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

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Final Report

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

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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.

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

Final report - Part 1.

The effect of fire frequency on soil organic matter and bulk density in jarrah and karri forest.

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Abstract

I examined the impact of fire frequency on soil organic carbon and nitrogen, and bulk density using a retrospective study of five sites in the high, intermediate, and low rainfall zones of the jarrah and karri forests. The soil carbon content ranged from 2% to 9% at these sites. The greatest response of carbon and nitrogen was observed in the surface soils. Across all sites, regular burning reduced the concentration of carbon and nitrogen in the surface soils and increased the bulk density. Within a site the total mass of carbon and nitrogen in the surface soil layer was unaffected by fire frequency, however changes in 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 implies that fire alters the biological processes in the soil, and at the soil/litter interface. These changes increased the bulk density of the soil and reduced the carbon and nitrogen concentration on regularly burnt sites.

Within a site the carbon content of the litter was constant across fire treatments, but litter mass and nitrogen concentration decreased with increased fire frequency. The mass of

carbon stored in the litter on each treatment was driven by the mass of litter on the site. Within a site the litter nitrogen concentration and the mass of nitrogen in the leaf litter were generally lower on regularly burnt treatments.

Introduction

As a member of the Montreal Process Working Group Australia has agreed to seven criteria of sustainable forest management, these having the objectives of maintaining biological diversity, productive capacity, ecosystem health and vitality, soil and water resources, global carbon cycles, socio-economic benefits and providing an effective legal, institutional and economic framework. The Working Group is committed to reporting how the proposed Montreal Criteria and their associated Indicators can be applied in Australian forests, and to support this work, Australia is undertaking a number of research and development projects that aim to deliver practical, cost-effective and sensitive indicators.

Maintenance of soil structure, nutrient supply and soil biology underpin forest health and vitality. Soil organic matter is a central contributor to soil quality as it mediates many of the chemical, physical, and biological processes controlling soil performance and the sustainability of its use. Montreal Indicator 4.1d, and the related interim indicator, provide a basis for reporting on the sustainability of forest soil use (Anon., 1997).

Indicator 4.1d :

4.1.d Area and percent of forest land with significantly diminished soil organic matter and/or changes in other soil properties.
Interim Indicator – The total quantity of organic carbon in the forest floor (< 25 mm diameter components) and the surface 30 cm of soil.

Indicator 4.1d is classed as a category C indicator; ie. requiring longer-term research and development, in contrast to category A indicators which can be measured immediately for most forests. To progress the Montreal process in Australia, the Forest and Wood Products Research and Development Corporation (FWPRDC) has provided funding under the Wood and Paper Industry Strategy (WAPIS) to set up a national Soil Indicators project group to research and develop indicators 4.1d and 4.1e. The research reported here is part of Western Australia's contribution to the national Soil Indicators project and conforms with the measurement protocols of the national project (Rab 1998). This research investigates the use of soil organic matter as an indicator of ecologically sustainable forest management in Western Australian jarrah (*Eucalyptus marginata*) and karri (*E. diversicolor*) forests. As fire is a regularly applied management tool in these forests, the focus of this work has been on the effect of fire on soil organic matter.

A large number of studies have examined the effects of forest fires on the ecology of eucalypt forests (Nicholls, 1972; Abbott et al., 1984; Inions, 1985; Perry et al., 1985; Burrows, 1987; Abbott and Van Heurck, 1988; Lindenmayer et al., 1990; Wardell-Johnson and Nichols, 1991; Attiwill, 1994; Burrows et al., 1995; Burrows and Friend, 1998; McCarthy et al., 1999; Jurskis, 2000) with several examining the effects of fire on litter and soils (Hatch, 1959; Hatch, 1960; O'Connell et al., 1979; O'Connell et al., 1981; Abbott et al., 1984; Raison, 1985; Guinto et al., 1998; Guinto et al., 1999). In the jarrah forest Hatch (1959) found no significant difference in surface soil properties between annual and triennially burnt fire breaks compared to adjacent compartments unburnt for 15 to 25 years. However, Abbott et al. (1984) compared adjacent stands, one unburnt for 45 years, the other regularly burnt, and found most soil nutrients (including organic carbon) had higher values in the burnt stand. Soil properties vary naturally across the landscape, and it is important in paired plot studies to be able to separate out treatment effects from the natural variation. Guinto et al. (1998) compared effects of fire frequency on dry and wet sclerophyll sites in south-east Queensland using clay content as a covariate, and found that differences in organic carbon content were significant on the wet site but were not significant on the dry site. Hingston et al. (1980a, 1980b, 1989), and O'Connell (1986) have conducted extensive research into nutrient distribution, cycling, and the effects of fire. Hingston et al. (1989) in reviewing studies of fire effects on nutrients in the jarrah forests concluded that although burning affects nutrient cycling, any changes in nutrient levels attributable to fire regime would be difficult to detect due to the large background variation, and cited the long term growth studies of Abbott and Loneragan (1983) which showed no significant growth reduction in forests regularly burnt over periods of 30 to 50 years.

This research project further examines the impact of fire on organic carbon and attempts to clarify the effect of fire on organic carbon in the forests of south-western Australia.

Methods

Sites

The single karri forest site at Strickland and two jarrah forests sites at McCorkhill and Yackelup were established to examine fire behaviour and the impacts of fire regimes on forest flora (Table 1). Treatments at these sites had been randomly assigned to small forest plots. Additional jarrah forest sites at Amphion and Chandler were subsequently added to the study to increase statistical power and to determine if the responses observed across the first three sites were statistically significant. These additional sites consisted of regularly burnt and long unburnt areas, separated by a track. The fire treatments had not been randomly assigned to these study plots but were an outcome of historical burning practices.

The nine plots studied on the Strickland site (karri) consisted of three replicates of three treatments with replicates located at positions high, intermediate, and low in the topography. At McCorkhill I studied two replicates of three treatments, with two subplots located on sand and gravelly sand areas in each treatment. The 12 plots at Yackelup consisted of four replicates of three treatments, and at Amphion and Chandler I studied three replicates of two treatments (Table 2). At Amphion and Chandler replicate pairs were located on opposite sides of the track that separated the treatments, and pairs were dispersed across the topography.

