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Final report - Part 3.

The impact of soil compaction on the growth of even aged karri (*Eucalyptus diversicolor* F. Muell.) regrowth stands.

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Abstract

We examined the effects of timber harvesting on soil compaction and its effects on tree and stand growth at four sites in the wet sclerophyll karri forests of south-west Western Australia. Log extraction by tracked and tyred machines caused significant increases in soil compaction on snig tracks. Tree growth was measured on snig tracks and adjacent areas. Tree growth on snig tracks was 26% of that on the control plots 10 m away from the snig track. This reduction in growth occurred as significantly reduced diameter and height growth and significantly lower stand density on snig tracks. However, tree and stand growth immediately adjacent to the snig tracks was enhanced. When growth was averaged across the four sites the increased growth on transitional areas compensated for the loss of growth observed on the snig tracks. The increased growth on the transitional areas occurred as increased diameter and height growth, and significantly higher stand density when compared with control areas. The growth response on individual sites differed. It was greatest on those sites with the highest growth rates (11.5 m^3 ha^{-1} yr^{-1}) where the increased growth on transitional areas exceeded that lost from the snig tracks by approximately 3.4 m^3 yr^{-1} for every hectare of snig track. However on sites with lower growth rates (6.7 m^3 ha^{-1} yr^{-1}), there was a net loss of growth of the order of 2.5 m^3 yr^{-1} for every hectare of snig track. On sites with growth rates of the order of 7 to10 m^3 ha^{-1} yr^{-1}, snig track compaction causes a loss in site productivity and care should be taken to minimize the area of snig tracks and the compaction of snig tracks on these sites.

Introduction

In timber harvesting operations the falling and removal of logs from the forest creates a range of soil disturbances: soil displacement, soil mixing and soil compaction (Rab, 1999). Though present throughout harvested areas, these disturbances, and particularly soil compaction, are most intensively focused on the snig tracks used to extract logs from the forest.

Soil compaction has a range of impacts. It affects plant growth by altering soil hydrology, decreasing soil porosity, aeration and infiltration capacity, and by increasing soil strength (Greacen and Sands, 1980; Rab, 1992; Kozlowski, 1999). Soil compaction may also produce changes in plant growth hormones and reduce the absorption of soil nutrients. Water absorption is frequently reduced by soil compaction and this can alter plant water status. With severe compaction, root respiration becomes anaerobic (Kozlowski, 1999). These changes in physical conditions of the soil, and the effects on plant physiological functions, contribute to the reduced photosynthesis and also lower the leaf area of plants growing on compacted soils.

This reduced growth of trees growing on compacted soil has been reported by Wert and Thomas (1981), Rab (1994), Pennington et al. (2001), Dykstra and Curran (2000), and reviewed by Greacen and Sands (1980), Wronski and Murphy (1994) and Kozlowski (1999). Pennington et al. (2001) and Dykstra et al. (2000) also reported increased growth of trees on transitional areas adjacent to compacted snig tracks, with Pennington et al. (2001) demonstrating that the increased growth adjacent to snig tracks compensated for the loss of growth on the snig track. Conversely, several authors have reported a reduction in growth on transitional areas compared to control areas (Helms and Hipkin, 1986; Wert and Thomas, 1987). We examined this proposition in the wet sclerophyll karri forests of the south-west of Western Australia to determine if changed growth occurred adjacent to snig tracks, and the size of any change. We also examined the bulk density of the soil with the aim of identifying the point at which soil compaction caused a reduction in tree growth.

Methods

Site descriptions

The four study sites were located in the karri forests 30 to 55 km south southeast of Manjimup Western Australia. Rainfall ranged from 1150 mm to 1400 mm. Soils and landforms were described by Churchward (1992) as Crowea brown (CRb), a brown gravelly duplex soil on the crests and upper slopes of spurs and ridges; Bevan yellow (BEy), a sandy duplex soil of gently undulating terrain and minor valley floors; and Collis brown (COb), a brown gravelly duplex soil on low hills (Table 1).

Table 1. Locations and descriptive information for four study sites in the karri forests of south west Western Australia used to examine the impact of soil compaction on the growth of even aged karri regrowth stands.

Site	**Site code**	**Rainfall** (mm)	**Soil mapping unit**[a]	**n replicates**	**n plots**	**n trees**	**Stand age** (years)	**Regeneration treatment**
Weld 4	W4	1150	CRb	6	23	293	23	Seeded, Scrub rolled
Sutton 13	S13	1150	CRb	6	24	311	18	Planted, Scrub rolled, Agras no.1 80 g/tree
Poole 7	P7	1200	BEy	8	30	422	20	Hand seeded, Scrub rolled
Boorara 14	B14	1400	COb	6	22	418	23	Seeded, Scrub rolled

a: Soil mapping units are those of Churchward (1992).

Field procedures

The study consisted of 6 to 8 replicates at each of the four sites. Aerial photographs, taken shortly after each site was logged, were used to identify the location of snig tracks which were confirmed on the ground by the presence of wheel ruts. Sets of plots where then laid out along straight sections of snig track. A replicate consisted of either three or five 5 x 20 m plots. Each set included: a single plot on the snig track, one or two transitional plots immediately adjoining the snig track plot on one or both sides, and one or two control plots aligned with the other plots but located 5 m from the edge of the transitional plots. Double-sided plots, with two transitional and two control plots, were used where possible to account for the effects of slope and other small-scale site variation. Disturbance on one side of the track, such as a merging snig track, or large coppicing stumps were the most common reasons for not establishing transitional and control plots on both sides of the snig track.

In each plot all trees and understorey plants with a diameter over bark at 1.3 m (DOB) greater than 5 cm were recorded, tree or understorey species was noted, and height, crown break height, and DOB were measured. Crown depth was calculated as the difference between tree height and height to crown break.

