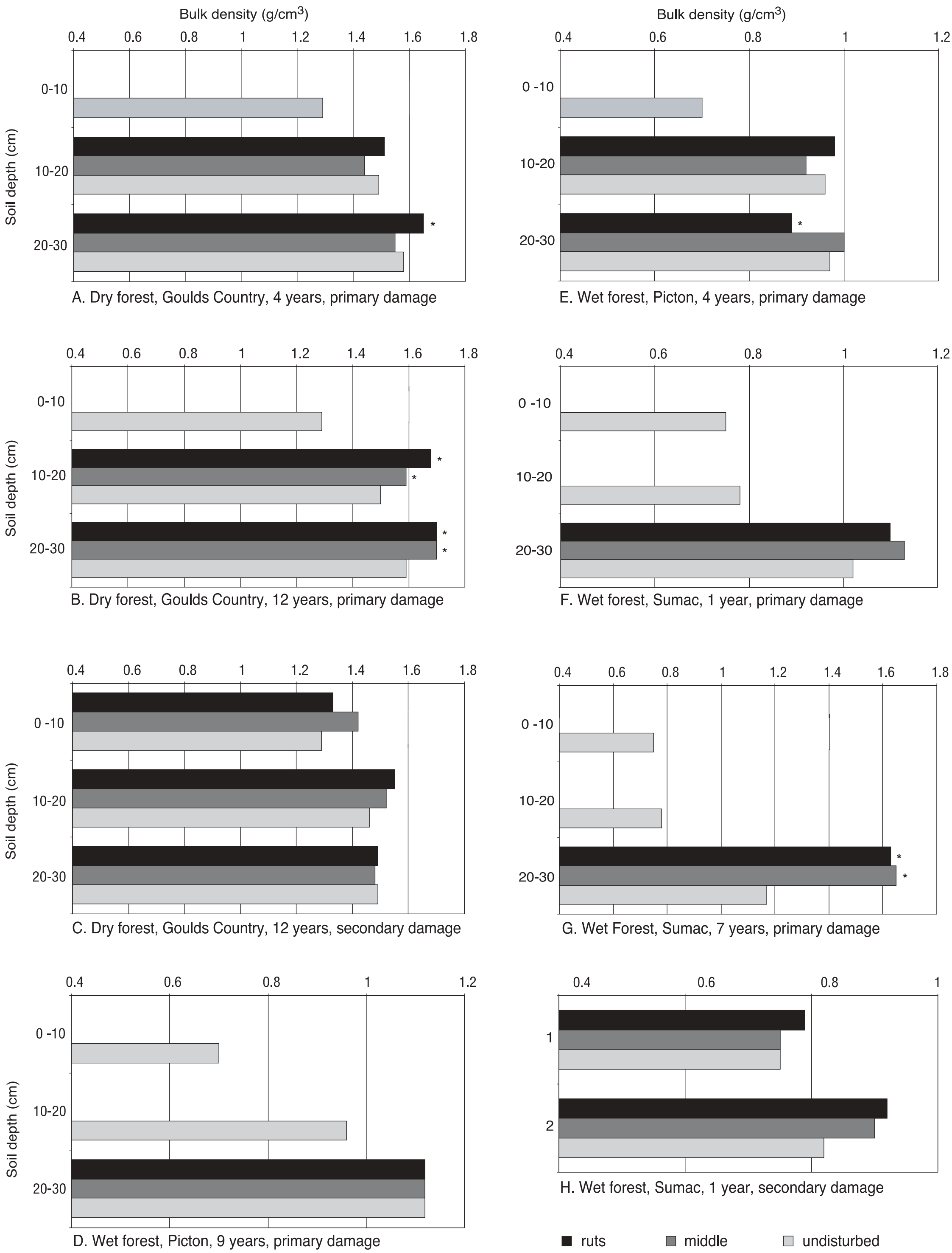

Figure 1. Soil bulk density (g/cm^3) for undisturbed sites, middle of snig tracks, and wheel ruts for: A, B, dry forest sites at Goulds Country with primary damage; C, a dry forest site at Goulds Country with secondary damage; D, E, wet forest sites at Picton with primary damage; F, G, wet forest sites at Sumac with primary damage; H, a wet forest site at Sumac with secondary damage. (Significantly different from the undisturbed horizon, P < 0.05).*

Table 1. Age (years since harvesting), depths studied, snig-track damage class (1 = primary; 2 = secondary) and soil strength for different disturbance classes on six harvested areas.