Table 1. Locations and descriptions of five study sites used to examine the effect of fire frequency on soil organic matter

Block	**Rainfall (mm)**[2]	**Forest type**	**Area**	**Latitude and Longitude**	**Soil**	**CRA ecosystem type**[1]
Strickland	1370	Karri	Manjimup	34° 21', 116° 49'	Red earth	Karri - main belt
McCorkhill	1100	Jarrah marri	Nannup	33° 57', 115° 32'	Brown sandy gravels to brown sands	Jarrah forest - Blackwood plateau
Yackelup	750	Jarrah marri	Perup	34° 11', 116° 37'	Brown sandy gravel	Jarrah forest - south
Amphion	1235	Jarrah marri	Dwellingup	32° 48', 116° 03'	Sandy gravel	Jarrah forest - northwest
Chandler	1100	Jarrah marri	Jarrahdale	32° 20', 116° 50'	Yellow to orange gravel with a loamy sand matrix	Jarrah forest - northwest

[1] Ecosystem types of the Comprehensive Regional Assessment for the regional forest agreement of WA.

[2] Estimated values from ESOCLIM or Data-drill

Table 2. Fire treatments studied at each site.

Site	**Treatments**			**Replicates**
	1	2	3	
Strickland	36 years unburnt	26 years unburnt	8 year cycle	3
McCorkhill	23 years unburnt	5 year cycle	4 year cycle	2 with 2 subplots
Yackelup	18 years unburnt	7 year cycle	5 year cycle	4
Amphion	79 years unburnt	8 year cycle		3
Chandler	64 years unburnt	7 year cycle		3

Field procedures

A plot of approximately 60 x 60 m was located on each treatment at each site. Plots of this size could be used on all of the existing experimental sites, and they were small enough to limit the variation in soils within the plots.

Paired cores of 60 mm diameter were collected from 3 depths (0-75, 75-150, and 150-300 mm) at 10 locations distributed systematically across each plot (only the top 75 mm was considered at the Yackelup, Amphion, and Chandler sites). The 20 soil samples from each plot were air dried, weighed, sieved and the coarse fraction (>2mm) sorted into roots, charcoal, and gravel. The fine earth samples (<2 mm) from each soil depth layer in each plot (n = 20) were then combined, mixed and repeatedly passed through a sample splitter, to yield four sub-samples per plot from each soil depth. These sub-samples were ground, mixed and again subsampled to yield four subsamples per plot for carbon and nitrogen analysis. The sorted charcoal, gravel and roots were combined for each plot, subsampled, ground and analysed for carbon and nitrogen.

Chemical analyses

Samples used for chemical analysis were ground to <0.2 mm. Total soil nitrogen concentration (%) was determined using a Kjeldahl digestion procedure (Rayment and Higginson, 1992). Total soil carbon concentration (%) was determined using a combustimetric technique (LECO). The same procedures were used for all other carbon and nitrogen analyses except for the nitrogen concentration of roots and litter which were determined colorimetrically after digestion with sulphuric acid and hydrogen peroxide following the method of Yuen and Pollard (1954).

Physical analysis

Soil particle size was measured for use as a potential covariate to separate fire treatment effects on soils from intrinsic variation. Clay (<0.002 mm), silt (0.002-0.02 mm) and sand (0.02-2 mm) were estimated on bulked soil subsamples from each sample depth from each plot using a modified "plummet" procedure (Loveday, 1974). Preliminary analysis of the data from the first three sites (Strickland, McCorkhill, and Perup) indicated that clay content was not a useful covariate. Clay content was not measured at the Amphion and Chandler sites.

Bulk density was estimated for surface soils at all sites by taking the mean bulk density from cores collected at ten 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, the mass of both <2 mm and >2 mm fractions determined and the volume of the coarse fraction (>2 mm) determined by displacement. The bulk density of the fine earth fraction (<2 mm) and bulk density of the undisturbed sample were calculated.

Carbon mass

The carbon and nitrogen stores were calculated on a soil volume basis as the product of percentage carbon (or nitrogen) in the fine earth and the mass of fine earth in the 0-100mm soil layer over 1 ha. Hence, soil carbon store describes the mass of carbon per volume of soil and has units of tonnes ha^{-1}. This approach takes into account treatment effects that may affect soil bulk density. The presentation of this value presumes that the relatively small amounts of carbon and nitrogen in the coarse fraction (>2mm) are unavailable to plants and not involved in short term nutrient cycling (Hingston et al., 1989).

Litter

Litter (leaves, twigs, fruit and branches <2 cm in diameter) was collected from 10 quadrats (300 x 300 mm) adjacent to the soil sample points on each plot. All litter samples were oven dried at 45°C to a constant weight. The 10 litter samples were bulked, ground and subsampled and carbon and nitrogen determined on one subsample from each plot.

Statistical analysis

Analysis of variance and analysis of covariance were used to determine the effect of fire treatments on dry weight of litter, dry weight of roots, and carbon and nitrogen concentration of litter and soil. Analysis of covariance was used to examine the relationship between fuel age, soil carbon concentration, and site.

Results

Site descriptions

The soils of this region have been summarized by Churchward and Dimmock (1989) and McArthur (1991). Soils and vegetation of the five sites were distinct (Table 3). Soils at the Strickland site were deep red earths. These soils are mapped as part of the Donnelly Unit by Churchward (1992) and invariably are comprised of colluvium overlying kaolinitic clays derived from the weathering of the basement rock. Weathering, and thus rooting depth, is likely to be quite variable. At Yackelup the soils were brown sandy gravelly loams and at McCorkhill the soils ranged from brown sandy loams to brown sands. The soil at Chandler was a yellow to orange lateritic gravel with a loamy sand matrix. At Amphion the soil was a sandy gravel. The gravel content of the surface soils ranged from 0% to 83%, at individual sample points, and bulk densities ranged from 0.40 to 1.56 g cm^{-3}. Table 3 gives the mean values for each site.

Table 3. Particle size analysis and bulk densities of soils from fire frequency study sites. Values are means ± standard error.