Physical analysis

Bulk density was estimated for surface soils (0-100 mm) at two sites (Sutton 13 and Weld 4) by determining the mean bulk density from cores collected at either 9 or 6 (snig track) and 6 or 4 (transitional and control) locations, systematically located across each plot. Corers had a 66.9 mm inside diameter, a sampling depth of 100 mm, and a total volume of 348 ml. Soils were dried at 105° C for 48 hours, sieved through a 2 mm mesh, and the mass of the fine earth (<2 mm) and coarse fractions (>2 mm) was determined. The volume of the coarse fraction was also determined using a water displacement technique. The bulk density of the fine earth fraction and the bulk density of the undisturbed sample were then calculated.

Volume calculations

The bole volume of each stem with a DOB greater than 5 cm was calculated using the karri volume equation of Rayner (1992)(equation 1).

$$\text{Volume} = \exp(-10.8299+2.1068*\ln(\text{DOB})+0.9443*\ln(\text{height}))$$

The annual tree volume increment m^3yr^{-1} and the mean annual plot volume increment (MAI, $m^3ha^{-1}yr^{-1}$) were calculated from the individual tree volumes and the stand age, and the total plot standing volume and the plot area. As species other than karri were a relatively minor component of these stands (28% of all stems and 7% of stand volume) the use of the karri volume equation for all species was considered acceptable.

Statistical analysis

The experiment was analysed by ANOVA, and treatment and site means were compared using Fisher's least significant difference test. Some individual treatments comparisons were made using single degree of freedom contrasts. To ensure the assumptions underlying ANOVA were met, the residuals were checked for outliers, approximate normality and homoscedasticity. Where large outliers were excluded from the analyses, this is indicated below with the results.

Results

Site differences

The sites had varying distributions of tree species (Table 2) and differed most in their distributions of species other than karri. Weld 4 and Poole 7 were the most similar, with their distributions consisting of similar proportions of karri (approximately 84%), marri, and sheoak (Table 2). At both Weld 4 and Poole 7 the trees other than karri were mainly marri and sheoak. The proportion of karri trees was similar at Boorara 14 and Sutton 13 (approximately 60%). Sutton 13 had a high proportion of marri trees, and Boorara 14 had a high proportion of karri hazel. Two sites, Weld 4 and Sutton 13, were the same landform type (Crb). Rainfall was greatest at Boorara 14 (1400 mm) and lowest at Sutton 13 (1150 mm) with Weld 4 and Poole 7 taking intermediate values. Logs were extracted by rubber tyred machines at all sites except Sutton 13 where a tracked machine was used.

Table 2. The number of stems measured at each site, the stand density, the distribution of plant species at each site and the distribution for all sites combined. Minor species were: Acacia species, Bosseia aquifolium subspecies laidlawiana, Melaleuca species, Persoonia longifolia, and Banksia grandis. As each plot was 0.01 ha, stems per ha = (trees per plot) x 100.

Site	n stems	n stems per plot	Karri %	Marri %	Karri hazel %	Sheoak %	Jarrah %	Minor species %
B14	418	19.0[a]	61.0	0.5	35.2	1.0	0.0	2.4
W4	293	12.2[b]	83.3	8.2	1.4	5.1	0.0	2.0
P7	422	14.1[b]	83.9	5.5	0.0	8.8	0.9	0.9
S13	311	13.0[b]	58.5	37.0	0.0	1.3	1.6	1.6
All sites	1444	14.9	71.7	11.4	10.5	4.2	0.6	1.7

The sites also differed in their ages, tree sizes, stand densities, and tree and stand growth rates (Tables 1 and 3). The regrowth on Boorara 14 and Weld 4 was the oldest at 23 years, Poole 7 was 20 years old and Sutton 13 had the youngest regrowth (18 years) (Table 1). The mean diameter and heights of trees on the three sites varied with Weld 4 having the largest trees, and Poole 7 having the smallest (Table 3). Stand density also varied with Boorara 14 having significantly higher stand density (1900 stems ha^{-1}) than the other three sites, which ranged from 1220 stems ha^{-1} (Weld 4) through to 1410 stems ha^{-1} (Poole 7) (Table 2). The most meaningful comparison of the tree growth on these sites is provided by the MAI's as these integrate the combined effects of tree growth, stand density and stand age. The volume increments for plots at Boorara 14 and Weld 4 were approximately twice those of Sutton 13 and Poole 7. These calculated MAI's for each site included all treatments and were reduced by the low MAI of snig track plots.

Table 3. The mean number of trees per plot, and the mean dimensions and growth rates for individual trees and plots across all treatments at four sites in the karri forest. MAI = mean annual volume increment. Means followed by different letters were significantly different (LSD test, $\alpha = 0.05$). One outlier plot was excluded from calculations for Weld 4.

Site	**n plots**	**n trees per plot**	**Site MAI** ($m^3 ha^{-1} yr^{-1}$)	**Mean tree volume** (m^3)	**Tree MAI** ($m^3 tree^{-1} yr^{-1}$)	**Mean DOB** (cm)	**DOB ann. inc.** ($cm\ yr^{-1}$)	**Mean Tree height** (m)	**Tree height ann. inc.** ($m\ yr^{-1}$)
B14	22	19.0^a	11.21^a	0.137^{ab}	0.0060^{ab}	12.48^b	0.54^c	14.84^a	0.64^a
W4	23	12.2^b	9.88^a	0.180^a	0.0078^a	15.77^a	0.69^b	16.64^a	0.72^a
P7	30	14.1^b	5.56^b	0.080^c	0.0040^b	12.70^b	0.64^b	12.79^b	0.64^a
S13	24	13.0^b	5.73^b	0.095^{bc}	0.0053^b	14.54^a	0.81^a	12.90^b	0.72^a

Treatment differences

Table 4 shows the stand density and the distributions of trees and shrubs on snig track, transitional and control plots. The distributions are presented in three structural classes: overstorey trees, understorey trees, and large understory shrubs (DOB > 5 cm). Snig track plots had less than half the stand density of control and transitional plots, which had similar stand densities.