Site	Age (years)	Depth (cm)	Damage class	Soil strength (kPa)		
				Ruts	Middle	Undisturbed
Goulds Country (Dry forest site)	4	10–20	1	55	52	17
		20–30		73	98	34
	12	10–20	1	76	87	34
		20–30		202	149	67
	12	0–10	2	21	15	11
		10–20		49	38	26
		20–30		69	56	45
Picton (Wet forest site)	4	10–20	1	59	75	49
		20–30		24	28	27
	9	20–30	1	55	49	42
Sumac (Wet forest site)	1	20–30	1	139	126	44
	7	10–20	1	280	377	46
	1	0–10	2	45	33	29

after harvesting on another (Figures 1F, 1G). On this seven-year-old harvested area, there was evidence of severe puddling, damage to structure and mixing of the soil under wet conditions. There was no evidence of increased compaction one year after harvesting for snig tracks suffering secondary damage (Figure 1H). However, the BD of surface soil with primary damage on the snig tracks remained much higher than the surface BD of the topsoil of adjacent undisturbed areas (Figure 1).

Soil strength

Under dry forest at Goulds Country, significantly higher soil strength was recorded on snig tracks compared with undisturbed areas four and 12 years after disturbance. Secondary snig tracks showed a smaller but still significantly higher soil strength than undisturbed sites. Sumac primary snig tracks showed significantly higher soil strengths on disturbed areas compared to undisturbed areas. Soil strength was also higher on secondary snig tracks at Sumac, although soil strength on the snig tracks was not high. The wet forest site with very high rainfall at Picton showed little increase in strength with primary snig track disturbance on both harvested areas at four and nine years (Table 1).

Soil organic matter

No significant differences in OM content were recorded under dry forest at Goulds Country with either secondary or primary snig tracks, despite topsoil displacement from the primary skid trails (Figure 2A). Significantly lower OM levels of up to 90%, with surface soil displacement, were recorded on primary snig tracks on the wet forest site with very high rainfall at Sumac. Secondary snig tracks on the harvested area of age seven years also recorded significantly lower OM contents compared to undisturbed sites, with reductions in the order of 40% (Figure 2B). Undisturbed soil OM levels were high (25%+ LOI). On the wet forest