Site and soil depth (mm)	**Sand**[a] %	**Silt**[a] %	**Clay**[a] %	**Gravel content**[b] %	**Total bulk density** g cm^{-3}
Strickland					
0 - 75	80.6 ± 1.21	13.2 ± 0.64	6.3 ± 0.60	15.6 ± 3.1	0.69 ± 0.017
75 - 150	78.7 ± 1.44	13.3 ± 0.58	7.9 ± 0.98	18.7 ± 2.5	
150 - 300	74.3 ± 1.72	13.2 ± 0.72	12.6 ± 1.20	23.6 ± 2.6	
McCorkhill					
0 - 75	93.1 ± 1.17	2.8 ± 0.35	4.1 ± 0.84	15.7 ± 5.2	1.09 ± 0.013
75 - 150	93.3 ± 1.26	1.8 ± 0.38	4.8 ± 0.93	5.1 ± 2.5	
150 - 300	91.8 ± 1.70	1.9 ± 0.15	6.3 ± 1.56	8.8 ± 4.4	
Yackelup					
0 - 75	86.8 ± 1.70	6.7 ± 0.79	6.5 ± 0.94	42.3 ± 5.0	1.07 ± 0.014
Amphion					
0 – 75	.	.	.	46.4 ± 1.7	1.10 ± 0.021
Chandler					
0 - 75	.	.	.	60.4 ± 1.5	1.22 ± 0.022

[a] Percentage of fine earth (<2mm fraction) [b] Percentage of all soil

Litter weight and nutrient levels

As would be expected, regular burning reduced the amount of litter, and litter weight was greatest on the sites with highest rainfall (Table 4). Across all sites the weight of leaf litter generally increased with increasing time since fire. At Strickland, the only karri site, this increase in litter weight (~9 t ha^{-1}) between the regularly burnt and the unburnt treatments was not significant ($p = 0.106$). These increases at McCorkhill (~17 t ha^{-1}), Yackelup (3 t ha^{-1}), Amphion (4 t ha^{-1}) and Chandler (6 t ha^{-1}) were significant (McCorkhill, $p = 0.013$; Yackelup, $p = 0.005$; Amphion, $p = 0.049$ and Chandler, $p = 0.004$) (Table 4). The difference in litter weight between regularly burnt and long unburnt treatments was greatest at the McCorkhill site with much higher leaf litter mass on the long unburnt plots.

The concentration of carbon in the leaf litter varied little across all sites and treatments, with a mean value of approximately 45%. A notable exception was the low carbon concentration of litter on treatment 3 at McCorkhill (Table 4) (4 year burning cycle, 40.8 % C). The differences in carbon concentration between treatments were not significant at McCorkhill ($p = 0.083$), Yackelup ($p = 0.866$), Amphion ($p = 0.686$), or Chandler ($p = 0.860$), and were marginally significant at Strickland ($p = 0.056$).

The response of litter carbon mass (t ha^{-1}), which is the product of litter mass (t ha^{-1}) and litter carbon concentration (C%), closely followed the response of litter mass on each treatment (Table 4). Although the long unburnt treatments at Strickland had the highest litter carbon (20 t ha^{-1} compared to 14 t ha^{-1} on the regularly burnt plot), reflecting both the greater amounts of litter on these treatments and the higher concentration of carbon in that litter, this difference was not significant ($p = 0.071$). Litter carbon mass was significantly different between fire treatments at McCorkhill ($p = 0.018$) with values of 2.9 t ha^{-1} (4 and 5 year cycle) and 10.5 t ha^{-1} (23 years unburnt), largely reflecting the greater amount of litter present on the long unburnt treatment. At Yackelup the long unburnt treatment also had a significantly greater amount of litter carbon (6.6 t/ha, $p = 0.004$) though this was not significantly different from the 7 year treatment. At Chandler the long unburnt treatment had approximately 3 tonnes per ha more litter carbon than the regularly burnt treatment and this difference was significant ($p = 0.027$). The difference in litter carbon mass at Amphion was not significant. Long unburnt plots have a greater mass of litter and this leads to a greater total mass of carbon in the litter layer.

Litter nitrogen concentration generally followed the response of carbon concentration to fire frequency (Table 4), despite being relatively poorly correlated with carbon concentration (r = 0.59, n = 33, p<0.0005). Litter nitrogen concentration was not significantly different between treatments, however within a site, litter on the most frequently burnt plots consistently had a lower nitrogen concentration than litter on long unburnt plots.

Differences in litter nitrogen mass between burning treatments at the sites were an expression of both differences in litter mass, and differences in nitrogen concentration. The litter nitrogen mass was significantly different between treatments at Strickland (p = 0.014), McCorkhill (p = 0.062), Yackelup (p = 0.011) and Amphion (p = 0.033) with the regularly burnt plots at these sites having a significantly lower mass of nitrogen in the litter layer than long unburnt plots.

Table 4. Mass of the leaf litter, carbon and nitrogen concentrations of leaf litter, and the mass of carbon and nitrogen in the litter layer for a range of fire frequency treatments at five sites in the jarrah and karri forests. Values are means ± standard error. Means with different letters are significantly different (Tukey test, p = 0.05).

Site	**Fire frequency**	**Fuel age when sampled**	**Litter mass**	**Carbon**		**Nitrogen**	
	(years/cycle)	(years)	(t ha^{-1})	(%)	(t ha^{-1})	(%)	(t ha^{-1})
Strickland	fire excluded	36	40.4 ± 3.03	48.2 ± 0.82	19.5 ± 1.76	0.98 ± 0.03	0.39 ± 0.03^{q}
	fire excluded	27	41.2 ± 2.60	48.5 ± 0.67	20.0 ± 1.45	0.93 ± 0.02	0.38 ± 0.03^{q}
	7	8	30.9 ± 3.65	45.4 ± 0.86	14.0 ± 1.61	0.86 ± 0.06	0.26 ± 0.02^{r}
McCorkhill	fire excluded	23	23.9 ± 4.54^{b}	43.4 ± 1.72	10.5 ± 2.40^{m}	0.65 ± 0.07	0.16 ± 0.053^{t}
	5	6	6.5 ± 1.98^{c}	46.1 ± 1.83	2.9 ± 0.87^{n}	0.66 ± 0.05	0.04 ± 0.011^{t}
	4	4	7.0 ± 1.87^{c}	40.8 ± 1.68	2.9 ± 0.86^{n}	0.44 ± 0.05	0.03 ± 0.006^{t}
Yackelup	fire excluded	18	14.4 ± 0.60^{d}	45.6 ± 1.22	6.6 ± 0.32^{o}	0.54 ± 0.01	0.08 ± 0.00^{u}
	7	7	13.2 ± 0.40^{dc}	45.5 ± 0.76	6.0 ± 0.13^{o}	0.57 ± 0.02	0.07 ± 0.00^{u}
	5	3	11.4 ± 0.37^{c}	44.9 ± 0.68	5.1 ± 0.07^{p}	0.51 ± 0.03	0.06 ± 0.00^{v}
Amphion	fire excluded	79	29.8 ± 1.36	47.9 ± 2.04	14.2 ± 0.07	0.64 ± 0.02	0.19 ± 0.014^{w}
	7	8	26.1 ± 1.10	46.7 ± 1.91	12.2 ± 1.03	0.56 ± 0.03	0.14 ± 0.003^{x}
Chandler	fire excluded	64	29.8 ± 1.16^{f}	48.0 ± 1.91	14.3 ± 0.68^{q}	0.56 ± 0.07	0.16 ± 0.019^{y}
	7	1	23.6 ± 0.37^{g}	48.5 ± 1.77	11.4 ± 0.48^{r}	0.58 ± 0.02	0.14 ± 0.005^{y}