Table 4. The distribution of overstorey trees (karri, marri, jarrah), understorey trees (banksia, sheoak and persoonia), and understorey shrubs (DOB > 5 cm), on snig tracks, transitional and control plots across four sites in the karri forest.

Treatment	**n trees**	**n plots**	**Stand density** ($stems\ ha^{-1}$)	**Overstorey trees** %	**Understorey trees** %	**Understory shrubs** %
Snig track	177	25	708^c	67.4	12.0	20.7
Transitional	676	37	1827^a	85.7	3.8	10.5
Control	584	37	1578^b	86.5	3.1	10.4

Trees on snig tracks were significantly shorter, had less crown depth, and had significantly smaller diameters than trees on either transitional or control plots (Table 5.). Similarly the annual diameter and height increments of trees on snig track plots were significantly smaller than on transitional and control plots and this lead to a significantly lower annual growth rate of trees on snig tracks. There were also far fewer trees on snig tracks (71 stems ha^{-1}) than on transitional (183 stems ha^{-1}) and control areas (158 stems ha^{-1}). This lower stand density compounded the reduced growth found for individual trees, leading to a greatly reduced mean annual stand increment on snig tracks (2.4 m^3 ha^{-1} yr^{-1}). This mean annual increment of snig track plots was only 20% of that of transitional plots and 26% of that of control plots.

In contrast, trees on transitional plots had the largest diameters and heights, and the highest growth rates of trees on all of the treatments, although these differences between transitional and control plots were not statistically significant. The mean depth of tree crowns on transitional areas was the same as that on control areas (Table 5). However, transitional plots did have significantly more trees than control plots and this resulted in transitional plots having a significantly higher mean annual stand increment (12.36 m^3 ha^{-1} yr^{-1}) than control (8.98 m^3 ha^{-1} yr^{-1}) or snig track plots (2.36 m^3 ha^{-1} yr^{-1})(Table 5). The mean annual increment of transitional plots was 38% larger than that of control plots and 80% greater than that of snig track plots.

Table 5. The mean number of trees per plot, dimensions and growth rates for individual trees and plots across all treatments. Means followed by different letters were significantly different (LSD test, $\alpha = 0.05$).

Treatment	**n trees**	**n plots**	**trees per plot**	**MAI per tree** (m^3 yr^{-1})	**MAI per ha** ($m^3 ha^{-1} yr^{-1}$)	**DOB** (cm)	**DOB ann. inc.** (cm yr^{-1})	**Height** (m)	**Height ann. inc.** (m yr^{-1})	**Crown depth** (m)
Snig track	177	25	7.1^c	0.00297^b	2.36^c	11.05^b	0.541^b	12.14^b	0.588^b	3.69^b
Transitional	676	37	18.3^b	0.00701^a	12.36^a	15.12^a	0.729^a	14.96^a	0.715^a	4.22^a
Control	584	37	15.8^a	0.00605^a	8.98^b	14.31^a	0.691^a	14.74^a	0.705^a	4.22^a

Site treatment interactions and differences

Figure 1 shows the mean annual volume increment for each of the three treatments. The greatest differences between treatments existed on the sites with the highest annual volume increments, ie. Boorara 14 and Weld 4. On these sites the annual increment on snig tracks was approximately 2 m^3 ha^{-1} yr^{-1}, on control areas approximately 12 m^3 ha^{-1} yr^{-1}, and on transitional areas approximately 18 m^3 ha^{-1} yr^{-1}. On these sites growth on snig tracks was only 17% of that on control areas, whereas growth on transitional areas was 55% higher than growth on the control areas. Although the annual volume increment of snig tracks on Poole 7 and Sutton 13 was similar to that on Boorara 14 and Weld 4, the differences between the three treatments on the former sites was smaller. On Poole 7 and Sutton 13 there was little difference between the growth on control plots (approximately 7 $m^3 ha^{-1} yr^{-1}$) and on transitional plots (approximately 8 $m^3 ha^{-1} yr^{-1}$), and growth on these treatments was much lower than on Boorara 14 and Weld 4. This was most notable with the transitional areas which had MAI's of approximately 8 $m^3 ha^{-1} yr^{-1}$ on Poole 7 and Sutton 13 compared with approximately 18 $m^3 ha^{-1} yr^{-1}$ on Boorara 14 and Weld 4.

Bulk density

There was no significant difference between the total bulk density of transitional and control areas, or between the fine earth bulk density of transitional and control areas (Table 6). However, both the fine earth and total bulk density of snig tracks were significantly higher than that of transitional and control areas. This is the case for individual sites and for both sites combined (fig. 2). The bulk density on the control and transitional plots at Sutton 13 was 38% higher than on the control and transitional plots at Weld 4.

Table 6. Mean surface soil bulk density ± standard error for each of three treatments across two sites in the karri forest.

Treatment	**n**	**Total bulk density** ($g\ cm^{-3}$)	**Fine earth bulk density** ($g\ cm^{-3}$)	**Gravel %**
Snig track	87	0.966 ± 0.1035	0.850 ± 0.0260	18.1 ± 1.94
Transitional	86	0.747 ± 0.0805	0.638 ± 0.0194	20.2 ± 2.18
Control	86	0.745 ± 0.0804	0.631 ± 0.0201	21.0 ± 2.27

Discussion

Site differences

The four sites were very different. These differences included landform and rainfall differences which are reflected in the differing stand annual increments and stand structures of the four sites. The factor most relevant to this discussion is the similarities in growth rates. The four sites can be divided into two groups: Boorara 14 and Weld 4 which have MAI's of approximately 11.5 $m^3 ha^{-1} yr^{-1}$ and Poole 7 and Sutton 13 which have lower MAI's of approximately 6.7 $m^3 ha^{-1} yr^{-1}$.