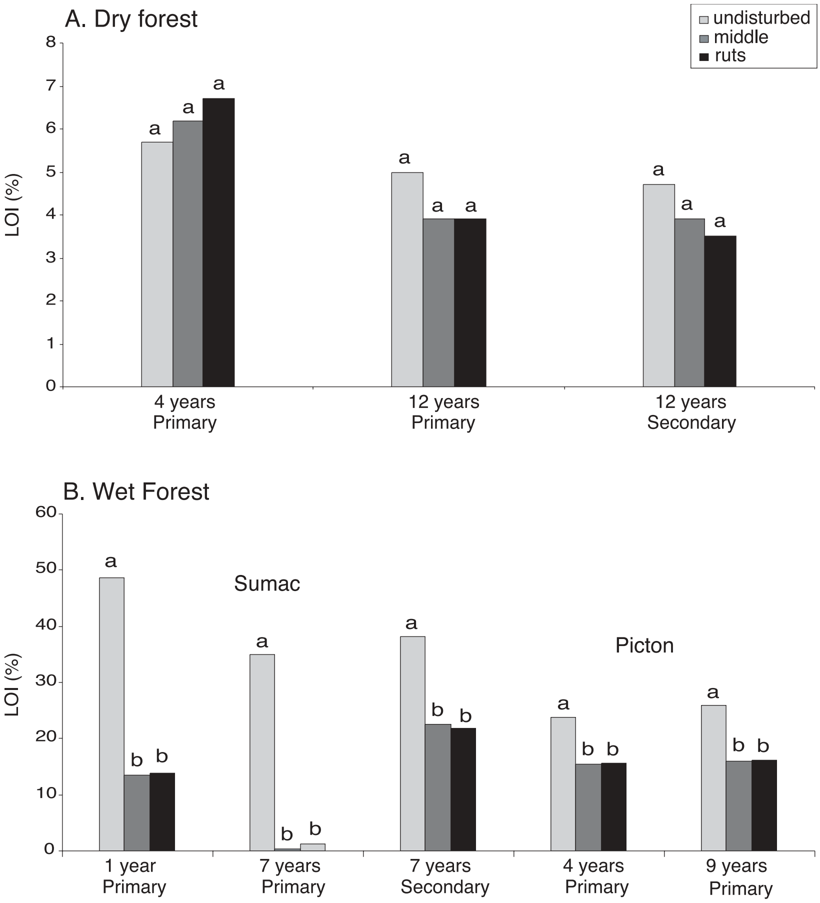

Figure 2. Soil organic matter of the surface 10 cm for all sites, estimated by LOI (loss on ignition), for the undisturbed site, middle of snig track and wheel ruts for: A. dry forest sites at Goulds Country; B. wet forest sites at Sumac and Picton. (Identical letters indicate non-significant subsets within each treatment, P *< 0.05.)*

site with very high rainfall at Picton, primary snig tracks followed the same trend that was apparent at Sumac, although not to the same degree. Both the harvested areas aged four years and nine years showed similar significantly lower OM levels, the ruts and middle having OM levels about 35% lower than undisturbed areas (Figure 2B).

Eucalypt regeneration

Under dry forest, there was little difference between regeneration of *E. sieberi* L.Johnson on undisturbed areas and on primary snig tracks (ruts or the middle) at ages four and 12 years. On secondary snig tracks on the harvested area aged 12 years, significantly more stems were growing on the ruts than on the middle and undisturbed areas (Figure 3A). On primary snig tracks under the wet forest with very high rainfall, there was very little regeneration still present at ages seven and nine years (Figure 3B) and surviving stems were stunted. Stocking of *Eucalyptus obliqua* L'Hérit. on the Sumac primary snig tracks at age one year was significantly higher on ruts than on the middle or undisturbed areas. However, the regeneration on ruts has been observed to fail over a period of time, eventually dying out. Picton areas at both four years and nine years had significantly higher stocking of

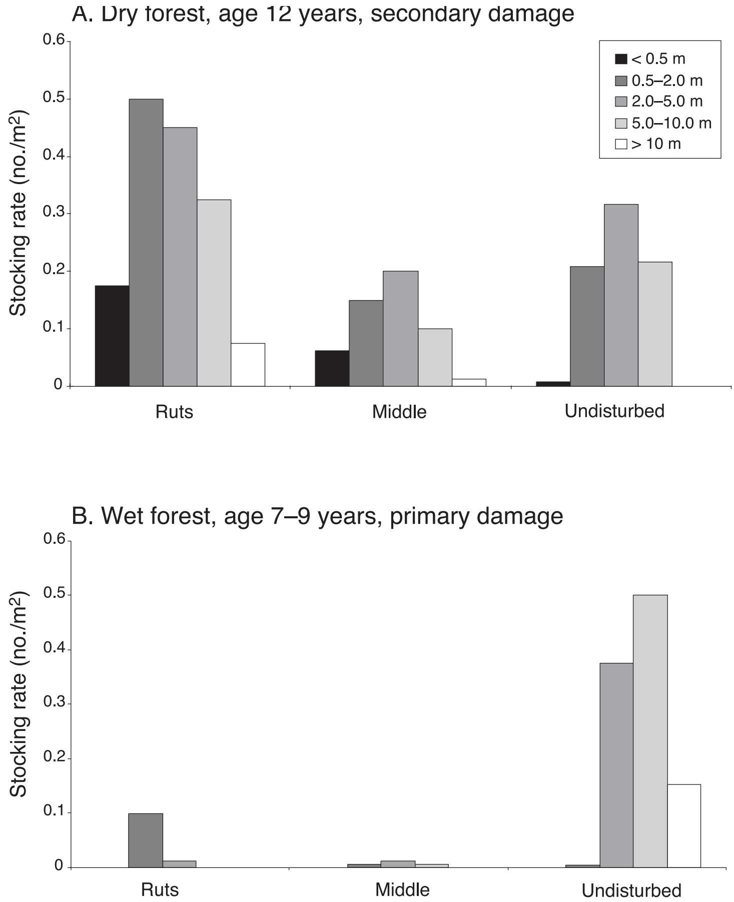

Figure 3. Eucalypt seedlings present on ruts, on the middle of snig tracks and on adjacent undisturbed areas for: A. secondary snig tracks on a dry forest site at Goulds Country; B. mean of primary snig tracks on wet forest sites at Sumac and Picton at ages seven and nine years respectively.