Variation in concentration of carbon in components of the coarse soil fraction (>2 mm)

There was very little carbon and nitrogen in the gravel at these sites (Table 5). Charcoal and roots both had much higher carbon and nitrogen concentrations compared to the levels found in fine earth. As the carbon and nitrogen levels of the gravel were low compared to those of fine earth, and these were excluded from the fine earth analyses, these concentrations were not measured at the Amphion and Chandler sites. Similarly, as large roots and charcoal were excluded from the fine earth analyses, these values were not determined for the Amphion and Chandler sites.

Table 5. The mean concentration of carbon and nitrogen in the fine earth (<2 mm), and constituents of the >2 mm soil fraction (gravel, charcoal, and roots) for surface soils (0-75 mm) at one karri and two jarrah forest sites. Values are means ± standard error.

Site	**Fine earth**		**Gravel**		**Charcoal**		**Roots**	
	C (%)	N (%)	C (%)	N (%)	C (%)	N (%)	C (%)	N (%)
Strickland	7.59 ± 0.631	0.38 ± 0.029	1.13 ± 0.059	0.06 ± 0.004	41.4 ± 0.780	0.30 ± 0.011	39.8 ± 0.058	0.52 ± 0.000
McCorkhill	2.23 ± 0.196	0.054 ± 0.005	0.74 ± 0.078	0.022 ± 0.002	48.3 ± 2.117	0.229 ± 0.002	28.9 ± 0.529	0.293 ± 0.009
Yackelup	5.05 ± 0.402	0.15 ± 0.010	0.67 ± 0.055	0.02 ± 0.002	47.7 ± 1.738	0.21 ± 0.006	35.8 ± 0.557	0.45 ± 0.024

Table 6. Surface soil (0-75 mm) attributes measured on fire frequency treatments at five sites. Values are means ± standard error. Means with different letters are significantly different (Tukey test, $p = 0.05$). Within a site, no carbon and nitrogen values were significantly different between fire treatments

Site	Fire frequency (years)	Carbon (%)	Nitrogen (%)	Carbon store (kg ha^{-1})	Nitrogen store (kg ha^{-1})	Total bulk density (g cm^{-3})	Fine earth bulk density (g cm^{-3})	Clay content (%)
Strickland	36	8.00 ± 0.94	0.401 ± 0.049	41354 ± 1748	2070 ± 100	0.66 ± 0.033^{a}	0.55 ± 0.035	4.83 ± 0.88
	27	9.05 ± 0.76	0.451 ± 0.030	43973 ± 5731	2201 ± 294	0.58 ± 0.021^{a}	0.50 ± 0.036	6.50 ± 0.58
	7	5.72 ± 0.64	0.300 ± 0.034	40807 ± 2428	2153 ± 224	0.84 ± 0.057^{b}	0.76 ± 0.106	7.50 ± 1.16
McCorkhill	23	2.82 ± 0.26	0.069 ± 0.0067	21423 ± 2434	519 ± 50	1.03 ± 0.028	0.84 ± 0.074	5.25 ± 2.31
	5	1.75 ± 0.13	0.040 ± 0.0039	17663 ± 1906	407 ± 52	1.10 ± 0.020	1.03 ± 0.032	2.25 ± 0.25
	4	2.13 ± 0.38	0.054 ± 0.0099	19969 ± 1855	505 ± 50	1.14 ± 0.040	1.03 ± 0.041	4.88 ± 0.75
Yackelup	18	5.13 ± 0.45	0.148 ± 0.011	27176 ± 1179	786 ± 46	1.05 ± 0.033	0.67 ± 0.036	5.88 ± 1.55
	7	6.01 ± 0.79	0.176 ± 0.016	27559 ± 1295	820 ± 67	1.08 ± 0.048	0.63 ± 0.060	9.62 ± 1.12
	5	4.02 ± 0.53	0.122 ± 0.016	28814 ± 5037	874 ± 144	1.10 ± 0.060	0.84 ± 0.087	4.12 ± 0.85
Amphion	79	6.66 ± 0.29^{a}	0.124 ± 0.002^{c}	33314 ± 1197	622 ± 22	1.14 ± 0.047	0.63 ± 0.006	.
	8	4.84 ± 0.34^{b}	0.099 ± 0.007^{d}	30389 ± 284	620 ± 10	1.06 ± 0.042	0.74 ± 0.041	.
Chandler	64	7.39 ± 0.35	0.133 ± 0.006	32908 ± 1031	592 ± 23	1.14 ± 0.044^{a}	0.58 ± 0.021	.
	1	6.00 ± 1.44	0.113 ± 0.024	28022 ± 2176	533 ± 27	1.30 ± 0.023^{b}	0.65 ± 0.073	.

Table 7. Soil carbon and nitrogen concentrations measured at 75-150 mm and 150-300 mm. Values are means ± standard errors for fire treatments applied at three sites in the jarrah and karri forests of south-west Western Australia. Within a site, no carbon and nitrogen concentrations were significantly different between fire treatments (at $p = 0.05$).