Bulk Density

Bulk density was only measured on two of the four sites. At Weld 4, fine earth bulk density on snig tracks was 28% above that of control areas, while at Sutton 13 this increase was 38%. These increases in bulk density were associated with reductions in MAI on snig tracks to 16% of that on control areas at Weld 4 and to 54% of that on control areas at Sutton 13. The bulk density increase was greatest at Sutton 13 yet this was the site with the smallest reduction in growth. These sites had similar soils and landform (Crb). Helms and Hipkin (1986) reported a 55% reduction in volume on skid tracks associated with a 30% increase in bulk density in ponderosa pine plantation. Many factors affect tree growth. Soil nutrient status, rainfall and evaporative demand, are primary determinants of site productivity. The impact of an increase in bulk density on the related soil properties that directly affect growth will vary with soil structure, and the differing bulk densities of the control plots at these two sites (fig. 2) implies differences in soil structure at the two sites. Consequently variations in bulk density are more likely to explain growth differences within a site rather than differences between sites. Soil disturbance and compaction on snig tracks will vary widely depending on the type of machinery used on the sites, the weather, the soil type and the number of passes across the measurement point. Consequently it is not surprising that the relative size of the bulk density increase on snig tracks at these two sites is not consistent with the size of the growth reduction. For these reasons and because of the cost of collecting bulk density measurements, bulk density was not measured on all sites.

Snig tracks

There were clear differences in stand structure between snig tracks, and transitional and control areas (Table 4). Structurally, transitional and control areas are very similar, but snig tracks had a lower percentage of overstorey trees, and higher percentages of understorey trees and understoreys shrubs. Combined with the low stand density of snig tracks (Table 5), these structural differences indicated a high level of disturbance on the snig tracks we studied.

Stand tree growth was suppressed substantially on snig tracks, being only 26% of the growth observed on control plots. Although the size of this growth suppression varied between sites, from a minimum of 54% to a maximum of 16%, the trend was observed consistently across a range of sites. Growth suppression on snig tracks was largest on the sites with the fastest growth rates, with growth rates on the compacted snig tracks being relatively constant across all the sites at 2.4 m^3 ha^{-1} yr^{-1}, and growth rates on control plots ranging from 6.4 to 12.2 m^3

ha^{-1} yr^{-1}. This may indicate that soil compaction and disturbance associated with snig tracks places a limit on growth rates regardless of the site quality.

Growth suppression on snig tracks has three elements: a significant reduction in annual diameter increment, a large but not statistically significant reduction in annual height increment, and a significant reduction in the stand density. The combined impact of these three elements produces a large and significant reduction in annual stand increment on snig tracks. Given the substantial disturbance and compaction evident from the measured bulk densities and the visible disturbance, this reduced growth on snig tracks would be expected. The growth suppression on snig tracks is substantial.

Transitional areas

What is of interest is the reported increased tree growth that occurs alongside snig tracks (Pennington et al., 2001; Dykstra et al., 2000). We observed substantially increased stand growth on transitional areas at all of the four karri forest sites studied. The increase in growth on transitional areas when compared to control areas was large (38%) and highly significant across all sites (ANOVA, contrast: control vs snig track, $p = 0.0001$). Within individual sites, the size of this increase in growth on transitional areas varied from a 58% increase at Weld 4 and a 53% increase at Boorara 14, down to approximately a 13% increase on Sutton 13 and Poole 7.

This growth response on transitional areas may be attributable to a reduction in competition from the adjacent snig track. Snig tracks have a greatly reduced stand density, and like stands that are thinned (Stoneman et al., 1997), the growth lost from the snig tracks is transferred onto the surrounding trees on the adjacent transitional areas. We attribute the increased growth on transitional areas to a reduction in competition due to the reduced tree numbers and reduced MAI on the adjacent snig tracks.

Many factors affect tree growth. Soil disturbance on snig tracks consists of soil mixing, compaction, and soil movement (Rab, 1999). The compaction reflected in measurements of bulk density impacts several soil attributes that affect tree growth. Increased bulk density is almost certainly responsible for the reduction of growth seen on snig tracks (though other soil disturbance will also be relevant). However the increased growth on transitional areas cannot be related to the very slightly elevated bulk densities observed on transitional areas. There appears to be no other beneficial improvement that could be occurring in soils adjacent to snig tracks. Consequently we attribute the increased growth observed on transitional areas to the reduction in stand density that occurs on snig tracks.

The observed response raises the question; does the increased growth on the transitional areas compensate for the loss of growth on the snig tracks? In this study the transitional area was taken as being 5 m wide, the same width as the snig track. (The increased growth that we observed may extend beyond 5 m but for the following estimates we assume it does not). The MAI values in Table 5 show that there is a loss of growth on the snig tracks of 6.6 m^3 ha^{-1} yr^{-1} when compared with the control plots. However there is also increased growth of 3.4 m^3 ha^{-1} yr^{-1} on the transitional areas when compared with the control plots. As the transitional areas occur on both sides of the snig tracks, the total increase in growth adjacent to snig tracks is 6.8 m^3 yr^{-1} for each hectare of snig track. This increase was slightly larger than the loss that occurred on snig tracks. Across these sites the loss of growth on snig tracks was compensated by increased growth on the transitional areas. The result for these sites is a calculated net increase in growth of 0.14 m^3 ha^{-1} yr^{-1} for every hectare of snig track, but given the precision of our estimates it is likely that this increase is not significantly different from zero.

