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Soil protection with logging residues during mechanised harvesting of native forests in Tasmania: a preliminary study

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Summary

In Tasmania, Australia, mechanised forest harvesting operations often use 'cording' to limit soil disturbance. This means logs are laid across the snig tracks, perpendicular to the flow of traffic, providing a rigid barrier between the machinery and the ground surface. At the conclusion of harvesting, the cording material is lifted using an excavator and burnt on site. This latter procedure enhances soil nutrition through the 'ash-bed' effect, whilst increasing the area of seedbed available for forest regeneration.

To date, the efficacy of cording in protecting soil values remains largely untested. The shallow and stony nature of many forest soils, and the presence of logging residues and cording material along snig tracks, make the investigation of soil physical properties difficult. In response, this study was undertaken to assess the effectiveness of cording by using forest regeneration (density of seedlings and seedling height) as an indicator of productivity along former snig tracks protected with cording. Available seedbed (%) and seedling form, including the incidence of browsing and disease, were recorded and key soil chemical properties (0–10 cm soil depth: organic carbon, total nitrogen and total phosphorus), were measured. In the absence of physical soil testing, the theoretical distribution and attenuation of machine loads by the cording are discussed.

Forest regeneration along the former snig tracks was consistently inferior in quantity and quality compared to that of the untrafficked control areas. This was attributed largely to: (a) a reduction in the available seedbed (%) due to incomplete combustion of the cording material and retention of logging residues, both on the ground surface and mixed with the upper soil layers, and (b) poor growing conditions — the combined effects of lowered organic carbon, nitrogen and phosphorus concentrations along the former snig tracks. Operational recommendations based on this study include: (a) avoiding trafficking of bare ground during the construction of cording, (b) beginning with a layer of small-diameter material to help spread machine loads more evenly and (c) where appropriate, leaving permanent snig tracks.

Keywords: logging; traffic; tracks; pavements; bearing characteristics; environmental impact; soil compaction; productivity; amelioration of forest sites; regeneration; growth; density

Introduction

The effects of harvesting traffic on soil physical properties are well documented (see reviews by Greacen and Sands 1980 and Wingate-Hill and Jakobsen 1982) and include increases in soil bulk density (where air only is expelled from the soil during loading) and strength, and also concomitant decreases in total porosity and hydraulic conductivity and increases in matric potential, the latter due to an increase in micro-porosity. Conversely, soils at or beyond field capacity tend to be displaced during wheel rutting, with consequences for erosion and off-site movement of nutrients.

In Tasmania, Australia, the Forest Practices Code (Forest Practices Board 2000) provides guidelines on many aspects of forest harvesting. To combat the negative and persistent effects of ground-based mechanised harvesting on the soil, the Code advocates the use of cording. To build a corded track, logs are laid across snig tracks, perpendicular to the flow of harvesting traffic. Bark is then laid over the top of the logs to provide a more even surface. The movements of all machines involved in felling or extraction of timber are then restricted, wherever possible, to the corded tracks.

Cording provides a physical barrier between machinery and the ground surface (Wilkinson 2001). This effectively reduces the incidence and severity of rutting and soil displacement. In addition, cording maintains vehicle flotation, even under wet conditions, leading to significant improvements in operational efficiency and a reduction of machine down-time during wet weather (Wronski and Humphreys 1994; Wilkinson 2000). It is assumed that cording also reduces the degree of soil compaction by spreading the weight of the machine over an area greater than that of the machine 'footprint' — the tyre or track area in contact with the ground surface. On completion of harvesting, the cording is lifted by an excavator and burnt on-site, along with other harvesting residues. This has the advantage of releasing valuable nutrients, the 'ash-bed' effect (Attiwill and Leeper 1987), whilst increasing the area of seedbed available for forest regeneration.