Site	**Soil depth** (mm)	**Treatment**	**Fire frequency** (years/cycle)	**Carbon** (%)	**Nitrogen** (%)
Strickland	75-150	1	36	3.83 ± 0.473	0.189 ± 0.021
		2	26	5.11 ± 0.771	0.258 ± 0.030
		3	8	3.42 ± 0.719	0.174 ± 0.024
	150-300	1	36	2.00 ± 0.325	0.096 ± 0.015
		2	26	2.58 ± 0.502	0.130 ± 0.021
		3	8	1.84 ± 0.456	0.094 ± 0.014
McCorkhill	75-150	1	23	0.96 ± 0.140	0.029 ± 0.002
		2	5	0.86 ± 0.090	0.020 ± 0.004
		3	4	0.87 ± 0.314	0.025 ± 0.009
	150-300	1	23	0.62 ± 0.142	0.022 ± 0.002
		2	5	0.62 ± 0.144	0.015 ± 0.004
		3	4	0.41 ± 0.059	0.016 ± 0.005

Variation in concentrations of soil carbon and nitrogen between sites and fire treatments

The concentration of carbon and nitrogen of the surface horizon of the soils was highest at Strickland (7.6% C, 0.38% N), intermediate at Chandler (6.7% C, 0.12% N), Amphion (5.8% C, 0.11 N) and Yackelup (5.0% C, 0.15% N), and lowest at the McCorkhill site (2.2% C, 0.05% N) (Tables 5 and 6). At all sites except Amphion the concentration of carbon and nitrogen in the surface soil did not vary significantly with fire treatment (Table 6, Fig. 1). However at all sites, other than Yakelup, the long unburnt plots had higher C and N concentrations than those burnt regularly (Table 6). Although there was high inherent variability in soil carbon and nitrogen, a consistent trend of higher concentrations of carbon and nitrogen in the surface soils of long unburnt plots was observed across these sites (Fig. 1).

The concentration of soil carbon varied between sites, yet all sites showed some increase in carbon concentration as the time since the last fire increased. Analysis of covariance was used to examine this relationship across all sites and determine if there was a consistent increase in soil carbon concentration as the time since the last fire increased. Sites were significantly different ($p = 0.0040$). Across all sites soil carbon concentration was significantly related to the time since the last fire (marginally significant at $p = 0.0505$).

The response of carbon and nitrogen concentration to fire treatment was greatly reduced in the deeper soil layers (75-150 and 150-300 mm) at the Strickland and McCorkhill (Tables 6 and 7). There was a general decline in soil carbon and nitrogen concentration with increasing soil depth and soil nitrogen concentration was highly correlated with soil carbon concentration ($r = 0.94$, $p<0.0001$). The trends observed for carbon and nitrogen concentrations in the surface soils are reflected in the trends found in the deeper soil samples (75-150 and 150-300mm), however the differences between fire treatments are reduced and are not statistically significant (Table 7).

Bulk density

Total bulk density of the surface soil was lowest at Strickland (0.69 g cm^{-3}) intermediate at the Yackelup (1.07 g cm^{-3}), McCorkhill (1.09 g cm^{-3}) and Amphion (1.10 g cm^{-3}) sites, and highest at Chandler (1.22 g cm^{-3}) (Table 6). Total bulk density also varied between fire treatments within the sites, the long unburnt plots having the lowest bulk densities at each site, compared to the regularly burnt plots (Table 6). However this difference in total bulk densities with fire treatments was only significant at the Strickland ($p = 0.009$) and Chandler ($p = 0.036$) sites. The differences at the McCorkhill site were marginally significant ($p = 0.074$), and at the Yackelup and Amphion sites the differences in total bulk density were not significantly related to fire treatment.

Fine earth bulk density of the surface soil was lowest on the Strickland site, highest on the McCorkhill site, with Yackelup, Amphion, and Chandler having intermediate values (Table

6). The long unburnt treatments had the lowest fine earth bulk densities at all sites except Yackelup; however differences between fire treatment were not significant at any of the sites (at $p = 0.05$). Across these sites there was a general decrease in fine earth bulk density as the frequency of the fire decreased ($r = -0.60$, $p = 0.0002$)(Fig. 2).

Across all sites, soils, and fire treatments, the fine earth bulk density decreased as carbon concentration in the soil increased ($r = -0.96$, $p = 0.0001$) (Fig. 4). A similar trend was evident with total bulk density, however this was not as strong ($r = -0.53$, $p = 0.0001$).

Soil carbon and nitrogen stores

Soil carbon store is the mass of carbon per hectare in the 0-100 mm soil layer and is the product of the carbon concentration and the mass of soil per hectare in the 0-100 mm layer. Nitrogen store is calculated in the same manner. Changes in bulk density alter the mass of fine earth in the 0-100 mm layer and thus impact the carbon and nitrogen store. As with soil carbon concentration, the Strickland site had the greatest amount of carbon per hectare (42 tonnes ha^{-1}). Amphion (32 tonnes ha^{-1}), Chandler (30 tonnes ha^{-1}), and Yackelup (28 tonnes ha^{-1}) had intermediate amounts of soil carbon, and McCorkhill had the lowest amount of soil carbon (20 tonnes ha^{-1}). The soil carbon store in the surface soil was not significantly different between treatments at any site (Table 6), with variation within treatments at a site equal to variation between treatments (Fig. 3).

Clay content

The mean clay content of the surface soils was greatest at the Yackelup (6.54 ± 0.94) and Strickland sites (6.28 ± 0.60), and least at the McCorkhill site (4.12 ± 0.84). Fig. 5 shows the variation of clay content within each site and the relationship between the clay and carbon concentration of the surface soil. At McCorkhill and Yackelup carbon concentration increased with increasing clay content. At the Strickland site carbon concentration generally decreased with increasing clay content of the soil. There was no correlation between clay content and time between fires ($r = 0.008$, $n = 33$).

Discussion

General trends in soil carbon and nitrogen

The greatest response of soil carbon and nitrogen to the fire treatments occurred in the surface soil layer (0-75mm). As the response of the deeper soil layers to the different fire treatments was comparatively diminished, the focus of discussion is directed at treatment and site differences in the surface soil layer.

Across all sites, and within individual sites, there was a marked increase in the carbon concentration of the surface soil with increasing burning interval. Generally, as the time between fires increased, the carbon concentration of the soil increased. Shorter periods between fires were associated with lower carbon concentrations of the surface soil (Table 6, Fig. 1). Analysis of covariance was used to examine this relationship between fuel age, soil carbon concentration, and site. Sites were significantly different ($p = 0.0040$). Across all sites soil carbon concentration was significantly related to the time since the last fire (marginally significant at $p = 0.0505$).