It should be noted that this is a generalized result for these four sites. From Figure 2 this effect varies across sites. It is greatest at Boorara 14 and Weld 4 where net increases in growth of 3.6 m^3 yr^{-1} (Boorara 14) and 3.3 m^3 yr^{-1} (Weld 4) occurred on the transitional areas for every hectare of snig track. However on Sutton 13 and Poole 7 the increased growth on transitional areas was insufficient to compensate for the loss of growth on snig tracks and a net **loss** of 1.3 m^3 yr^{-1} (Sutton 13) and 3.7 m^3 yr^{-1} (Poole 7) occurred for every hectare of snig track on these sites.

These calculations are simple and incorporate several assumptions. They ignore two effects that alter this simple sum: the effect of snig track intersections, which are numerous and increase the area of snig track relative to the areas of transitional, and the effect of changes in snig track compaction with snig track order (Rab, 1994; Wronski, 1984; Williamson, 1990) which may alter the compensating growth effect.

Snig track branching will increase the proportion of snig track area relative to that of transitional areas. This is essentially a widening of the snig track at the intersection point. If the zone of influence of the snig track does not increase with this snig track widening, then the calculations above will be altered. I took this effect as minor, and assumed a 2:1 ratio of transitional area to snig track area. Pennington et al. (2001) estimated that transitional areas were 1.75 times that of snig track areas (ie. a 1.75:1 ratio). Following this approach would reduce the total compensating growth on transitonal areas to 87.5% of the values I have used. This seems excessive for the karri sites I studied. Both approaches are estimates of the relative areas and the correct figure for karri would lie between these two extremes. Snig track intersections may reduce the compensating effect of transitional areas.

Changes in snig track compaction occur when snig tracks branch out as they proceed away from landings. The snig track order increases, and the number of machine passes over the soil surface, and the soil compaction, decrease (Table 7). Rab (1994) identified a linear relationship between seedling growth suppression and bulk density. Growth suppression on snig tracks is logically related to snig track order, with less growth suppression expected on the higher order and less compacted snig tracks. We were unable to identify this relationship in our data. Snig track order was not a significant variable in explaining variations in growth across the four sites, possibly because of the biased sampling of high order snig tracks (Table 8). Snig track order was not controlled in the design of this experiment and the sampling intensity of first and second order snig tracks was twice that of third order snig tracks (Table 8). This occurred because highly disturbed snig tracks were far easier to locate than lightly disturbed snig tracks in this retrospective study. Because of this bias, the snig track data presented here is representative of the higher levels of disturbance found on lower order snig tracks. Although unable to identify this relationship we expect that as compaction diminishes in higher order snig tracks, the loss of growth on these snig tracks will reduce, and the compensating growth on transitional areas that we liken to a thinning response, will similarly diminish. Consequently the size of the effect will change, but this effect will also be present on higher order snig tracks.

These calculations also do not consider whether any increased growth benefits particular components of the stand structure, ie. whether growth is lost from one component of the snig track stand structure, and is compensated for in a different component of the transitional area stand structure. Understorey species make up 0.16 m^3 ha^{-1} yr^{-1} of the growth of transitional areas, 0.13 m^3 ha^{-1} yr^{-1} of the growth on control areas and 0.11 m^3 ha^{-1} yr^{-1} of the growth on snig tracks reported in Table 5. Calculations of stand growth using only trees produce MAI values that have the same relative differences as those for all species (Table 5) and demonstrate a similar compensating effect. Any movement of growth within the stand structure is too small to detect in this data.

These calculations also do not consider if the increased growth has occurred in the tree bole or in the crown. Table 5 shows that there was no difference in crown depth between control and transitional areas. Consequently the increased growth on transitional areas was not at the expense of timber volume production (ie. log length). We conclude that these effects are relatively minor and though they will alter the actual values calculated slightly, they will not change the general trends reported.

This work examined four stands with a mean age of 21 years, the results are averaged over this period and it is not known whether the observed effect continues or changes over time.

Table 7. The mean bulk density of snig tracks at two sites in the karri forest.

Site	**Snig track order**	**n plots**	**Total bulk density ($g\ cm^{-3}$)**	**Fine earth bulk density ($g\ cm^{-3}$)**
W4	1	1	0.958	0.802
W4	2	3	0.847	0.695
W4	3	2	0.646	0.535
S13	1	3	1.097	0.998
S13	2	2	1.132	1.042
S13	3	1	0.877	0.741

Table 8. The distribution of snig tracks orders sampled at each site.

Site	**Order 1**	**Order 2**	**Order 3**
S13	3	2	1
W4	1	3	2
P7	3	3	2
B14	3	3	0
Total	10	11	5

Montreal Indicator 4.1e

For the purposes of the development of Montreal Indicator 4.1e it would be useful to define what constituted a significant increase in bulk density. We were unable to identify any relationship between the degree of compaction on snig tracks and the degree of growth suppression observed on snig tracks. We observed substantial reductions in growth associated with 28% and 38% increases in bulk density, however compensating increase in growth occurred adjacent to the snig tracks on the site with the 28% increase in bulk density but not on the site with 38% increase in bulk density. We suggest that the size of the compensatory growth adjacent to snig tracks is related to the overall site productivity.

Consequently what constituted a significant increase in bulk density will vary between sites. Setting a limit for the size of the increase in bulk density is probably most relevant for low productivity sites, which experience a loss of net growth due to snig track compaction.