Despite the broad use of cording, there are few experiential data to describe its effectiveness in mitigating the adverse effects of

trafficking on key soil properties, notably soil density and strength, and site productivity. In Tasmania, Pennington and Laffan (2004) found no significant increases in soil bulk density along snig tracks protected with cording (see Discussion below). However, the authors suggested caution when interpreting these data, as recruitment and growth appeared to be reduced along the tracks where cording remained, compared to undisturbed areas, following observations 3–5 y later (Pennington and Lewis, unpublished data, cited in Pennington and Laffan 2004).

Investigations of soil physical properties are often complicated by the shallow and stony nature of many forest soils, and the associated degree of variability in broader soil properties (Page-Dumroese *et al.* 1999). These problems can be exacerbated by the presence of water-logging, tree stumps, and the mixing of logging residues with soil layers (Greacen and Sands 1980; Pennington and Laffan 2004). In the operational study described below, differences in forest regeneration and soil chemical properties along previously-corded snig tracks and untrafficked control areas were used to examine the effectiveness of cording, and associated lifting/burning operations, in maintaining site productivity along snig tracks. Previous research suggests that the impacts from vehicle trafficking are most severe at the soil surface (Wronski 1984; Williamson 1990a; Rab 1994; Pennington and Laffan 2001; Bauhus *et al.* 2002). As a result, soil chemical analyses were confined to the upper 0–10 cm soil layer.

Methods

Site description

This study took place within the Warra Long Term Ecological Research (LTER) site (Brown *et al.* 2001) located in the Huon district, 90 km south-west of Hobart (Fig. 1). Mean annual precipitation is 1138 mm, occurring predominantly during winter and spring, with a mean annual temperature of 10.7°C fluctuating

seasonally (Ringrose *et al.* 2001). This site includes the Warra Silvicultural Systems Trial (SST), a 200-ha area established in 1997 to investigate alternatives to 'clearfell, burn and sow' silviculture in natural *Eucalyptus obliqua* forest (Hickey *et al.* 2001).

The soil types of the SST have been extensively described (Laffan *et al.* 1996; Hickey *et al.* 1999; Brown *et al.* 2001; Corbett and Balmer 2001; Laffan 2001), and show a strong relationship with the underlying Jurassic dolerite parent material. Typically, the soils are imperfectly drained, with thin, humic, clay-loam topsoils and yellowish-brown, medium clay subsoils (Laffan 2001). Total nitrogen and phosphorus concentrations were characterised as medium in the topsoils and low in the subsoils; organic matter was considered high and low for the topsoils and subsoils respectively (Grant *et al.* 1995).

Site selection

Two recently clearfelled logging coupes (Warra 8B and Warra 8H) were chosen within the SST where (a) prior harvesting operations conformed to the Forest Practices Code and included the use of cording, and (b) regeneration across each coupe was sufficiently advanced to allow comparisons between snig tracks and untrafficked control areas. The main merchantable species at each coupe was *E. obliqua*, with a gradient of wet sclerophyll to rainforest understorey species (Neyland 2001). The soils (upper 300 mm) on average consisted of, at Warra 8B, 47% well and moderately-well drained, 38% imperfectly drained and 15% poorly drained, and at Warra 8H, 68% well and moderately-well drained, 27% imperfectly drained and 5% poorly drained (Pennington and Laffan 2004). Full profile descriptions for an adjacent coupe (Laffan 2001), considered typical of the two coupes used in this study (Laffan *pers. comm.*¹, 2005), are appended.

