

Impact of major snig tracks on the productivity of wet eucalypt forest in Tasmania measured 17–23 years after harvesting

P.I. Pennington^{1,2}, M. Laffan³, R. Lewis³ and K. Churchill¹

¹CSIRO Forestry and Forest Products, Tasmanian Research Centre, Private Bag No. 12, Hobart, Tasmania 7001, Australia

²Email: Phillip.Pennington@csiro.au

³Forestry Tasmania, 15960 Midland Highway, Perth, Tasmania 7300, Australia

Revised manuscript received 5 May 2003

Summary

During ground-based harvesting operations the passage of machinery leads to the formation of a mosaic of major and minor snig tracks from tree stumps to the landing. The impact of heavy traffic can lead to significant changes in the underlying soil physical properties and potentially in long-term growth of trees on these tracks. This study examined the impact of major snig tracks on the productivity of wet eucalypt forest in Tasmania. The three stands studied were dominated by *Eucalyptus obliqua* that regenerated from clearfelling, slash burning and aerial sowing 17–23 y earlier.

Accumulated tree growth and soil physical and chemical properties were measured in three zones: snig tracks, transitional zone (edge of snig tracks), and control. There was a dramatic decline of 52–80% in the accumulated tree volume in snig track zones when compared to the control zones. This was accompanied by a significant increase in the soil bulk density of 20–23%, and measured changes in a number of soil properties including 22–33% decrease in organic carbon, 28–32% decrease in total N, and 3–11% decrease in total P on the snig track zones. There was no significant difference in either the soil physical or chemical properties of the transitional zones compared to the control zones, but there was a significant increase in tree growth in the transitional zones, ranging from 30% to 100%. An increase in stand density was the major factor contributing to improved growth in transitional zones, with increases in average diameter and average height having minimal effect.

After 17–23 y the increase in stand productivity in the transitional zone compensated for much of the productivity lost due to poor growth on the snig tracks. The overall negative impact of snig tracks on stand productivity was calculated to be of the order of 2–3%.

Keywords: regrowth; growth; tracks; soil compaction; *Eucalyptus obliqua*

Introduction

On slopes less than about 20°, the wet eucalypt forests of Tasmania are generally harvested by clearfelling using rubber-tyred skidders to drag fallen trees to a central landing. This practice forms a mosaic of major and minor snig tracks (skid trails) throughout the harvested area. Major tracks are the main arterial routes along which logs are dragged, and they are traversed many times by the

skidders. The impact of such heavy traffic on major tracks can lead to dramatic changes to the underlying soil physical properties and a significant reduction in the recruitment and early growth of seedlings on compacted areas (Lockerby and Vidrine 1984; McLeod 1988; Farrish 1990; Williamson 1990; Bates *et al.* 1993; King *et al.* 1993a,b; Rab 1994; Murphy *et al.* 1997; Senyk and Craigdallie 1997; Jansson and Wasterlund 1999; Pinard *et al.* 2000). On slopes steeper than 20°, cable-logging is the preferred method of harvesting.

In a study of the effects of ground-based mechanised forest harvesting on soil properties and site productivity in Tasmania, Williamson (1990) found that the initial growth and stocking of eucalypt seedling regeneration on snig tracks was dependent on the degree of disturbance. Four years after harvesting, the tertiary snig tracks (areas subject to removal of the litter layer and minor gouging of the A horizon to less than 10 cm) formed during the logging operation could not be distinguished from the surrounding undisturbed areas. On secondary snig tracks (areas where the topsoil was compacted in situ and there was minor rutting no deeper than 10 cm on the A horizon and/or partial removal of the A horizon) the growth and stocking of seedlings were found to be equal to if not better than on undisturbed soils. The impacts of harvesting were most obvious on primary snig tracks (areas where there had been removal or displacement of topsoil by gouging, puddling and mixing of soil profiles with rutting into the B horizon) where the initial growth and stocking were significantly below that on undisturbed sites. Williamson suggested that poorer growth and lower stocking on primary snig tracks would lead to few trees reaching merchantable size. King *et al.* (1993a,b) in studies of the impacts of forest harvesting in Victoria, also reported a significant decline in the height and diameter of 3-y-old *Eucalyptus regnans* seedlings growing on primary snig tracks.

Other studies have shown that the poor early growth on major snig tracks has led to lower productivity at later ages. Murphy *et al.* (1997) showed a 6.6% reduction in the tree volume of 11-y-old *Pinus radiata* on areas of the plantation subjected to topsoil removal and subsoil compaction when compared to undisturbed areas. In a stand of 32-y-old *Pseudotsuga menziesii* (Douglas-fir), Wert and Thomas (1981) reported a reduction in timber volumes from 129 m³ ha⁻¹ for undisturbed areas to 34 m³ ha⁻¹ for bladed snig tracks. McLeod (1988) estimated that >50% of the area of bladed snig tracks would be unsuitable for good tree growth. He recommended that these skid tracks should be viewed

as part of the permanent land base given over to road transport and, as such, be re-used at the end of the next rotation and not considered as productive areas.

Though the effect of major snig tracks on regeneration and productivity appears to be substantial, so far little effort has been made to quantify the loss of productivity on snig tracks in relation to the growth of the entire stand. Williamson (1990) speculated that if primary snig tracks were left unrestored, their proportional area would be indicative of the expected productivity loss. He also suggested that the trees adjacent to wide snig tracks may have denser branching at lower levels of the stem, which would reduce or eliminate their suitability for sawlogs. Hence the impact of major snig tracks on sawlog productivity may be greater than their proportional area. In a 32-y-old *Pseudotsuga menziesii* stand, snig tracks occupied 9.8% of the area but the loss of productivity for the stand was 11.8% (Wert and Thomas 1981).