E. obliqua on undisturbed areas. On ruts at age four years, no stems were recorded whereas at age nine years, 0.18 stems / m^2 were recorded. No stems were recorded on the middle of the snig track at either four years or nine years.

Understorey species development

At all sites, species diversity and abundance was highest on the older harvested areas. Abundance was highest on the middle of snig tracks at all sites, except for the primary snig tracks at Picton. However, the number of dominant species occurring on ruts and undisturbed areas was higher than on the middle of snig tracks. Generally, the number of dominant species occurring on ruts and undisturbed sites was similar.

Under dry forest at Goulds Country, dominant species on the ruts of primary snig tracks included species associated with impeded drainage such as *Ehrharta juncea* (R.Br.) Sprengel and *Diplarrena moraea* Labill., while *Acacia* species were only present on undisturbed areas. On areas with secondary disturbance, a wide range of species was dominant on all sites (Table 2).

The wet forest with very high rainfall at Sumac, suffering primary damage, had few

Table 2. Dominant understorey species as determined by greater than 50% constancy (Const.) across replicated plots and modal Braun-Blanquet abundance ratings (BB) for sites under dry forest at Goulds Country.

	Undisturbed		Middle		Ruts	
Species	Const. (%)	BB	Const. (%)	BB	Const. (%)	BB
Goulds Country – 4 years old – Primary						
Acacia terminalis (Salisb.) Macbr.	62.5	3				
Acaena novae-zelandiae Kirk	50	1				
Bedfordia linearis (Labill.) DC.	50	1			50	1
Gahnia grandis (Labill.) S.T.Blake	62.5	1	82.5	1	100	1
Gonocarpus teucrioides DC.	62.5	1				
Pteridium esculentum (G.Forst.) Cockayne	100	4	62.5	1	100	2
Ehrharta juncea (R.Br.) Sprengel					62.5	1
Viola hederacea Labill.	50	1				
Goulds Country – 12 years old – Primary						
Acacia dealbata Link	50	1				
Allocasuarina littoralis (Salisb.) L.Johnson	100	2	100	3	100	2
Austrodanthonia pilosa (R.Br.) H.P.Linder	50	1				
Diplarrena moraea Labill.			50	1	50	1
Epacris impressa Labill.	62.5	1	50	1	50	1
Gahnia radula (R.Br.) Benth.	87.5	3	62.5	1	62.5	1
Gonocarpus tetragynus Labill.	50	1	62.5	1	62.5	1
Helichrysum scorpioides Labill.	50	1			50	1
Hypochoeris radicata L.					50	1
Pteridium esculentum (G.Forst.) Cockayne	50	1				
Viola hederacea Labill.					50	1
Wahlenbergia spp.	50	1				
Goulds Country – 12 years old – Secondary						
Acacia myrtifolia (Sm.) Willd.	50	1	62.5	1	62.5	1
Allocasuarina littoralis (Salisb.) L.Johnson	50	1				
Diplarrena moraea Labill.	100	1	75	1	75	1
Epacris impressa Labill.	100	1	87.5	1	75	1
Gonocarpus tetragynus Labill.	87.5	1	62.5	1	87.5	1
Gonocarpus teucrioides DC.			50	1	50	1
Goodenia lanata R.Br.			75	1	50	1
Helichrysum scorpioides Labill.			50	1	62.5	1
Lepidosperma concavum R.Br.	100	1	87.5	1	100	1
Lomatia tinctoria R.Br.	62.5	1				
Pteridium esculentum (G.Forst.) Cockayne	62.5	1				

dominant species in the middle of the snig track. Species associated with impeded drainage such as *Juncus* spp. were dominant only on ruts. On Sumac secondary snig tracks at age one year, the number of dominant species was smaller than for primary snig tracks of the same age although the total number of species was greater (Table 3). The range of dominant species was similar on disturbed and undisturbed areas. Harvested areas at Picton showed a similar response to those at Sumac in that few dominant species were represented in the middle of snig tracks. Ruts were dominated by species associated with impeded drainage such as *Gahnia grandis* (Labill.) S.T. Blake, although this was also present on the undisturbed site (Table 4).