Each coupe was logged using the clearfell, burn and sow system. At Warra 8B (47°50'70"E, 52°28'58.3"N), harvesting took place between 17 August and December 1998. Logging residues were burnt on 26 March 2000 and the coupe was aerially sown with eucalypt seed on 1 April 2000. At Warra 8H (47°43'22"E, 52°28'44.2"N), harvesting took place between 26 October 2000 and 15 March 2001. Logging residues were burnt on 7 April 2001 and the coupe was aerially sown with eucalypt seed on 16 April 2001. In each case, harvesting was carried out using a steel-tracked excavator with a felling head attached to the boom. At Warra 8B, extraction was completed with a steel-tracked bulldozer, where logs were attached by chain and dragged behind the machine, and at Warra 8H, by a rubber-tyred skidder with wheel chains for traction. Cording was applied as per the Forest Practices Code current at the time of harvesting (Lee Edwards, *pers. comm.*², 2005); major snig tracks were covered with layers of understorey and non-commercial species, and large amounts of bark; minor snig tracks were covered with understorey slash only (Pennington and Laffan 2004).

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Figure 1. Location of the Warra Long Term Ecological Research site

Figure 2. Typical layout of each site and sample plot (not to scale)

Data collection

Within each coupe, three primary snig tracks (major arterial routes to the landing) and three secondary snig tracks (those adjoining primary snig tracks and providing access to the broader site) were identified using aerial photographs (Fig. 2a). Tracks varied in length between about 200 and 400 m. Sample plots of 5 × 20 m were located along the primary snig tracks ($n = 6$ in both coupes) and secondary snig tracks ($n = 6$ at Warra 8B, $n = 5$ at Warra 8H where, in one instance, a suitable sample area could not be found), each at a distance about $\frac{1}{4}$ and $\frac{3}{4}$ the length of the track. These were chosen to maximise coverage of the site whilst allowing

reasonable access for data collection. Untrafficked control sample plots were located at right angles 10 m from the snig track sample plots on the true right (i.e. looking down the slope) ($n = 12$ at each site).

The layout of each sample plot is shown in Figure 2b. On the ground, each plot was split into 10 sections, each of 4.0 × 2.5 m. This design, adapted from Pennington *et al.* (2004), targeted the seedlings on the snig tracks instead of those to the side which may have been influenced by lateral soil displacement rather than direct trafficking (Pennington *et al.* 2004). Furthermore, this allowed for a more systematic assessment of forest regeneration within each sample plot.

Assessing forest regeneration

The available seedbed (%) in each sample plot was recorded using the Visual Percentage Estimation Chart (Northcote *et al.* 1975). In addition, the total number of seedlings was counted (n_s seedlings), and for each seedling, the height (cm) and form (Table 1) were recorded.

Assessing soil chemical properties

A single 1-kg surface soil sample (0–10 cm) was collected from each sample plot for chemical analysis. Sampling beyond a depth of 10 cm was impractical given the shallow and stony nature of the soil in both coupes. Surface litter, ash and logging residues were first cleared by shovel, and where required, a chainsaw was used to cut through the larger-diameter logs.

In the laboratory, each sample was air dried for 48 h, crushed and passed through a 0.5 mm sieve in preparation for chemical analysis. From each sample, three 10-g sub-samples were taken for analysis of organic carbon (OC), total nitrogen (tot N) and total phosphorus (tot P) using standard laboratory procedures (Rayment and Higginson 1992).

Table 1. Definition of form characteristics

Characteristic	Description
Browsed (%)	Proportion of seedlings with majority of foliage browsed by either insects or higher animals
Diseased (%)	Proportion of seedlings with majority of foliage displaying signs of disease (unspecified)
Double leader (%)	Proportion of seedlings with double, or multiple, leaders
Sweep (%)	Proportion of seedlings with lower stem defect, generally curved or bent, and typically resulting from exposure to wind
Socket (%)	Proportion of seedlings where movement of the tree due to wind action has resulted in a cone-shaped depression in the soil around the base of the stem, causing instability and root rot through the accumulation of water
Broom (%)	Proportion of seedlings with no apical dominance (several competing stems with shallow crown narrowing at the base) — an indirect measure of slowing in seedling vigour (Stoate and Wallace 1938)
Dome (%)	Proportion of seedlings with no apical dominance (several competing stems with shallow dome-shaped crown) — an indirect measure of seedling supression (Stoate and Wallace 1938)
Conical (%)	Proportion of seedlings with strong apical dominance (single straight stem with deep conical crown) — an indirect measure of good seedling vigour (Stoate and Wallace 1938)

Table 2. Summary of seedling regeneration data. The first figure in each cell is the mean; the figures in brackets are the standard deviation and number of observations respectively.