Conclusion

Compaction on major snig tracks during harvesting of mature karri stands causes severe localized growth suppression of karri regrowth. On the four sites we studied, growth on snig tracks was only 26% of growth on control plots, and ranged from 16% to 54% across the four sites. Snig track growth suppression occurs as reductions in tree height growth, diameter growth, and stand density. Stand growth adjacent to snig tracks is enhanced, with transition areas having greater height and diameter growth than control areas, and significantly higher stand density than control areas. Averaged across the four sites we studied, this increase in growth adjacent to the snig tracks compensated for the loss of growth that occurred on the snig tracks. This response varied between sites and was greatest on the two sites with the largest growth rates (11.5 m^3 ha^{-1} yr^{-1}). On these sites the increase in growth adjacent to snig tracks exceeded the loss of growth on the snig track. However on sites with lower growth rates (6.7 m^3 ha^{-1} yr^{-1}) there was a net loss in stand growth due to growth reduction on snig tracks. On sites with growth rates of this order (7 to 10 m^3 ha^{-1} yr^{-1}), snig track compaction causes a loss in site productivity and particular care should be taken to minimize the area of snig tracks.

We were unable to identify any relationship between the degree of compaction on snig tracks and the degree of growth suppression observed on snig tracks.

Acknowledgments

This project was jointly funded by the Forest and Wood Products Research and Development Corporation under the Wood and Paper Industry Strategy, and by the Western Australian Department of Conservation and Land Management. D. Blechynden of the Department of Conservation and Land Managements Forest Management Branch assisted with site selection. Pam Laird willingly undertook demanding laboratory work. M. Rayner, L. McCaw, and J. McGrath provided advice and support that assisted with the establishment and completion of this project and L. McCaw, and J. McGrath provided comments that improved the presentation of this work.

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Figure 1. The mean annual volume increment for each of three treatments across the four sites in the karri forests. The treatments were snig tracks, transitional areas adjacent to snig tracks, and control plots 10 m distant from the snig tracks. Sites were Boorara 14 (B14), Weld 4 (W4), Poole 7 (P7) and Sutton 13 (S13).

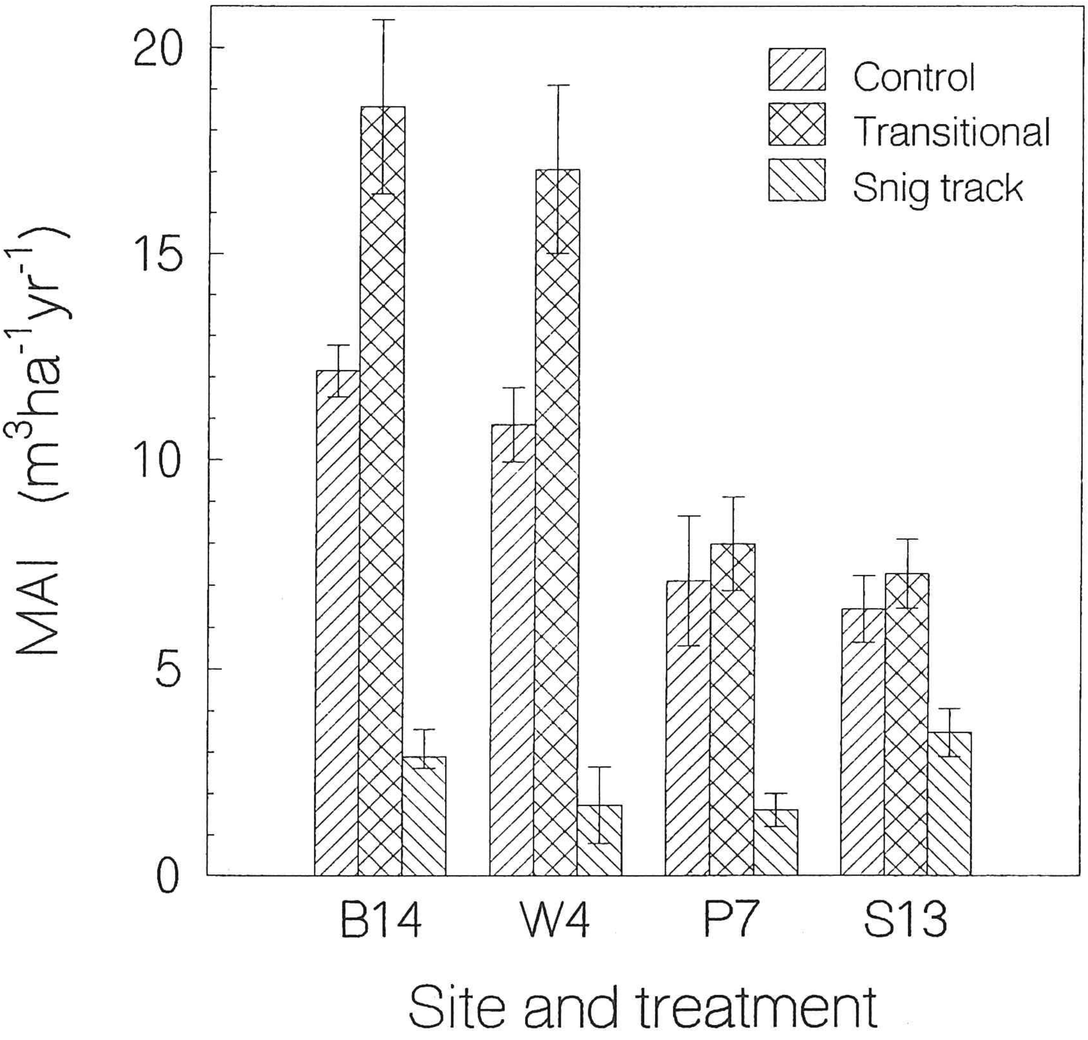
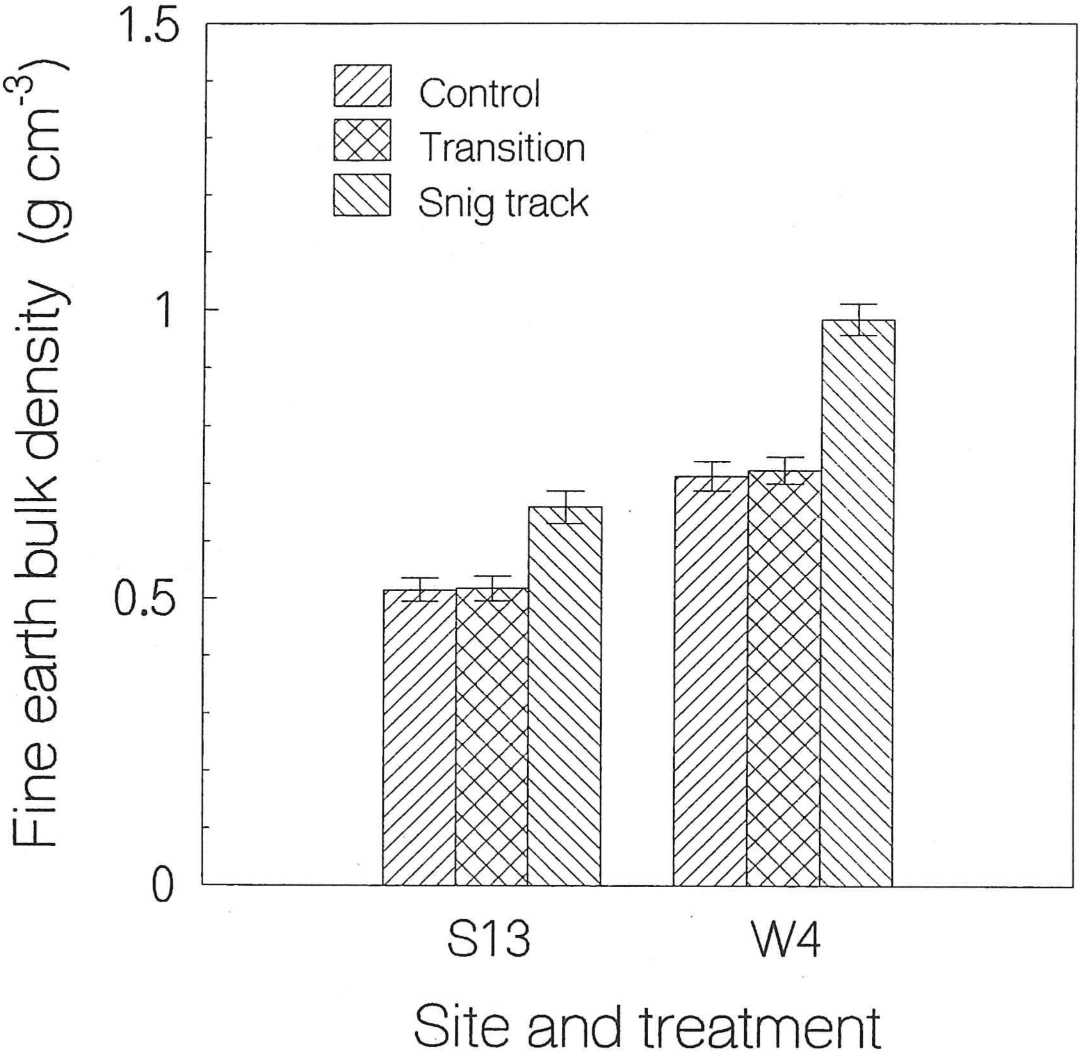