The aim of the study reported here was to examine the medium term (17–23 y after logging) impacts of major snig tracks on stand productivity of *E. obliqua*, currently the major commercial native forest timber species harvested from wet eucalypt forest in Tasmania. The studies were carried out in three stands in northern and southern Tasmania dominated by this species.

Methods

Study area description

Table 1 summarises the location of the experimental stands, and their soil type, forest type and size, the silvicultural system used and the age of regeneration.

In southern Tasmania both study sites (WR3G and AR82E) were located on gradational soils formed on Jurassic dolerite. The main soil type (Kermandie soil profile class) is well drained with a profile characterised by relatively thin (<10 cm) dark brown clay loam topsoils (A1 horizon) overlying reddish-brown clayey B horizons. Soil structure typically consists of moderately developed 2–5 mm subangular blocky topsoils and strongly developed 2–5 mm and 5–10 mm subangular blocky subsoils. Mean annual rainfall is 1100–1200 mm with a winter maximum. Summer soil moisture deficits are generally weak and uncommon.

Table 1. Stands used in current study

	WR3G	AR82E	GC6
Location	Southern forest	Southern forest	North-eastern forest
Grid reference	43°10'S, 146°44'E	43°4'S, 146°46'E	41°7'S, 148°5'E
Silvicultural system	Clearfell with seed trees	Clearfell with seed trees	Clearfell
Age of regeneration (y)	17	23	17
Forest species	<i>E. obliqua</i>	<i>E. obliqua</i> <i>E. regnans</i> (minor)	<i>E. obliqua</i> <i>E. regnans</i> <i>E. amygdalina</i> (minor)
Parent material	Jurassic dolerite	Jurassic dolerite	Devonian granite
Soil profile class ¹	Kermandie (p. 171)	Kermandie (p. 171)	Stronach (p. 153)
Australian Soil Classification ²	Haplic, Red Ferrosol	Haplic, Red Ferrosol	Melanic-Acidic, Dystrophic, Brown Dermosol

¹According to Grant *et al.* (1995).

²Isbell (1996)

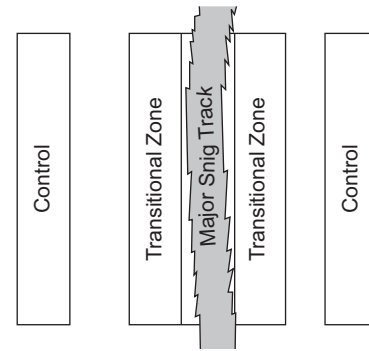


Figure 1. Layout for growth assessment plots

The soils at the north-eastern site (GC6) are formed from Devonian granite. The major soil type (Stronach soil profile class) is well drained with gradational profiles characterised by relatively thick (>20 cm) dark-brown coarse sandy loam topsoils (A1) overlying brown coarse sandy clay loam and light to medium clay B horizons. Soil structure varies from moderately developed 2–5 mm granular structure in the A1 horizon to moderately developed 20–50 mm angular blocky structure that breaks to strongly developed <2 mm granular structure in B horizons. Mean annual rainfall is ~1000 mm with a marked soil moisture deficit occurring during the summer months.

Due to a combination of higher rainfall, moister soils and more frequent machine passes in the southern forest stands (WR3G and AR82E), deeply entrenched major snig tracks had primary damage with loss of the A horizon and gouging into the B horizon. Some major snig tracks were >1 m below the original surface. In the north-eastern stand (compartment GC6), disturbance on major snig tracks was generally shallower, with part of the A horizon still intact but with ruts ~10 cm deep. For WR3G, a ground-based survey (transects at 100 m spacing) determined that major snig tracks occupied a total of 8.2% of the stand area. For the two other stands (GC6 and AR82E), the area of major snig tracks was estimated at ~7%, from aerial photography.

Growth assessment plots

Growth assessment plots (5 m wide x 20 m long) were established in three main zones: (i) major snig tracks, (ii) transitional zones,

Table 2. Bulk density (Mg m^{-3} , mean \pm sd) of the upper 0–100 mm soil layer for the different zones at WR3G and GC6

Stand	Control zone	Transitional zone	Snig track zone All sites		
WR3G	0.70 ^a \pm 0.10	0.70 ^a \pm 0.08	0.87 ^b \pm 0.08	<i>Compacted</i>	0.90 \pm 0.09
				<i>Displaced</i>	0.84 \pm 0.06
GC6	1.02 ^a \pm 0.06	1.04 ^a \pm 0.05	1.23 ^b \pm 0.09		

Mean figures within the rows with different letters differ significantly at $P < 0.05$.

The results under compacted and displaced are subsets of the snig tracks 'All sites' data.

Bulk densities shown include gravel >2 mm. Gravel content at WR3G was $1\pm 1\%$ with no significant difference between zones, and at GC6 it was $39\pm 10\%$ with no significant difference between zones.

adjacent to major snig tracks, and (iii) control areas subject to low or nil soil disturbance. All control plots were at least 10 m from any visible major soil disturbance. A typical plot layout at WR3G is shown in Figure 1. At GC6 and AR82E, only single-sided plots were used, with the major snig track, one transitional zone and one control zone being assessed. At each stand, seven sites covering a range of aspects and slope were sampled, though at each site all plots were on uniform aspect and slope.