Coupe	Property	Control	Primary snig tracks	Secondary snig tracks
8B	Available seedbed (%)	60 a (21,12)	9 b (8,6)	20 b (19,6)
	No. seedlings	53 a (18,12)	10 b (6,6)	33 c (18,6)
	Height (cm)	200 a (33,12)	64 b (30,6)	102 b (43,6)
8H	Available seedbed (%)	44 a (15,12)	15 b (10,6)	63 c (21,5)
	No. seedlings	100 a (41,12)	19 b (16,6)	99 a (63,5)
	Height (cm)	123 a (19,12)	55 b (23,6)	71 b (22,5)

Unlike letters within rows denote significant treatment differences ($P < 0.05$)

Analysis

The statistical significances of observed differences in seedling regeneration, seedling form and soil chemistry data between control areas and snig tracks were considered using analysis of variance (ANOVA) and Fisher’s least significant difference test, each performed in Excel (Microsoft Corporation 1997). Mean data recorded and presented as percentages (Tables 2, 3 and 4), were first transformed in Excel for the purpose of ANOVA using:

$$t = ASIN\left(\sqrt{\frac{x}{100}}\right)$$

where t was the transformed value and x was the original mean percentage value. Stepwise multiple regression analysis was carried out using S-PLUS (Insightful Corporation 2001) to determine which variables best described variation in the dependent variables — number of seedlings (n_s) and seedling height (cm). All differences were considered significant at $P = 0.05$.

Results

Seedling regeneration

Seedling regeneration data are summarised in Table 2. In all cases, available seedbed (%), n_s seedlings and height were significantly lower along the primary snig tracks compared to the control. Along the secondary snig tracks, these values were significantly lower than those of the control in all but one case. At Warra 8B, n_s seedlings was significantly lower along the primary snig tracks compared to the secondary snig tracks, and the same was true of available seed bed (%) and n_s seedlings at Warra 8H.

Seedling height distribution along the primary and secondary snig tracks was skewed in favour of the smaller height classes; this contrasted markedly with the more normal distribution observed for the control (Figs 3a and 3b).

Seedling form

Seedling form data are summarised in Table 3. At Warra 8B, the incidence of sweep and socketing was significantly greater along the primary snig tracks when

compared with the control. The same was true of sweep along the secondary snig tracks. At Warra 8H, the incidence of browsing, socketing and domed crowns was significantly greater along the primary snig tracks than that observed for the control. The same was true of browsing, disease, sweep, socketing and broomed crowns along the secondary snig tracks. For the primary and secondary snig tracks, only the higher incidence of sweep and socketing along the primary snig tracks was significant.

Soil chemistry

Soil chemistry data are summarised in Table 4. At Warra 8B, OC (%), tot N (%) and tot P (%) were significantly lower along the primary snig tracks compared to the control. At Warra 8H, only OC (%) was significantly lower along both the primary and

Figure 3. (a) Seedling height distribution at Warra 8B; (b) Seedling height distribution at Warra 8H

Table 3. Summary of seedling form data. The first figure in each cell is the mean; the figures in brackets are the standard deviation and number of observations respectively.