Table 3. Dominant understorey species as determined by greater than 50% constancy (Const.) across replicated plots and modal Braun-Blanquet abundance ratings (BB) for sites under wet forest with very high rainfall at Sumac.

	Undisturbed		Middle		Ruts	
Species	Const. (%)	BB	Const. (%)	BB	Const. (%)	BB
Sumac – 1 year old – Primary						
Acacia melanoxylon R.Br.	50	1			50	1
Acacia mucronata Willd. ex H.Wendl.					62.5	1
Blechnum wattsii Tindale	87.5	1				
Carex spp.					50	1
Juncus bufonius L.					75	1
Monotoca glauca (Labill.) Druce	75	1	75	1	62.5	1
Senecio biserratus Belcher					62.5	1
Tasmannia lanceolata (Poir.) A.C.Smith	75	1				
Sumac – 7 years old – Primary						
Acacia mucronata Willd. ex H.Wendl.	50	5	No dominant species recorded			
Blechnum wattsii Tindale	50	1				
Histiopteris incisa (Thunb.) J.Smith	62.5	2				
Hydrocotyle hirta R.Br. ex A.Rich.	62.5	1				
Juncus pauciflorus R.Br.					75	1
Juncus procerus E.Meyer					87.5	1
Monotoca glauca (Labill.) Druce	100	1			87.5	1
Polystichum proliferum (R.Br.) C.Presl	100	1			62.5	1
Pteridium esculentum (G.Forst.) Cockayne	87.5	1				
Tasmannia lanceolata (Poir.) A.C.Smith	75	1			75	1
Sumac – 1 year old – Secondary						
Acacia melanoxylon R.Br.	62.5	1				
Acacia mucronata Willd. ex H.Wendl.	50	1			50	1
Hypochoeris glabra L.			50	1	50	2
Monotoca glauca (Labill.) Druce					75	1
Tasmannia lanceolata (Poir.) A.C.Smith	50	1	100	1	100	1

Discussion

Primary snig tracks on wet forest sites

Displacement and removal of surface soil during harvesting is identified as the major form of degradation on primary snig tracks. On wet forest sites in this study, compaction has generally recovered to near pre-harvesting levels fairly quickly when compared with equivalent soil horizons. However, the soil profiles on the snig tracks, with surface soil displacement, bear little resemblance to those of undisturbed areas. Surface soils (A1 horizons) in Tasmanian forests are generally less than 15 cm thick and all or most of the surface soil is displaced from primary snig tracks. The OM levels of the surface of the snig track soils are much lower than those of the undisturbed soils. Soil OM occurring naturally can be some hundreds of years old (Beckmann and Hubble 1974; O'Brien and Stout 1978) and removal or destruction of this material points to a very long time for recovery. This has been noted elsewhere, with large reductions in OM on snig tracks and disturbed areas following the removal of surface layers 20 years earlier (Calais and Kirkpatrick 1983), and reduced OM levels evident decades after harvesting (Hatchell *et al.* 1970; Dickerson 1976; Jakobsen 1983;

Table 4. Dominant understorey species as determined by greater than 50% constancy (Const.) across replicated plots and modal Braun-Blanquet abundance ratings (BB) for sites under wet forest with very high rainfall at Picton.

	Undisturbed		Middle		Ruts	
Species	Const. (%)	BB	Const. (%)	BB	Const. (%)	BB
Picton – 4 years old – Primary						
Acacia melanoxylon R.Br.	50	1				
Chiloglottis spp.			75	1	100	1
Gahnia grandis (Labill.) S.T.Blake	87.5	2			87.5	1
Histiopteris incisa (Thunb.) J.Smith	100	3				
Monotoca glauca (Labill.) Druce	100	2				
Phyllocladus aspleniifolius (Labill.) Hook.	50	1				
Picton - 9 years old – Primary						
Acacia melanoxylon R.Br.	87.5	1	No dominant species recorded			
Blechnum wattsii Tindale	50	1				
Gahnia grandis (Labill.) S.T. Blake	100	4			50	3
Histiopteris incisa (Thunb.) J.Smith	87.5	2				
Monotoca glauca (Labill.) Druce	50	1				
Nematolepis squamea (Labill.) Paul G.Wilson	100	2			75	1
Pteridium esculentum (G.Forst.) Cockayne	62.5	2			50	2

Froehlich *et al.* 1985; Froehlich *et al.* 1986; Corns 1988; Kamaruzaman 1996).