Measurement of soil properties

At WR3G and GC6, soil samples were collected from randomly located points in each plot (9 in control and transitional zones and 18 in snig tracks). At WR3G, the major snig tracks were deeply entrenched with substantial soil displacement during the logging operations resulting in the loss of the nutrient-rich A horizon. At the GC6 site the snig tracks generally had only shallow ruts and there had been less disruption and movement of the upper soil layer from the tracks. Sampling locations within the snig track zone at WR3G were also differentiated into compacted or displaced soils based on a visual assessment. Bulk density cores were collected using a steel tube, 70 mm diameter \times 100 mm length. A pine block, 100 mm \times 50 mm \times 200 mm, was placed over the top of the steel tube and the tube was driven into the soil by a club hammer. After carefully extracting the tube from within the soil profile without disturbing the core, the ends were trimmed as required and the soil transferred to a plastic bag for transport to the laboratory. Cores containing large roots or rocks were discarded and substitute cores collected. Bulk density was determined by oven-drying cores at 105°C for 40 h. To determine the gravel (>2 mm) content, a subset of dried bulk-density samples (of known dry weight) was shaken overnight in a 1% solution of Calgon. The slurry was washed through a 2 mm sieve. The gravel was collected and dried overnight at 105°C prior to weighing.

Soil samples were not collected from AR82E because the soils and degree of disturbance due to logging were similar to those at WR3G.

Samples for chemical analysis were taken adjacent to the bulk density sample. After air-drying at 25°C for 40 h, they were passed through a 2 mm sieve. Gravel, root material and soil fauna were discarded. Sieved samples were then fully air-dried and a 30 g sub-sample was ground and passed through a 0.5 mm sieve. Soils were analysed for the following components using the methods described by Rayment and Higginson (1992): pH (method number 4A1), organic carbon (6A1), and total N and P (4A1), followed by Lachat-FIA analysis.

Measurement of forest growth

At all sites trees >10 cm diameter at breast height over bark (dbhob) were measured for height and diameter (bhob), and were classified as either pulpwood or potential sawlog. Potential sawlogs were dominant or co-dominant trees of good form with one or more sawlogs 3 m long, and free of visible defect (damage or branch stubs or decay >30 mm) on at least three sides. Estimated standing volume (ESV) was calculated by using the VOLS program developed by Forestry Tasmania (A. Goodwin *pers. comm.*). The ESV was calculated for each individual tree and the total for each plot was converted to volume per hectare. For trees growing within the snig track zones, the location of the tree on compacted or displaced soil was also recorded.

To calculate the effect of the major snig tracks on stand productivity the following assumptions were made. Major snig track zones occupied 8%, transitional zones 14%, and control zones 78% of the total area. A small area of transitional zones is lost around the points where major snig tracks merge. Due to significant soil disturbance there is strong justification for considering the area of landings to be part of the permanent infrastructure, as are access roads. Hence this area has been excluded from all calculations.

Results

Soil properties

For the upper 0–100 mm soil layer there was no significant difference in bulk density between the transitional and control zones at either WR3G or GC6 (Table 2). However, a significant difference between these two zones and the snig track zone occurred at both sites. There was no significant difference between the compacted and displaced locations within the snig track zone. The 7% difference in bulk density was less than expected, but many of the displaced sites were found to have a thin (30–50 mm) layer of displaced soil over compacted soil.

At WR3G, the concentrations of both organic carbon and total N were significantly lower in snig track zones, though no significant difference was seen in concentrations of total P (Table 3). When concentration and bulk density values were converted to kilograms per hectare for the 0–100 mm depth, differences in organic carbon and total N were not significant, even though the organic carbon and total N values for the snig track zones were 17% and 12% below those of the control zone. At GC6 only total N (%) in the snig track zones was significantly ($P < 0.05$) lower than in the

Table 3. Concentration (mean \pm se) of various soil components in the upper 0–100 mm soil layer for the different zones at WR3G and GC6

Stand	Component	Control zone	Transitional zone	Snig track zone	
				All sites	
WR3G	Organic C (%)	5.4 ^a \pm 1.3	5.4 ^a \pm 1.2	3.6 ^b \pm 0.7	<i>Compacted</i> 3.5 \pm 0.8 <i>Displaced</i> 3.9 \pm 0.5
	(kg ha ⁻¹)	37100	36000	30900	
	Total N (%)	0.22 ^a \pm 0.06	0.20 ^a \pm 0.03	0.15 ^b \pm 0.03	<i>Compacted</i> 0.15 \pm 0.03 <i>Displaced</i> 0.16 \pm 0.02
	(kg ha ⁻¹)	1485	1385	1310	
	Total P (%)	0.035 \pm 0.008	0.034 \pm 0.006	0.032 \pm 0.07	<i>Compacted</i> 0.033 \pm 0.010 <i>Displaced</i> 0.031 \pm 0.006
	(kg ha ⁻¹)	231	234	277	
GC6	Organic C (%)	5.8 \pm 1.0	5.0 \pm 1.0	4.5 \pm 0.6	
	(kg ha ⁻¹)	34300	32100	34900	
	Total N (%)	0.32 ^a \pm 0.04	0.27 ^{ab} \pm 0.06	0.23 ^b \pm 0.01	
	(kg ha ⁻¹)	1870	1710	1790	
	Total P (%)	0.028 \pm 0.009	0.026 \pm 0.006	0.025 \pm 0.005	
	(kg ha ⁻¹)	168	165	189	
pH	4.7 \pm 0.4	4.7 \pm 0.2	4.8 \pm 0.3		

Mean figures within the rows with different letters differ significantly at $P < 0.05$.