The effect of time between fires on soil nitrogen and organic carbon concentration in the jarrah forest has been studied by Hatch (1959) and by Abbott et al (1984). Hatch (1959) reported no significant difference in soil nitrogen or organic carbon in long unburnt and regularly burnt jarrah forest (2.96%C, 0.125%N and 3.00%C, 0.128%N respectively, surface soils 0-90 mm). Abbott et al. (1984), reported 2.58% organic carbon and 0.078% nitrogen in unburnt, and 2.78% organic carbon and 0.090% nitrogen in the burnt stands (0-150mm depth) from a study of the same Chandler site where I observed 7.39% organic carbon and 0.133% nitrogen in unburnt, and 6.00% organic carbon and 0.113% nitrogen in the burnt stands. These are substantial differences. I observed generally higher levels of soil carbon and nitrogen, than these authors, greater differences in soil carbon and nitrogen between the regularly burnt and long unburnt stands, and a consistent trend of higher percentage soil carbon and nitrogen on long unburnt sites.

There are several possible reasons for these different observations and conclusions. Both Hatch (1959) and Abbott et al. (1984) examined soil samples that included greater soil depths (89 mm and 150 mm respectively) than those in this study (0-75 mm). The lower carbon concentration of these deeper soils would tend to lower the measured soil carbon values and dilute any observed response due to fire treatment. Some of these differences may simply be due to variations within and between sites. These authors also used the Walkley-Black technique to determine organic carbon, while this work made use of the LECO combustimetric analysis. This may explain the lower carbon values observed by these authors and variability introduced by the Walkley Black technique may have obscured treatment differences. The differences between these studies highlights the difficulties in sampling and measuring soil carbon and nitrogen and the substantial differences introduced by different sampling and analysis techniques.

Clay as a covariate

Guinto et al. (1998) emphasised the need to account for natural soil variation unrelated to fire history, and used clay content as a covariate when examining the response of soil carbon to fire frequency. I observed a general increase in soil carbon with clay content on the McCorkhill and the Yackelup sites, (Fig. 5) however clay content was not a significant covariate on these sites. Clay content was a significant covariate at the Strickland site, however the response here was negative and inconsistent with the expected trend; carbon concentration decreased as clay content increased. As this response was counter-intuitive, clay content was not used in the analysis of these data and was not collected at the Amphion and Chandler sites.

Carbon concentration, carbon store, and fine earth bulk density

The strongest relationship observed across all sites and treatments in this study was a negative relationship between surface soil carbon concentration, and fine earth bulk density, (Fig. 4) (r = -0.96). A similar though weaker relationship exists for total bulk density and surface soil carbon concentration (r = -0.53). Denser, compacted surface soils have a lower carbon concentration than less compacted soils. What is the importance of the strength of this relationship?

Within and across sites there was a general decrease in fine earth bulk density as the time between fires increased (Fig. 2.). Infrequently burnt sites and treatments have less dense surface soils than frequently burnt sites and treatments. The carbon store of the surface soil layer varies between sites, but does not vary between fire treatments within a site (Fig. 3). Site differences, presumably related to overall productivity, account for major differences in the soil carbon store, while fire frequency within a site has little effect on this mass of carbon in the surface soil layer.

So what causes the increase in soil carbon concentration (%) on the long unburnt sites? This result can be explained by the decrease in fine earth bulk density that occurs with increasing time between fires. Long unburnt sites have relatively low fine earth bulk density, ie. less soil mass per unit volume. Yet this lighter soil volume contains approximately the same mass of carbon as an equivalent soil volume on regularly burnt treatments. This leads to a higher mass of carbon in the mass of soil, and hence a lower soil carbon concentration.

The strength of the relationship between fine earth bulk density and soil carbon concentration indicates that processes in the soil that increase soil carbon are the same processes, or closely related to, processes that are lowering the soil bulk density.

The fire frequency is one of, but not the only factor affecting these processes (Figs. 1 and 2). Fire is known to affect a number of soil processes. The mineralization of organic matter can be affected by the changes in microbial activity resulting from soil heating, the addition of ash and partly combusted organic matter, and long term changes in soil microclimate caused by frequent burning (O'Connell et al., 1981). In south east Queensland Jones and Richards (1977) found that regular burning of native forest reduced bacterial numbers, and Springett (1976) has shown a reduction in soil fauna species diversity and density associated with regular burning. Hatch (1955) examined soil aggregation and proposed that organic matter derived from litter promoted soil aggregation. All of these factors are likely to affect both the carbon concentration, and the structure and density of the soil. This study was not intended to examine these processes, however observations of soil samples from the jarrah and karri forest sites of this current work support the observation of Malajczuk and Hingston (1981) in the jarrah forest, that the abundance of mycorrhizal roots was greater in long unburnt forest than in regularly burnt forest.

This observation that mass of carbon in the surface soil layer is not affected by fire frequency raises questions about changes in the type of carbon present in the soil. It would be expected that frequent burning would increase the amount of carbon present as charcoal in the soil. Hence if the carbon store in the soil is unchanged but the frequently burnt plots contain a greater proportion of carbon as charcoal, then the amount of carbon derived from organic matter in the soil would be even lower on these regularly burnt sites. This presumes that fine charcoal particles produced in burning the surface litter are readily incorporated into the surface soil layers. This may not occur.

Within an individual site I would expect the less dense soils on the long unburnt plots to have greater amounts of carbon (excluding charcoal) than the denser surface soils on frequently burnt plots. The lower bulk densities of the long unburnt plots should result in increased root growth and other biological activity that would tend to increase the amounts of organic C in the soil (excluding charcoal). This expected trend may be masked by the presence of greater amounts of charcoal in the more frequently burnt plots. Unfortunately the contribution of charcoal to the total carbon content of the soils is not known and is difficult and expensive to determine. Knowledge of the contribution of charcoal to the soil carbon concentration would further clarify the impacts of fire frequency on soil organic matter.

Litter

Litter weight varies greatly between treatments within a site. Fire consumes litter, and as a consequence, frequently and more recently burnt plots carry less litter than long unburnt plots. The organic matter contributed by litter alters the physical and chemical environment at the soil litter interface and affects soil fauna (Springett, 1976; O'Connell et al., 1981) and nutrient cycling (O'Connell et al., 1979). I observed consistently lower nitrogen levels in the litter from regularly burnt plots. Although these study sites have experienced relatively few fire cycles under these treatment regimes, the lower nitrogen levels of litter on regularly burnt plots may indicate changes in site fertility associated with these fire treatments.