Under wet forest with very high rainfall, displacement of topsoil on snig tracks suffering primary damage resulted in long-term detrimental effects on, and consequences for, revegetation and forest development. Although initial germination of seedlings was good, the fact that seedlings were growing in subsoil on the primary snig tracks ultimately resulted in failure of the regeneration through severe mortality and height stagnation. The death of trees occurring after a number of years following regeneration may be due to a number of reasons, including mechanical impedance to root growth in the exposed subsoil, low nutrient status, and moisture and aeration stresses. Cremer (1969) concluded that although early establishment of *Eucalyptus regnans* was not inhibited by heavy compaction, trees stagnated and eventually died. Significant reductions in stocking rates on primary snig tracks two to five years after regeneration in North America have been reported (Hatchell *et al.* 1970; Lockaby and Vidrine 1984). The failure of regeneration and revegetation generally on primary snig tracks will further slow the recovery of these soils. Redistribution of topsoil by physical movement from surrounding areas, spreading of roots from adjacent regenerated areas and encroachment of vegetation are slow processes.

Native pioneer species were the most common colonisers of all disturbed sites in the areas investigated in this research. Understorey species associated with impeded drainage were dominant on the ruts, probably a result of the persistent increased soil strength and reduced infiltration. This agrees with the findings of Cremer and Mount (1965) who reported that species tolerant of poorly aerated soil such as *Carex* spp., *Juncus* spp. and *Gahnia* spp. were the most prominent early colonisers on snig tracks. On undisturbed, regenerated sites, native pioneer species were vigorous colonisers. In East Gippsland, Loyn *et al.* (1983) reported a similar conclusion. In the areas investigated in the present study, initial colonising species persisted on all sites and are noted to persist for several decades on older harvested areas. Development of successional vegetation communities approaching that of the undisturbed site, or the original forest, is slow.

If total rehabilitation of harvested areas is required on wet forest sites, damage to topsoil must be avoided. Unprotected soils in these environments will only sustain minimal traffic before there is topsoil displacement (Williamson and Neilsen 2000). Protection of primary snig tracks by cording with logs may limit displacement of topsoil but rehabilitation is difficult. Regeneration of wet forest sites in Tasmania requires the use of fire to remove sufficient debris to create adequate areas of seedbed (Gilbert and Cunningham 1972). Ideally, such fires should be hot enough to adequately remove surface debris, and they should be surface fires so as to minimise any effects on the soil. Lifting and burning of logs used for cording can result in very hot localised fires and, with some logs partially buried, may affect topsoil, reducing OM levels. Matting with understorey scrub species substantially reduces the impact of harvesting (King and Haines 1979; Jakobsen and Moore 1981). However, if matting is not removed, it impacts on regeneration and if it is removed by burning, very hot fires may result and these damage the soil by oxidisation of OM. In forest production areas on wet forest sites, the use of permanent, corded, primary snig tracks could be a preferred alternative to attempts at rehabilitation. In this case, the objective would be to minimise the area occupied by such snig tracks.

Because the research study was retrospective, the precise conditions under which harvesting was carried out could only be estimated. Although compaction lessened over time, persisting increased soil strength indicated some soil structure changes in addition to compaction. These could have been caused by greater disturbance in actual operations than that achieved in controlled research (Williamson and Neilsen 2000), greater disruption of soil structure, or further deterioration following harvesting. The persistence of increased soil strength pointed to a long time for recovery. The period required for a soil to recover, following damage, is dependent on the level of initial compaction and the soil type (Froehlich *et al.* 1985). It was likely that the harvested area aged seven years at Sumac was harvested under very wet conditions and persisting degrade was likely to be a result of puddling. Under better control, such damage should be avoidable.