'Compacted' and 'Displaced' results are subsets of the snig tracks 'All sites' data.

The number of soil samples taken from displaced areas of the snig tracks at GC6 was minimal so the samples were not divided into these two subsets.

control zone. There were no significant differences apparent in any element when compared on a kilogram per hectare basis.

Forest growth

The average diameter, average height and stand density of all trees at the three sites are shown in Table 4. For the southern stands (WR3G and AR82E) the average diameter, average height and stand density of all groups of trees in the snig track zone were less than those in the corresponding control zone. Within the snig track zones at both WR3G and AR82E, most (>80%) of the trees were growing on areas of displaced soil and the severely compacted areas were bare, except for the occasional struggling pulpwood tree. At the northern stand, the average diameter and average height of all trees were similar on the control and snig tracks zones, while the stand density of trees on the snig track zone was significantly lower. The wattles growing on the snig track zones at AR82E were of similar height, diameter and density to the wattles growing in the other zones. The average diameter, height and stand density was higher on all transitional zones when compared to the control zones, though the only significant differences were stand density at AR82A and tree height at GC6.

Table 4 also shows the average diameter, average height and density for the pulpwood and potential sawlog trees at all sites. There was no significant difference in the average diameter or height of potential sawlogs between the control and transitional zones at any site. In all cases the average height and diameter were almost identical. Stand density in the transitional zones was notably higher than in the control zones, with a 43% and 61% increase at WR3G and AR82E, respectively. Though ANOVA showed that there was no significant difference in the density of potential sawlogs at WR3G ($P = 0.081$) or AR82E ($P = 0.052$), more than 85% of the transitional zones had a higher density of

sawlogs than their paired control zones. At GC6 there was a significant difference, with the density of potential sawlogs on the transitional zones being 2.59 times that on the control zones.

When examining the figures for the pulpwood trees only, conflicting trends are seen. In the 23-y-old stand at AR82E there was a significant increase in average diameter ($P = 0.038$), average height ($P = 0.029$) and density ($P = 0.010$) of pulpwood trees in the transitional zones compared to the control zones. For the 17-y-old stand at WR3G and GC6 there was no significant difference in either diameter, height or stand density.

The estimated standing volume (ESV) of all the trees (>10 cm dbhob) measured in the three zones is shown in Figure 2. At all sites the ESV was significantly lower within the snig track zones than in the control zones. The difference in tree volume was

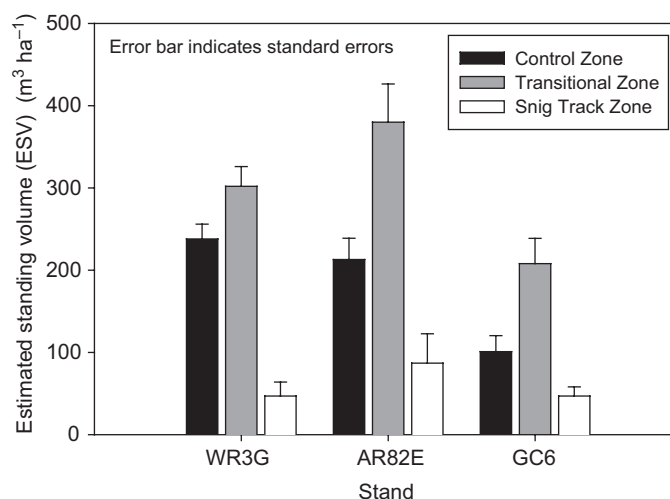


Figure 2. Estimated standing volume for all trees (>10 cm dbhob) in the three stands

Table 4. Mean diameter at breast height, mean height and density (stems ha⁻¹) for all trees (>10 cm dbhob) split according to tree classification and the three zones: control, transitional and snig track