Conclusion

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. Although the mass of carbon and nitrogen in the surface soil layer (0-100 mm) was not affected by fire frequency, changes in soil bulk density altered the concentration of these nutrients. The correlation between soil carbon concentration and bulk density indicates that these changes with fire treatment are most likely 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. O'Connell et al., (1981) identified changes in microbial activity resulting from soil heating, the addition of ash and partly combusted organic matter, and long term changes in soil microclimate caused by frequent burning as factors with the potential to alter the mineralization of organic matter. In the jarrah forest Malajczuk and Hingston (1981) found the abundance of mycorrhizal roots was greater in long unburnt forest than in regularly burnt forest. Hatch (1955) examined soil aggregation and proposed that organic matter derived from litter promoted soil aggregation. All of these factors are likely to affect both the carbon and nitrogen concentration, and the structure and density of the soil.

The gross differences in soil carbon between sites are related to differences in site productivity. Within a site small variations in the mass of carbon in the soil are 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.

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.

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Fig. 1. The mean concentration of carbon (%) in the soils of plots burnt under a range of fire frequencies at five sites.

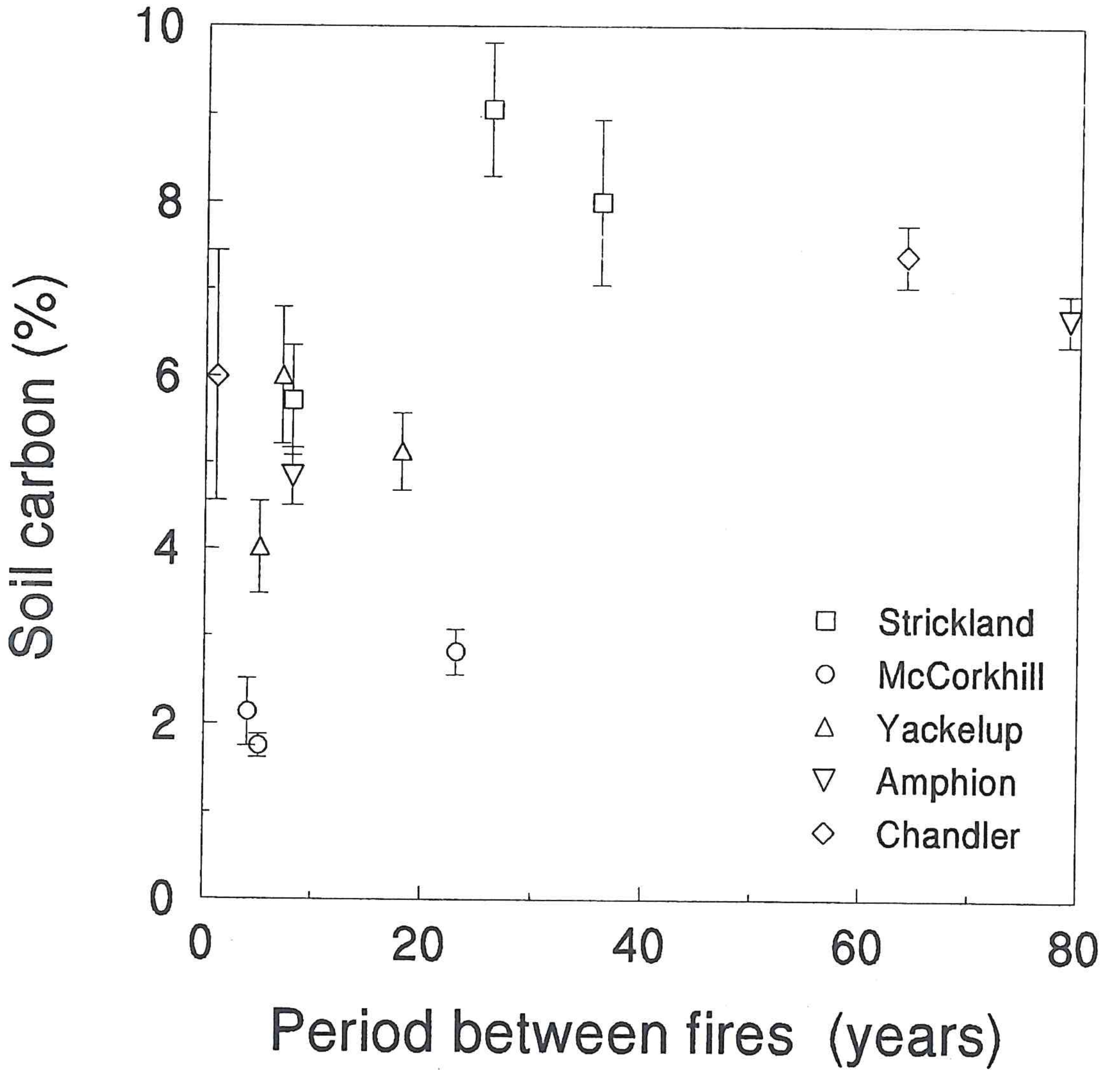


Fig. 2. The fine earth bulk density of surface soils (0-75 mm) for plots burnt under a range of fire frequencies at five sites.