Coupe	Property	Control	Primary snig tracks	Secondary snig tracks
8B	Browse (%)	34 a (13,12)	45 a (27,6)	60 a (16,6)
	Disease (%)	23 a (14,12)	34 a (30,6)	23 a (10,6)
	Double leader (%)	10 a (5,12)	22 a (40,6)	8 a (9,6)
	Sweep (%)	15 a (7,12)	43 b (23,6)	17 c (15,6)
	Socket (%)	1 a (3,12)	35 b (35,6)	6 a (5,6)
	Broom (%)	7 a (5,12)	5 a (6,6)	8 a (6,6)
	Dome (%)	31 a (14,12)	51 a (29,6)	30 a (16,6)
	Conical (%)	61 a (16,12)	44 a (31,6)	62 a (18,6)
8H	Browse (%)	12 a (9,12)	47 b (32,6)	51 b (28,5)
	Disease (%)	16 a (8,12)	30 ab (23,6)	40 b (28,5)
	Double leader (%)	7 a (2,12)	15 a (12,6)	13 a (4,5)
	Sweep (%)	8 a (3,12)	19 ab (17,6)	29 b (6,5)
	Socket (%)	0 a (0,12)	11 b (11,6)	11 b (7,5)
	Broom (%)	3 a (1,12)	9 ab (9,6)	14 b (7,5)
	Dome (%)	29 a (9,12)	57 b (24,6)	49 ab (14,5)
	Conical (%)	68 a (9,12)	35 b (21,6)	36 b (13,5)

Unlike letters within rows denote significant treatment differences ($P < 0.05$)

Table 4. Summary of soil chemistry data. The first figure in each cell is the mean; the figures in brackets are the standard deviation and number of observations respectively.

Coupe	Property	Control	Primary snig tracks	Secondary snig tracks
8B	OC (%)	7.16 a (4.18,12)	2.69 b (1.04,6)	4.93 ab (2.13,6)
	Tot N (%)	0.262 a (0.147,12)	0.101 b (0.047,6)	0.156 ab (0.063,6)
	Tot P (%)	0.020 a (0.008,12)	0.010 b (0.007,6)	0.015 ab (0.003,6)
8H	OC (%)	5.59 a (1.69,12)	3.31 b (1.22,6)	3.75 b (1.72,5)
	Tot N (%)	0.215 a (0.099,12)	0.152 a (0.051,6)	0.149 a (0.086,5)
	Tot P (%)	0.018 a (0.005,12)	0.012 a (0.003,6)	0.017 a (0.004,5)

Unlike letters within rows denote significant treatment differences ($P < 0.05$)

secondary snig tracks. Differences between primary and secondary snig tracks were not significant.

Overall, available seedbed (%) explained 57% of the variation in n_s seedlings and 63% of the variation in seedling height at Warra 8B. At Warra 8H, no single variable adequately explained the variance in n_s seedlings, though OC and available seedbed (%) together explained 40% of the variation in seedling height.

Discussion

In practice, the benefits of cording are considered to be two-fold. Firstly, operational efficiency is maintained, primarily as a result of improved traction and vehicle flotation. Secondly, site productivity values are sustained due to (a) a reduction in soil disturbance, and (b) the ‘ash-bed effect’ — an increase in soil nutrients associated with lifting and burning of the cording, and other logging residues, once logging operations are complete.

Eucalypt regeneration: quantity and quality

Along the primary snig tracks at Warra 8B, considerable amounts of partially combusted cording were evident — typically large

logs beneath thick layers of bark, both being incorporated into the surface soil layers (Fig. 4a). This indicated that the lifting process was incomplete. At Warra 8H, similar amounts of material remained despite burning, though much of this was on the ground surface (Fig. 4b). At both coupes, the surface soil layers along the primary snig tracks were waterlogged and contained large amounts of partially decomposed vegetation, which in addition to a strong unpleasant odour, were indicative of anaerobic soil conditions. Wheel-rut formation and soil displacement were evident where cording had been incomplete.

The secondary snig tracks at Warra 8B resembled the primary snig tracks elsewhere within the coupe, with large amounts of partially combusted large diameter logs and bark material incorporated in the surface soil layers. In contrast, secondary snig tracks at Warra 8H were characterised by deep rutting and soil displacement, a likely result of a lack of cording material combined with harvesting during wet ground conditions. During the harvesting phase, the availability of cording material was not assessed so no judgment can be made as to whether this was an operational limitation or just poorly constructed cording.