Tree classification, stand and property		Control zone	Transitional zone	Snig track zone
<i>All trees ≥10 cm dbhob</i>				
WR3G	dbhob (cm)	17.5 ± 5.9	18.2 ± 5.6	16.1 ± 5.7
	Height (m)	19.6 ^a ± 4.5	20.2 ^a ± 4.5	17.6 ^b ± 5.2
	Density (stems ha ⁻¹)	1140 ^a ± 430	1460 ^a ± 480	360 ^b ± 230
AR82E	dbhob (cm)	18.2 ± 6.9	18.8 ± 7.4	16.6 ± 5.7
	Height (m)	17.9 ± 4.2	18.8 ± 4.1	17.1 ± 4.1
	Density (stems ha ⁻¹)	1100 ^b ± 260	1800 ^a ± 330	420 ^c ± 440
GC6	dbhob (cm)	17.9 ^{ab} ± 5.6	20.1 ^a ± 6.7	17.2 ^b ± 3.6
	Height (m)	13.9 ^a ± 3.2	15.5 ^b ± 3.8	15.0 ^{ab} ± 2.1
	Density (stems ha ⁻¹)	770 ^{ab} ± 290	1100 ^a ± 490	430 ^b ± 350
<i>Pulpwood trees only</i>				
WR3G	dbhob (cm)	14.4 ± 4.3	14.9 ± 4.7	15.0 ± 4.2
	Height (m)	17.0 ± 4.2	17.3 ± 4.2	16.0 ± 4.9
	Density (stems ha ⁻¹)	460 ^a ± 250	490 ^a ± 250	160 ^b ± 120
AR82E (Eucalypt)	dbhob (cm)	14.0 ^b ± 3.5	16.4 ^a ± 6.8	12.6 ^b ± 3.3
	Height (m)	15.4 ^b ± 2.9	17.0 ^a ± 3.7	14.9 ^b ± 2.1
	Density (stems ha ⁻¹)	570 ^b ± 230	930 ^a ± 210	220 ^c ± 280
AR82E (Wattle)	dbhob (cm)	18.1 ± 5.2	17.8 ± 4.1	19.2 ± 5.8
	Height (m)	18.3 ± 4.0	19.6 ± 2.5	17.8 ± 4.6
	Density (stems ha ⁻¹)	90 ± 120	160 ± 180	100 ± 140
GC6	dbhob (cm)	17.0 ± 5.6	18.7 ± 7.2	15.2 ± 3.6
	Height (m)	13.1 ± 2.9	14.2 ± 3.5	13.6 ± 1.6
	Density (stems ha ⁻¹)	600 ^a ± 240	660 ^a ± 430	190 ^b ± 180
<i>Potential sawlog trees only</i>				
WR3G	dbhob (cm)	19.6 ± 5.9	19.8 ± 5.3	16.8 ± 5.6
	Height (m)	21.3 ^a ± 3.8	21.7 ^a ± 3.9	18.6 ^b ± 5.3
	Density (stems ha ⁻¹)	670 ^b ± 310	960 ^a ± 320	210 ^c ± 160
AR82E	dbhob (cm)	23.6 ± 6.9	22.3 ± 7.3	22.9 ± 2.2
	Height (m)	23.0 ± 3.6	20.9 ± 3.9	22.0 ± 3.2
	Density (stems ha ⁻¹)	440 ^a ± 190	710 ^a ± 270	110 ^b ± 90
GC6	dbhob (cm)	21.2 ^{ab} ± 4.8	22.4 ^a ± 5.1	18.7 ^b ± 2.8
	Height (m)	16.6 ± 2.7	17.9 ± 3.0	16.0 ± 2.0
	Density (stems ha ⁻¹)	170 ± 110	440 ± 260	240 ± 190

Mean figures within the rows with different letters differ significantly at $P < 0.05$.

calculated as 53% at GC6, 59% at AR82E and 80% at WR3G. The ESV for the transitional zones at all three stands was significantly higher than that for the control zones. This increase in volume was 27% at WR3G, 78% at AR82E and 106% at GC6. At only three of the 28 matched control and transitional plots assessed did the ESV of the control zone exceed that of the transitional zone.

At the southern forest sites where there had been severe disturbance of the major snig tracks, the ESVs per hectare of all potential sawlog trees on the snig track zones were significantly below those of the corresponding control zones (Fig. 3). The ESV of potential sawlogs on the transitional zones was 35% and 44% higher than the control zones at WR3G and AR82E respectively. ANOVA indicated that there was no significant difference between the zones ($P = 0.124$) at AR82A, but a significant difference at WR3G ($P = 0.026$). At the northern site, GC6, where there was

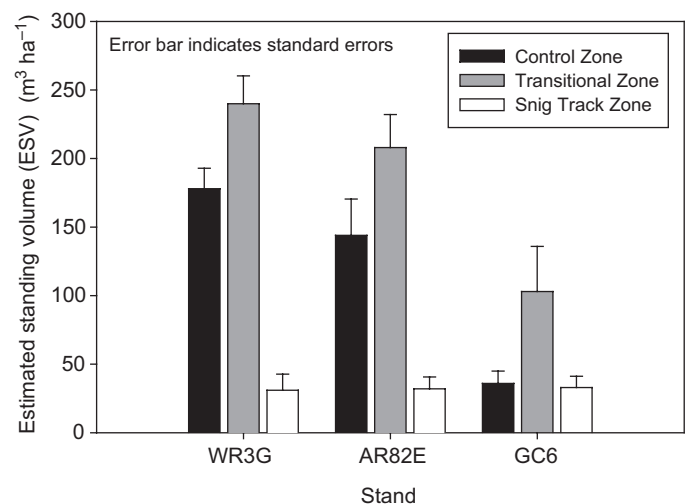


Figure 3. Estimated standing volume for potential sawlog trees in the three stands

less soil disturbance on the major snig tracks, no significant difference was apparent between zones ($P = 0.064$), but the volume on the transitional zones was notably higher at $103 \text{ m}^3 \text{ ha}^{-1}$.

Using the previously described assumptions of 8% snig track zones, 14% transitional zones and 78% control zones, the additional volume in the transitional zones offsets most if not all the productivity loss due to the poor growth associated with the major snig tracks. For WR3G, the calculated volume for all trees in the stand was $232 \text{ m}^3 \text{ ha}^{-1}$ ($0.08 \times 47 \text{ m}^3 \text{ ha}^{-1} + 0.14 \times 302 \text{ m}^3 \text{ ha}^{-1} + 0.78 \times 238 \text{ m}^3 \text{ ha}^{-1}$), compared to an estimate of $238 \text{ m}^3 \text{ ha}^{-1}$ ($1.0 \times 238 \text{ m}^3 \text{ ha}^{-1}$) if the entire stand had been similar to the control area. This equates to a 3% drop in stand productivity compared to the 8% area occupied by major snig tracks. At the other stands there were small productivity gains owing to minor increases in tree diameter and height, and large increases in stand density. Within reason, adjusting the area defined as snig track zone had only minor effect on the overall result. Assuming 10% of the area is snig tracks, 14% is transitional zones and 76% is control zones, the productivity loss at WR3G was ~4%.