Figure 2. The mean fine earth bulk density of control, transitional, and snig track plots on two sites in the karri forests.



FOREST & WOOD PRODUCTS
Research & Development Corporation

DEPARTMENT OF
Conservation
AND LAND MANAGEMENT
Conserving the nature of WA

Evaluation of key soil indicators of sustainability in Australian Mediterranean forests (Indicators 4.1d, 4.1e)

K.R. Whitford

Final Report

PROJECT NUMBER: PN99.802

September 2001

Project PN 99.802 - Evaluation of key soil indicators of sustainability in Australian mediterranean forests (Indicators 4.1d, 4.1e)

CONTENTS

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SUMMARY

This project consisted of three separate studies. Part 1 examined the impact of fire frequency on soil carbon and nitrogen and soil bulk density in the jarrah and karri forests of south-west Western Australia. Part 2 examined the utility of survey techniques of the draft protocol for Montreal Indicator 4.1e at three sites in the jarrah forests, and Part 3 examined the effects of compaction caused by timber harvesting, on tree growth in the karri forests.

Part 1

The impact of fire frequency on soil organic carbon and nitrogen and bulk density was examined on five sites in the high intermediate and low rainfall zones of the jarrah and karri forests. The carbon content of the soils on these sites ranged from 2% to 9%. The greatest response of carbon and nitrogen to the fire treatments was observed in the surface soils. Two effects of fire frequency were consistently observed on these sites. Regular burning increased the fine earth bulk density, and reduced the concentration of carbon and nitrogen in the soil. Within a site the total mass of carbon and nitrogen in the surface soil layer was unaffected by fire frequency, however changes in the bulk density of the soil altered the concentration of carbon and nitrogen in this layer. Soil carbon concentrations were highly correlated with fine earth bulk density across all sites ($r = -0.96$). This correlation between soil carbon concentration and bulk density indicates that these changes with fire treatment are expressions of changes to soil processes that closely relate to these two soil attributes. Several processes that are likely to alter both the carbon concentration, and the structure and density of the soil are potentially involved.

When comparing the five sites there were gross differences in soil carbon between the sites that presumably relate to differences in site fertility and productivity. Within a site small variations in the mass of carbon in the soil were related to fire frequency. However this may be masked somewhat by the presence of greater amounts of charcoal in the regularly burnt plots. The charcoal content of the soils on these fire treatment study sites needs to be determined to further clarify the effect of fire frequency on soil carbon.