Primary snig tracks on dry forest sites

On a dry forest site following primary damage, compaction in ruts was measured at about half of that attained in a study of compaction (Williamson and Neilsen 2000) four and 12 years after harvesting. Soil strength on these disturbed sites also persisted at much higher levels than on the undisturbed sites. OM levels were not significantly lower in the surface soil, despite topsoil displacement. Topsoil on these sites has generally low nutrient levels, and similar levels persist to moderate depths (Grant *et al.* 1995). Although understorey species associated with impeded drainage still dominated on the ruts, regeneration of eucalypts was similar on disturbed and undisturbed sites. This indicates that the tree seedlings germinating on these sites survived and grew, unlike those on the wet forest sites.

Secondary snig tracks

Following secondary damage on the wet forest sites of Picton and Sumac with very high rainfall, there were few measurable differences seven and nine years after harvesting. Soil strength remained significantly higher on the ruts, but there was no significant increase in BD or decrease in OM levels. Eucalypt regeneration was slightly less prolific on the ruts. Understorey species were similar on disturbed and undisturbed sites. Suitable seed beds for *Eucalyptus regnans* F.Muell. are provided by exposure of the mineral topsoil by mechanical disturbance or fire (Cunningham 1960). Mechanical disturbance is often preferable and compaction does not appear to decrease germination and early survival (Cremer 1969). Following secondary damage on the dry forest site, there were few measurable differences 12 years after harvesting. Soil strength remained significantly higher on the ruts but there was no difference in BD or OM levels. Eucalypt regeneration was more prolific and larger on the ruts, indicating a preference of dry country eucalypts to germinate on disturbed soil. With secondary snig tracks, the retention of topsoil, even with some compaction, means that recovery of the soil to pre-harvesting condition is rapid and vegetation development is not substantially different from that on undisturbed areas. On sites in Germany, with adequate nutrients and moisture, lasting changes to soil structure caused no adverse effects on tree growth (Kremer and Matthies 1997).

Soils under dry forest can sustain more traffic before primary damage occurs (Williamson and Neilsen 2000), and snig tracks suffering primary damage are less frequent than on harvested areas in wet forest. With sufficient planning, primary damage might be avoided on dry forest sites and the A1 soil horizon retained *in situ* by using dispersed snig tracks during harvesting. Longer rotation lengths required to achieve merchantable crops on these drier sites should allow ample time for recovery of any soil damage.

Acknowledgements

Financial support for this project was provided by the National Soil Conservation Program, the Tasmanian Forest Research Council and Forestry Tasmania. We wish to thank Gordon Davis and Ron King for advice and assistance in developing the research. Special thanks go to Tom Lynch who provided assistance in the field.

References

Beckmann, G.G. and Hubble, G.D. (1974). The significance of radiocarbon measurements of humus from krasnozems (Ferrosols) in sub-tropical Australia. *Transactions 10th International Congress of Soil Science* 6: 362–371.

Blake, G.R. (1965). Bulk density. In: *Methods of Soil Analysis* (eds C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger and F.E. Clark), pp. 374–390. American Society of Agronomy, Madison, Wisconsin.

Calais, S.S. and Kirkpatrick, J.B. (1983). Tree species regeneration after logging in temperate rainforest, Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 117: 77–83.

Corns, I.G.W. (1988). Compaction by forestry equipment and effects on coniferous seedling growth on four soils in the Alberta foothills. *Canadian Journal of Forest Research* 18: 75–84.

Cremer, K.W. (1969). Fertilization with blood and bone as an aid to the establishment of *Eucalyptus regnans* by sowing or planting. *Australian Forest Research* 4: 3–13.

Cremer, K.W. and Mount, A.B. (1965). Early stages of plant succession following the complete felling and burning of *Eucalyptus regnans* in the Florentine Valley, Tasmania. *Australian Journal of Botany* 13: 303–322.

Cunningham, T.M. (1960). The natural regeneration of *Eucalyptus regnans*. *Bulletin No. 1*. School of Forestry, University of Melbourne, Australia.

Dickerson, B.P. (1976). Soil compaction after tree length skidding in Northern Mississippi. *Journal of Soil Science* 40: 965–966.