Similar patterns were seen when considering potential sawlogs only. The volume of sawlogs at WR3G was $175 \text{ m}^3 \text{ ha}^{-1}$ ($0.08 \times 31 \text{ m}^3 \text{ ha}^{-1} + 0.14 \times 240 \text{ m}^3 \text{ ha}^{-1} + 0.78 \times 178 \text{ m}^3 \text{ ha}^{-1}$), compared to an estimated $178 \text{ m}^3 \text{ ha}^{-1}$ ($1.0 \times 178 \text{ m}^3 \text{ ha}^{-1}$) if the entire stand had been similar to the control. For AR82E the calculated volume is $149 \text{ m}^3 \text{ ha}^{-1}$ compared to an estimated $154 \text{ m}^3 \text{ ha}^{-1}$, and the productivity loss is 3%.

Discussion

The increase in soil bulk density in the snig track zones of 24% at WR3G and 20% at GC6 was not surprising. In Australian studies of ground-based logging the increase in bulk density has been reported to range from 18% (Rab *et al.* 1992 and Lacey *et al.* 1994) through 27% (Incertia *et al.* 1987), 34% and 41% (Pennington *et al.* 1999), to 64% (Rab 1994) and 69% (Lacey *et al.* 1994). Generally the impact of soil compaction on growth is considered to be unfavourable. Greacen and Sands (1980) found that 24 out of 26 of papers reviewed reported a yield reduction in various tree species due to the compaction of forest soils. The mechanism by which compaction affects growth has been the subject of a number of reviews (Lull 1959; Greacen and Sands 1980; Rab 1992; Soane and van Ouwkerk 1994; Kozłowski 1999), but is beyond the scope of this paper.

Current ground-based forestry operations have significant effects on the physical properties of soils. On the major snig tracks the processes of soil compaction, mixing, displacement and puddling may all occur. The implementation of a Forest Practices Code is likely to reduce these impacts by such means as (i) the use of cable-logging equipment on steep slopes or areas with significant erosion hazard, (ii) limiting wet-weather logging, (iii) better coupe planning, (iv) more suitable machinery, and (v) the use of cording on major snig tracks. Even with these improvements the extent of major snig tracks using ground-based machinery is likely to be in the order of 6% of the coupe area (Pennington and Laffan, unpublished data). Cording may reduce the displacement of soil, but unless it is lifted after logging and reduced significantly in size by burning, corded snig tracks may prove to be non-productive.

For the three stands examined, the ease with which major snig tracks were able to be located at intervals of 17–23 y after logging indicated that the rehabilitation of these sites is going to be a long process and may never occur within the first forest rotation. Consideration should be given to McLeod's (1988) recommendation that they should form part of the permanent roading structure. The current study showed clearly that the soil bulk density was still significantly higher than in the control areas, though in terms of soil chemistry the picture was not so clear. The presence of earthworms in some of the samples from snig track zones indicated that biological activity was returning to these areas.

The impact on the ESV was most dramatic on major snig tracks, which were found to carry less than 50% of the ESV measured on the control zones. A number of reports have looked at the short-term (<5 y) effects of compaction on growth. Rab (1998), using data from King *et al.* (1993a,b), calculated a 25% reduction in height growth and 35% reduction in diameter growth in 3-y-old *E. regnans* saplings growing on subsoil-disturbed snig tracks. Senyk and Craigdallie (1997) reported that the height of 3-y-old planted *Picea engelmannii* was 8.9–28.3% below the height of seedlings planted on undisturbed sites. Lockaby and Vidrine (1984) reported that a 14% increase in bulk density on primary snig tracks led to a 39% decrease in height growth of 5-y-old *Pinus taeda* L.

Studies of productivity in later-age forest in relation to soil compaction are few. Murphy *et al.* (1997) reported that a decline in volume growth of an 11-y-old *Pinus radiata* plantation was related closely to the degree of disturbance. They found a 20% decline where the litter had been removed, a 55% decline where the topsoil had been removed and the subsoil compacted by two passes of a loader, and a 65% decline where the subsoil was compacted by eight passes with the loader. Perry (1964) reported a 46% decline in volume of 26-y-old *Pinus taeda* L. growing in old tracks compared to the surrounding site. Wert and Thomas (1981) showed a 74% decrease in the volume of 32-y-old *Pseudotsuga menziesii* (Mirb.) Franco growing on skid roads compared to undisturbed areas. Helms and Hipkin (1986) reported a 55% reduction in volume on skid tracks subject to a bulk density increase of 30% compared to areas of the lowest bulk density. The 80%, 59% and 53% decrease in standing volume seen for the snig track compared to the control zones for WR3G, AR82E and GC6, respectively, are in the same order as in these other studies.