Figure 4. (a) Residual cording along primary snig tracks at Warra 8B; (b) residual cording along primary snig tracks at Warra 8H

Seedling numbers were lower along the snig tracks compared to the control areas; this was consistent with previous studies (Greacen and Sands 1980; Froehlich *et al.* 1985, 1986; Williamson 1990b; Johnson 1994; Rab 2004). At Warra 8B, this was explained to a large degree by available seedbed (%), though at Warra 8H no single factor adequately explained the variability. The reduction in available seedbed (%) at each site was due to the incomplete combustion of the cording material (except secondary snig tracks in Warra 8H), and also incorporation of large-diameter logging residues in the surface soil layers.

Seedling height distributions were skewed in favour of the smaller height classes along both primary and secondary snig tracks at each coupe, and contrasted markedly with the more normal distribution of seedling height for the control areas. Similar results were found by Williamson (1990b), and reflect a slowing of the differentiation into dominance classes typical of even-aged stands (Florence 1996). Whilst any suppression of seedlings within the control areas (unrecorded) was likely to be a result of overtopping by neighbouring trees (Oliver and Larson 1996), that observed along the snig tracks was likely to have been influenced by a combination of factors including unfavourable soil properties (see below), heavy browsing and a higher incidence of disease.

Soil properties

Soil organic carbon, total N and total P concentrations were consistently lower along the primary and secondary snig tracks when compared with the control areas. This was attributed to the anaerobic conditions retarding the decomposition of organic material (Teepe *et al.* 2004) and oxidation of carbon within the disturbed soil profile (Nussbaum *et al.* 1995; Woodward 1996). Individual soil chemical properties did little to explain the variability in n_s seedlings and seedling height, demonstrating the strong relationship between these soil properties as a whole. Nutritional stress can lead to an increased predisposition to browsing and disease (Gaumann 1950; Schoeneweiss 1975; Larsson *et al.* 1983; Oliver and Larson 1996), both of which were evident along the snig tracks in this study, whilst rates of recovery may be compromised (Schoeneweiss 1975). Ease of access might also explain the increased browsing of seedlings along the snig tracks.

Soil physical properties, notably bulk density and soil strength, were not measured in this study. This was due to the shallow, stony nature of the soil, and also the presence of partially-combusted cording material on the ground surface and incorporated in the surface soil layers along the snig tracks. In an earlier study, Pennington and Laffan (2004) reported pre-harvest soil bulk densities at 10 cm soil depths of 0.71 g cm^{-3} at Warra 8B and 0.67 g cm^{-3} at Warra 8H. Post-harvest surveys by the authors, at Warra 8B only, returned bulk density values of 0.83 g cm^{-3} and 0.70 g cm^{-3} at 10 cm depth for the primary and secondary snig tracks respectively. Previous studies have demonstrated adverse effects on tree growth at soil densities of $0.91\text{--}0.96 \text{ g cm}^{-3}$ (Rab 1994), though more commonly at $1.20\text{--}1.50 \text{ g cm}^{-3}$ (Minore *et al.* 1979; Canarache 1990; Wronski and Murphy 1994; McLaren and Cameron 1996; Senyk and Craigdallie 1997). Post-harvest bulk density values measured by Pennington and Laffan (2004) did not represent a significant increase compared to pre-harvest values, nor did they approach the threshold values cited above. However, post-harvest sampling at Warra 8B was limited due to the large amounts of cording material. Furthermore, as no additional characteristics such as soil strength, water content and porosity were measured, no firm conclusion can be drawn regarding overall impacts on soil physical properties.

Cording: construction and effectiveness

In this study, field observations demonstrated that whilst goals relating to operational efficiency were met, assumptions regarding the protection of site productivity by the use of cording should be questioned.