Froehlich, H.A., Miles, D.W.R. and Robbins, R.W. (1985). Soil bulk density recovery on compacted skid trails in Central Idaho. *Soil Science Society of America Journal* 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. *Forest Ecology and Management* 15: 285–294.

Gilbert, J.M. and Cunningham, T.M. (1972). Regeneration of harvested forests. *Appita* 26: 43–46.

Grant, J.C., Laffan, M.D., Hill, R.B. and Neilsen, W.A. (1995). *Forest Soils of Tasmania. A Handbook for Identification and Management.* Forestry Tasmania, Hobart.

Greacen, E.L. and Sands, R. (1980). Compaction of forest soils. A review. *Australian Journal of Soil Research* 18: 163–189.
Hatchell, G.E., Ralson, C.W. and Foil, R.R. (1970). Soil disturbance in logging. *Journal of Forestry* 68: 772–775.
Jakobsen, B.F. (1983). Persistence of compaction effects in a forest Krasnozem. *Australian Forestry Research* 13: 305–308.
Jakobsen, B.F. and Moore, G.A. (1981). Effects of two types of skidders and of a slash cover on soil compaction by logging of Mountain Ash. *Australian Forestry Research* 11: 247–255.
Kamaruzaman, J. (1996). Estimation of rate of recovery of disturbed soils from ground-based logging in Peninsular Malaysia. *Journal of Tropical Forest Science* 9 (1): 88–100.
King, T. and Haines, S. (1979). Soil compaction absent in plantation thinning. USDA Forest Service Research Note, Southern Forest Experiment Station, SO–251.
Kremer, J. and Matthies, D. (1997). Effect of soil compaction by vehicles on the growth of forest vegetation. *AFZ Der Wald, Allgemeine Forst Zeitschrift fur Waldwirtschaft und Umweltvorsorge* 52: 474–477.
Lockaby, B.E. and Vidrine, C.G. (1984). Effect of logging equipment traffic on soil density and growth and survival of young Loblolly Pine. *Southern Journal of Applied Forestry* 8: 109–112.
Loyn, R.H., Fagg, P.C., Piggin, J.E., Morton, A.G. and Tolhurst, K.G. (1983). Changes in composition of understorey vegetation after harvesting eucalypts for sawlogs and pulpwood in East Gippsland. *Australian Journal of Ecology* 8: 43–53.
Moehring, D.M. and Rawls, I.W. (1970). Detrimental effects of wet weather logging. *Journal of Forestry* 68: 166–167.
Mueller-Dombois, D. and Ellenberg, H. (1974). *Aims and Methods of Vegetation Ecology*. John Wiley and Sons, New York.
O'Brien, B.J. and Stout, J.D. (1978). Movement and turnover of soil organic matter as indicated by carbon isotype movements. *Soil Biology and Biochemistry* 10: 309–317.
Reinhart, K. (1964). Effect of a commercial clearcutting in West Virginia on overland flow and storm runoff. *Journal of Forestry* 62: 167–171.
Webb, R.H. (1983). Compaction of desert soils by off-road vehicles. In: *Environmental Effects of Off-Road Vehicles. Impacts and Management in Arid Regions* (eds R.H. Webb and H.G. Wilshire), Chapter 4. Springer Verlag, New York.
Wert, S. and Thomas, B.R. (1981). Effects of skid roads on diameter, height and volume growth in Douglas Fir. *Soil Science Society of America Journal* 45: 629–632.
Williamson, J.R. and Neilsen, W.A. (2000). The influence of soil and forest type on rate and extent of soil compaction and profile disturbance of skid-trails during ground based harvesting. *Canadian Journal of Forest Research* 30: 1196–1205.
Wronski, E.B. (1984). Impacts of tractor thinning operations on soils and tree roots in a Karri forest, Western Australia. *Australian Forestry Research* 14: 319–332.
Wronski, E.B. (1985). Prediction of soil trafficability in a Karri forest, Western Australia. *Australian Forestry Research* 15: 367–380.
Young, J.A., Hedrick, D.W. and Keniston, R.F. (1967). Forest cover and logging: Herbage and browse production in the mixed coniferous forest of Northeastern Oregon. *Journal of Forestry* 65: 807–813.