The most surprising result was the increase in ESV associated with the transitional zone at the edge of the snig tracks. There has been little reporting of forest growth in transitional zones. The findings of Helms and Hipkin (1986) and Wert and Thomas (1981) contrast with those of this study. Helms and Hipkin (1986) reported a 13% reduction in volume on areas adjacent to snig tracks. However, these areas had been subject to a bulk density increase of 18% compared to areas of the lowest bulk density. Wert and Thomas (1981) found that the transitional zones (within a 3-m band on both sides of the skid road) carried only 75% of the volume of the undisturbed area though no bulk density or chemical data were reported. This decline was due to a 5% decrease in average diameter, 9% decrease in average height, and an 18% decrease in stand density. Supporting the findings in the current study, Pfister (1969) observed a significant increase in both the height and diameter of trees in the zone immediately below roads in western

white pine plantations. This greater height and diameter led to a 30% increase in the volume within this zone. There was a slight increase in the growth of trees above the road but this was not significant. Earlier studies by Kramer (1958) and Landbeck (1965) also found an increase in the diameter of pure stands of various species adjacent to roads. While Kramer (1958) reported increased height, Landbeck found a decrease in height. Both authors reported a decrease in stand quality. Since all these sites were planted, the impacts of tree density on edge effects would have been minimal. Butt (1987) showed superior height and diameter growth of 25-y-old planted and naturally established *P. menziesii* trees within 3 m of skid tracks led to an increased volume on 9 out of 13 transitional zones examined, though this increase was significant on only two of these nine plots. In these other studies it was improved diameter, and in some cases improved height growth, which led to increased stand volume. Though diameter and height were marginally higher in the current study, the major cause of the increase in ESV in the transitional zones was the increase in stem density. In all the studies cited, unfortunately, planting spacing controlled the stand density.

The mechanism for this improved growth within the transitional zones was not studied. Pfister (1969) attributed the improved growth above the roads to reduced competition for space and below roads to reduced competition and improved water availability, while Megahan (1988) speculated that increased growth along the edges of roads may be due to increased soil moisture. For the southern forest stands (WR3G and AR82E) it is unlikely that water deficit would limit growth, while the nutrient data from WR3G indicates that the control and transitional zones are very similar. Hence, we assume that the increased access to light resulting from the lack of growth on the major snig tracks may be the principal cause of an increase in the number of trees reaching their growth potential in the transitional zones.

Contrary to the suggestion by Williamson (1990) that the proportion of primary (major) snig tracks would be proportional to the loss in productivity in the developing stand, our research indicates that increased productivity in the transitional zone substantially reduces the potential loss. For potential sawlog trees the loss, of the order of 2%, is well below the area of major snig tracks of 8%, and for the whole stand the decrease can be much less. As the stand develops and the required spacing between crop trees increases, the loss of productivity is most likely to continue to decrease.

Conclusions

The results of this study clearly show that tree regeneration and growth on major snig tracks is significantly reduced. Higher soil bulk density and lower nutrient status lead to poorer establishment and early growth of regeneration, and these deficiencies are not overcome in the period to 17–23 y of stand age. Bulk density data indicate that the process of amelioration will be long and slow. Generally, trees developing in the snig track zones are growing on areas of displaced soil, with only an occasional poor-quality pulpwood tree on the compacted areas.

Notably there was a marked increase in volume accumulation in the transitional zones, due in large part to an increase in the density of stems of both potential sawlog trees and pulpwood trees. After

17–23 y of growth, volume accumulation in the transitional zone compensated for much of the production lost due to poor growth on the snig tracks. The overall impact of major snig tracks was calculated to be a loss of stand productivity of 2–3%.

Additional studies are recommended in a variety of forest types to determine whether the pattern apparent on these three forest sites is repeated elsewhere. Also additional investigations are required to determine which factor or combination of factors is the cause of the improved growth within the transitional zones. The authors consider that increased light availability for trees growing on the transitional zone may be the major factor contributing to the higher density and higher biomass within this zone.

While our results indicate that major snig tracks are unlikely to have a significant impact on forest productivity, they do not in any way imply that logging operations and the location and use of snig tracks should be less carefully planned. Poorly planned major snig tracks in a regenerating forest may be a major source of soil erosion, resulting in reduced water quality in adjacent streams.

Acknowledgements

The study reported in this paper was undertaken as part of a collaborative research program between Forestry Tasmania (FT) and CSIRO Forestry and Forest Products (CFFP). The study was supported from major funding provided by the Wood and Paper Industry Strategy as part of the Montreal Process Soil Indicators Project. The Tasmanian Forest Research Council Inc. provided additional funding. The authors acknowledge the cooperation and the professional and technical support of Bill Neilsen, Ann LaSala, Rodney Evans and Sean Blake (FT), and of John Raison and Petr Otahal (CFFP). Chris Beadle, John Raison and Phil Smethurst (CFFP) provided helpful comments on the manuscript.

References

- Bates, P.C., Blinn, C.R. and Alm, A.A. (1993) Harvesting impacts on quaker aspen regeneration in northern Minnesota. *Canadian Journal of Forest Research* **23**, 2403–2414.
- Butt, G. (1987) Effects of skidder compaction on tree productivity. MacMillian Bloedel Limited, Nanaimo, BC. Unpublished report. 62 pp. Abstracted on p.5 of: Lousier, J.D. (ed.) *Impact of Forest Harvesting and Regeneration on Forest Sites*. Land Management Report No. 67, Ministry of Forests and Lands, BC. March 1990.
- Farrish, K.W. (1990) Effects of soil loss on emergence and growth of loblolly pine. *Journal of Soil and Water Conservation* **45**, 415–417.
- Forestry Tasmania (1998) *Thinning Regrowth Eucalypts*. Native Forest Silviculture Technical Bulletin No. 13. Forestry Tasmania, Hobart.
- 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.
- Helms, J.A. and Hipkin, C. (1986) Effects of soil compaction on tree volume in a California ponderosa pine plantation. *Western Journal of Applied Forestry* **1**, 121–124.
- Incertia, F.R., Clinknick, P.F. and Williat, S.T. (1987) Changes in soil physical properties of a forest soil following logging. *Australian Forestry Research* **17**, 91–108.