There were also gross differences in the mass of litterfall between the sites. Within a site litter mass decreased with fire frequency and the carbon content of the litter was constant across fire treatments. The mass of carbon stored in the litter on each treatment was driven by the mass of litter on the site. However within a site the nitrogen concentration of the litter

decreased with increasing fire frequency and the mass of nitrogen in the leaf litter was generally lower on regularly burnt treatments.

The importance and impact of these changes observed with fire frequency must be considered with knowledge of the long term natural frequency of fire in these ecosystems, and interpretations and ecosystem management decisions made against this background. Fire is one of many agents that may impact on nutrient status and fire frequency is only one aspect of fire regime. Fire season and fire intensity are the other components of the fire environment that must be considered.

Part 2

Survey techniques proposed in the draft protocol for Montreal Indicator 4.1e (Rab, 1999) were used to compare the extent and intensity of disturbance on three faller's blocks in the northern jarrah forest of south-west WA. This process was used to examine the relationship between visually assessed soil disturbance, bulk density, and soil strength, and to investigate a variety of displacement and coring techniques for measuring bulk density in gravelly forest soils.

Displacement techniques for measuring bulk density were slow, cumbersome and inappropriate for the type of extensive survey proposed for Montreal Indicator 4.1e. Variability caused by practical aspects of these techniques in these gravelly forest soils introduced errors equivalent to those found in coring techniques. Estimates of fine earth bulk density, of total bulk density, and of gravel content were made with three different corer sizes. No significant difference existed between estimates from the three corers. The efficiencies of using the smallest corer (internal diameter = 66.9 mm) indicated this as the best method of measuring bulk density in these highly gravelly soils (36%-70% gravel). Fine earth bulk density was a more informative measure than total bulk density and provided a more meaningful basis for interpreting the Indicator in these soils. Bulk density measurements were expensive and time consuming to collect.

A modified version of the visual disturbance classification system of the draft protocol (Rab, 1999) yielded meaningful assessments of changes to soil physical properties and has the potential to contribute to the cost effective implementation of Montreal Indicator 4.1.e in studies where assessment is conducted a short time after logging. Within the jarrah forest, approximately 30% of the total area of logging coupes showed some visual sign of soil disturbance. However only 12 - 14% of the area was covered by snig tracks and relatively small areas of these logging coupes (12%-16%) exceeding the 20% increase in bulk density proposed by Rab (1999) as a threshold for Montreal Indicator 4.1e.

Soil shear strength measurements produced meaningful assessments of soil disturbance on the site with 36% gravel content, despite the high gravel content of the soil. These measurements were relative cheap to collect. On the sites with 65% and 70% gravel content, soil strength measurements were not related to the visual assessments of soil disturbance, and are unlikely to provide useful information on these high gravel content sites.

I found large differences in estimates of snig track area occurred between transect-intercept-quadrat, line intercept, and traverse techniques. The source of this variability is unclear. The use of grid point intervals that are larger than the snig track width, parallelism between snig tracks and survey transects, and errors in classifying short sections of snig track are likely sources of these large errors. Photo-interpretation was unsuccessful as a method of determining snig track area and GPS ground traverse was the most efficient and accurate means of estimating snig track area. Snig tracks are the major disturbance on jarrah logging coupes and planning and managing the layout of snig tracks could significantly reduce the area of disturbance within the coupe.

Although bulk density is a valuable and objective measure of soil disturbance, the expense of collecting these measurements makes them inappropriate for frequent operational surveys. The soil disturbance survey technique of the draft protocol produced meaningful visual classifications of soil disturbance, and is a useful tool in the progression of Montreal indicator 4.1e. Visually assessed disturbance classes may be valid surrogates for assessing changes to soil physical properties, as these visual assessments can be related to measurable changes in soil physical properties. However visual soil disturbance assessments need to be made a short time after logging and are unsuited to retrospective studies or studies that assess the amelioration of disturbance over time.

Part 3

We examined the effects soil compaction produced in the harvesting of mature karri stands on tree and stand growth at four sites in the south-west Western Australia. Log extraction by tracked and tyred machines caused significant increases in soil compaction on major snig tracks and this caused severe localized growth suppression of karri regrowth. Tree growth was measured on snig tracks and adjacent areas.

Tree growth on snig tracks was 26% of that on the control plots 10 m away from the snig track, and across the four sites ranged from 16% to 54% of growth on control plots. This reduction in growth occurred as significantly reduced diameter and height growth and significantly lower stand density on snig tracks. The growth suppression on snig tracks is substantial. However, tree and stand growth immediately adjacent to the snig tracks was enhanced, with these transition areas having greater diameter and height growth than control areas, and significantly higher stand density than control areas. Averaged across the four sites we studied this increase in growth adjacent to the snig tracks compensated for the loss of growth that occurred on the snig tracks. This growth response varied between sites and was greatest on the two sites with the highest growth rates (11.5 m^3 ha^{-1} yr^{-1}) where the increased growth on transitional areas exceeded that lost from the snig tracks by approximately 3.4 m^3 yr^{-1} for every hectare of snig track. However on sites with lower growth rates (6.7 m^3 ha^{-1} yr^{-1}) there was a net loss in stand growth, of the order of 2.5 m^3 yr^{-1} for every hectare of snig track, due to growth reduction on the snig tracks. On sites with growth rates of this order (7 to 10 m^3 ha^{-1} yr^{-1}), snig track compaction caused a loss in site productivity and particular care should be taken to minimize the area of snig tracks and the compaction of snig tracks.

We were unable to identify any relationship between the degree of compaction on snig tracks and the degree of growth suppression observed on snig tracks.