During the construction of cording, harvesting machinery first traverses the intended route, flattening the understorey and clearing the way for the placement of cording material. Previous studies of forest soil compaction have demonstrated that the largest increases in soil density and/or strength occur after only a few machine passes (Hatchell *et al.* 1970; Burger *et al.* 1984; Wronski 1984), though total soil response varies with (a) soil conditions (Greacen and Sands 1980), (b) machine design (Burger *et al.* 1984; Seixas and McDonald 1997) and (c) the intensity of the machine loads applied to the ground surface (Lynse and

Burditt 1983; Furuberg-Gjedtjernet 1995). As a result, it is likely that considerable increases in soil density and/or strength, and concomitant decreases in hydraulic conductivity, often occur as the cording is placed along the snig tracks during routine harvesting operations.

To further consider the effectiveness of cording in maintaining acceptable soil physical properties, and in the absence of more rigorous testing, the distribution and attenuation of machine loads by cording are considered theoretically (Fig. 5).

Under cording, it is assumed that machine loads are transmitted vertically through the rigid logs, and distributed evenly at the ground surface over an area ab . Given the small surface area of the log initially in contact with the ground surface (ab), it is unlikely that the machine loads per unit of ground area are reduced: it is more likely that they are amplified, resulting in soil compaction and/or displacement. Only as the cording is pushed into the upper soil layers, particularly on wetter soils and resulting in a greater surface area of the log coming into contact with the ground surface (ac), will machine loads be distributed over a larger area and therefore reduced per unit area. Subsequently, machine flotation is maintained by adding more cording as that below is mixed with the upper, and later, lower soil layers.

Operational recommendations

During construction of cording, it is essential that initial trafficking of the unprotected ground surface is minimised wherever possible. The fact that most adverse soil impacts can occur during the first few passes of the machines means that, by the time the cording is in place, considerable and potentially irreversible damage to the soil structure may have already taken place.

When laying down cording, a lower layer of bark and small-diameter branchwood, over which the larger-diameter logs are laid, may help to distribute the machine loads over a greater area. On wet sites, this may also help to prevent cording material becoming incorporated in the upper soil layers, and thus make the process of lifting and burning more efficient.

Where incomplete lifting and/or burning of cording material and poor seedling regeneration are a likely outcome, it is suggested that cording be left intact and no attempt be made to rehabilitate the actual corded track as productive forest. The corded track would then provide a means of access during subsequent operations including thinning and fire management. Furthermore,

it is possible that increases in productivity observed adjacent to previously-corded tracks, possibly as a result of lateral displacement of soil (Pennington *et al.* 2004), may serve to offset any productivity losses associated with the retention of permanent tracks. Such a concept is not new, but the forest industry has raised concerns relating primarily to the retention of high fuel loads on site (cording) and the possibility of re-ignition of fires due to the presence of smouldering embers. These are legitimate concerns, though dependent on soil properties and the condition of residual cording, which being buried is likely to be wet and subject to a restricted oxygen supply. In this study, the poor combustion of cording material that had been lifted to enhance burning suggests that re-ignition will be unlikely.

This study did not include a comparison with unprotected trafficked areas because the benefits of cording in protecting soil properties by restricting harvesting machinery to a defined pathway are clear (Wilkinson 2000, 2001). Whether the loss of stocked area from a permanent track is significant, when regeneration can occur right up to the actual cording and trees can subsequently occupy the canopy space over the track, has yet to be determined. The authors suggest that as lifting and burning the cording after harvesting is difficult, expensive and will probably not result in adequate regeneration, best practice is to leave it in place.

Conclusion

In this study, the conventional use of cording to protect forest soils from damage during mechanised harvesting, and the subsequent method of snig track rehabilitation — lifting and burning of cording — were found to be largely ineffective when judged by seedling regeneration. Forest regeneration along the former snig tracks was consistently inferior in both quantity and quality to that of the untrafficked control areas. This was attributed to (a) a reduction in the available seedbed (%) due to incomplete combustion of the cording material and retention of logging residues in the upper soil layers, and (b) the combined effects of differences in soil chemistry along the snig tracks.