- Isbell, R.F. (1996) *The Australian Soil Classification*. CSIRO Publishing, Melbourne.
- Jansson, K.J. and Wasterlund, I. (1999) Effect of traffic by lightweight forest machinery on the growth of young *Picea abies* trees. *Scandinavian Journal of Forest Research* **14**, 581–588.
- 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 Internal Report No. 16, Department of Conservation and Natural Resources, Victoria. 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 Internal Report No. 16, Department of Conservation and Natural Resources, Victoria. 24 pp.
- Kozłowski, T.T. (1999) Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research* **14**, 596–619.
- Kramer, V.H. (1958) Wegebrette und Zuwachs im angrenzenden Bestand. (The effect of width of forest roads on increment in adjacent stands). (In German, with English summary.) *Allgemeine Forst und Jagdzeitung* **129**, 121–134.
- Lacey, S.T., Ryan, P.J., Huang, J. and Weiss, D.J. (1994) *Soil Physical Property Change from Forest Harvesting in New South Wales*. Research Division, State Forests of New South Wales, Sydney. 81 pp.
- Landbeck, H. (1965) Wegebrette und Randwirkung bei der Kiefer. (Road width and edge effects in Scotch pine.) (In German, with English summary.) *Archiv für Forstwesen* **14**, 41–59.
- Lockerby, B.G. and Vidrine, C.G. (1984) Effect of logging equipment traffic on soil density and growth and survival of young loblolly pine. *Southern Journal Applied Forestry* **8**, 109–112.
- Lull, H. (1959) *Soil Compaction of Forest and Rangelands*. Forest Service, US Department of Agriculture. 33 pp.
- McLeod, A.J. (1988) A pilot study of soil compaction on skid trails and landings in the Prince George forest region. In: Lousier, J.D. and Still, G.W. (eds) *Degradation of Forest Land: Forest Soils at Risk*. Proceedings, 10th Soil Science Workshop. BC Ministry of Forests and Lands, Victoria, BC, pp. 275–280.
- Megahan, W.F. (1988) Roads and forest site productivity. In: Lousier, J.D. and Still, G.W. (eds) *Degradation of Forest Land: Forest Soils at Risk*. Proceedings, 10th Soil Science Workshop. BC Ministry of Forests and Lands, Victoria, BC, pp. 54–65.
- Murphy, G., Firth, J.G. and Skinner, M.F. (1997) Soil disturbance effects on *Pinus radiata* growth during the first 11 years. *New Zealand Forestry* **47**, 27–30.
- Pinard, M.A., Barker, M.G. and Tay, J. (2000) Soil disturbance and post-logging recovery on bulldozer paths in Sabah, Malaysia. *Forest Ecology and Management* **130**, 213–225.
- Pennington, P.I., Laffan, M., Gibbons, A. and Churchill, C. (1999) Preliminary results and practical sampling problems associated with the use of Montreal indicator 4.1.e in wet *Eucalyptus obliqua* forest in southern Tasmania. Interim Report No. 1. of Project 99.804 to Forest and Wood Products Research and Development Corporation. 29 pp.
- Perry, T.O. (1964) Soil compaction and loblolly pine growth. *US Forest Service Tree Planters' Notes* **67**, 9.
- Pfister, R.D. (1969) Effect of road growth of western white pine plantations in northern Idaho. USDA Forest Service Research Paper Int-65, 8 pp.
- Rab, M.A. (1992) *Impact of Timber Harvesting on Soil Disturbance and Compaction with Reference to Residual Log Harvesting in East Gippsland, Victoria — A Review*. Value Adding and Silvicultural Systems Program, Department of Conservation and Environment, Victoria. VSP Technical Report No. 13, 18 pp.
- Rab, M.A., Anderson, H., Boddington, D. and van Rees, H. (1992) Soil disturbance and compaction. In: Squire, R.O. (ed.) *First Interim Report for the Value Adding Utilisation System Trial 1989–1991*. Department of Conservation and Environment, Victoria, pp. 25–31.
- Rab, M.A. (1994) Change in physical properties of a soil associated with logging *Eucalyptus regnans* forest in southeastern Australia. *Forest Ecology and Management* **70**, 215–229.
- Rab, M.A. (1998) Rehabilitation of snig tracks and landings following logging of *Eucalyptus regnans* forest in the Victorian Central Highlands — a review. *Australian Forestry* **61**, 103–113.
- Rayment, G.E. and Higginson, F.R. (1992) *Australian Laboratory Handbook of Soil and Water Chemical Methods*. Inkata Press, Melbourne.
- Senyk, J. and Craigdallie, D. (1997) *Effects of Harvesting Methods on Soil Properties and Forest Productivity in Interior British Columbia*. Information Report BC-X-365, Pacific Forestry Centre, Victoria, BC. 37 pp.
- Soane, B.D. and van Ouwerkerk, C. (1994) *Soil Compaction in Crop Production*. Developments in Agricultural Engineering Series No. 11. Elsevier, Amsterdam. 662 pp.
- Wert, S. and Thomas, B.R. (1981) Effects of skid roads on diameter, height and volume growth of Douglas-fir. *Soil Science Society of America Journal* **45**, 629–632.
- Williamson, J.R. (1990) *The Effects of Mechanised Forest Harvesting Operations on Soil Properties and Site Productivity*. Research Report No. 5. Tasmanian Forest Research Council, Inc. 193 pp.