Future research should consider the following:

- alternative methods for making corded tracks
- machine load distribution and attenuation under cording
- changes in soil physical properties along corded tracks
- more effective means of rehabilitating corded tracks
- the operational, economic and environmental implications of permanent snig tracks.

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Figure 5. Composition and theoretical load distribution under cording

Appendix 1. Profile descriptions typical of the well-drained and imperfectly-drained soils at Warra 8B and 8H (Laffan 2001)

Feature	Well-drained soil profile	Feature	Imperfectly-drained soil profile
Correlation	Kermandie profile (Grant <i>et al.</i> 1995)	Correlation	Murdunna profile (Grant <i>et al.</i> 1995)
Location	Warra 001B (centre of coupe)	Location	Warra 001B (50 m north of well-drained profile)
Landform	Undulating lower slopes of hill/mountain	Landform	Undulating lower slopes of hill/mountain
Vegetation	Wet eucalypt forest dominated by <i>E. obliqua</i>	Vegetation	Wet eucalypt forest dominated by <i>E. obliqua</i>
Parent material	Quaternary slope deposits derived from Jurassic dolerite	Parent material	Quaternary slope deposits derived from Jurassic dolerite
A1 0–3 cm	Dark brown (7.5YR 3/4) clay loam; very weak strength; moderately developed 2–5 mm subangular blocky structure; <10% subangular gravels (50–100 mm); many fine and medium roots	A1 0–7 cm	Very dark greyish brown (10YR 3/2) humic clay loam; few dark grey (10YR 4/1) 2–5 mm mottles; very weak strength; moderately developed 5–10 mm subangular blocky structure; 5–10% 40–50 mm subangular coarse fragments; many fine and medium roots
B21 3–55 cm	Yellowish brown (10YR 5/8) light to medium clay; weak strength; moderately developed 10–20 mm subangular blocky structure breaking to 5–10 mm subangular blocky structure; 20–30% subangular boulders (300–600 mm); few worm casts; few red (2.5YR 4/8) 5–10 mm mottles; common fine and medium roots	B21 7–30 cm	Yellowish brown (10YR 5/4) light clay; few grey (10YR 5/1) and strong brown (7YR 5/6) 2–5 mm mottles; weak strength; moderately developed 10–20 mm angular blocky structure; 10–15% subangular 100–150 mm dolerite fragments; common dark brown (10YR 4/3) worm casts; many fine and medium roots
B22 55–90+ cm	Yellowish brown (10YR 5/6) medium clay; few red (2.5YR 4/8) 5–10 mm mottles; weak strength; strongly developed 5–10 mm subangular blocky structure breaking to 2–5 mm subangular blocky structure; 20–30% subangular boulders (300–600 mm); common fine and medium roots	B22 30–58 cm	Yellowish brown (10YR 5/4) light to medium clay; many light grey (10YR 6/1) and yellowish red (5YR 5/6) 2–5 mm mottles; weak strength; moderately developed 10–20 mm angular blocky structure; few dark brown (10YR 4/3) worm casts; many fine and medium roots
		B23 58–90+ cm	Yellowish brown (10YR 5/6) medium clay; many greenish grey (5GY 6/1) and yellowish red (5YR 5/6) 2–5 mm mottles; weak strength; moderately developed 5–10 mm angular blocky structure; many fine and medium roots
Notes	Red mottles in B21 and B22 are probably very strongly red-weathered dolerite fragments or may result from previous hot fires in the root zone. Characteristic features: gradational texture profile with thin clay loam A1 horizon overlying uniformly coloured bright yellow-brown clayey subsoils often with red mottling.	Notes	Characteristic features: gradational texture profile with humic clay loam A1 horizon overlying grey and orange mottled clayey subsoil.

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