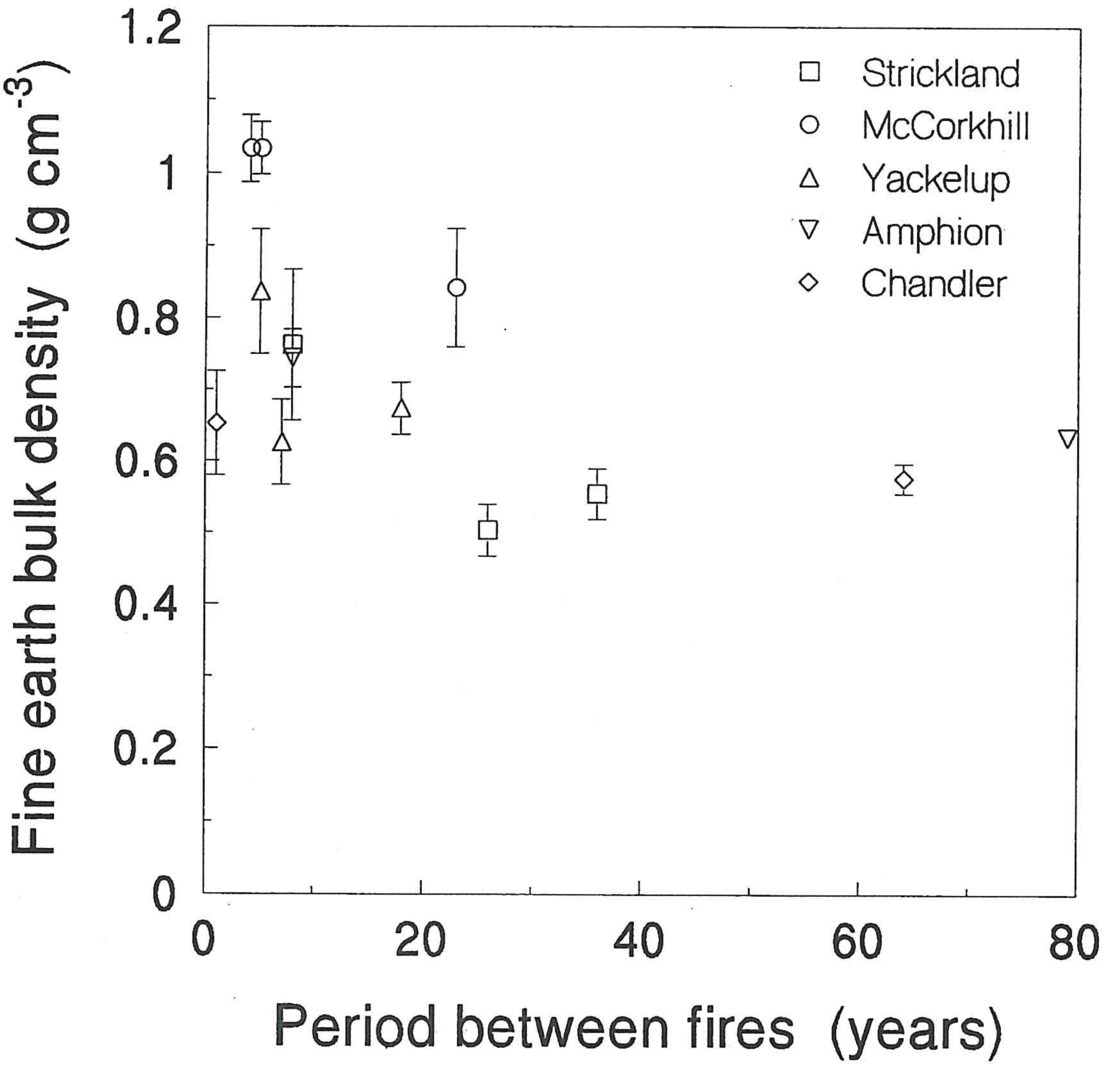


Fig. 3. The carbon store (g cm^{-3}) of surface soils (0-75 mm) for plots burnt under a range of fire frequencies at five sites.

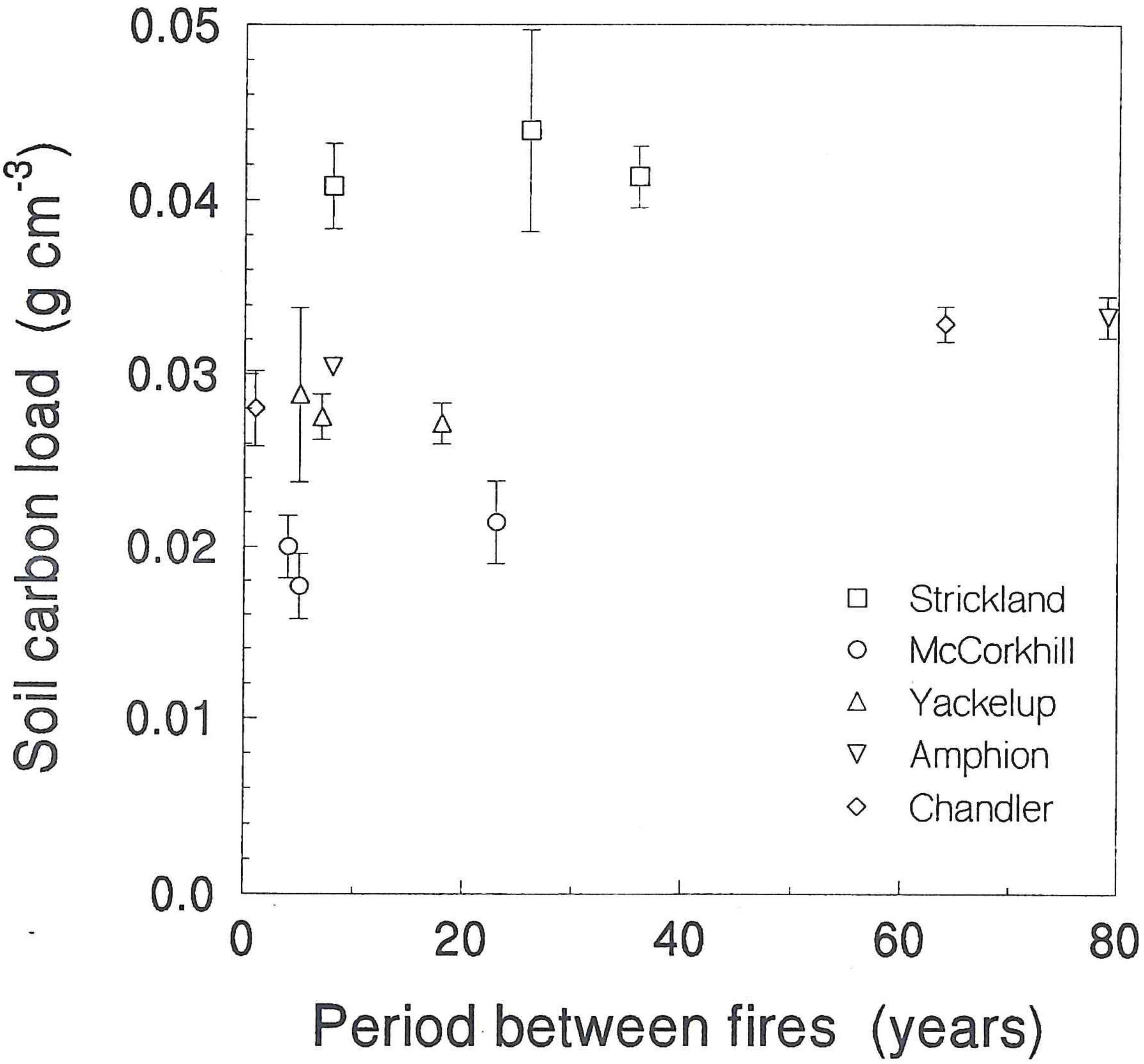


Fig. 4. The relationship between mean carbon concentration (%) and fine earth bulk density of surface soils (0-75 mm) for plots burnt under a range of fire frequencies at five sites.

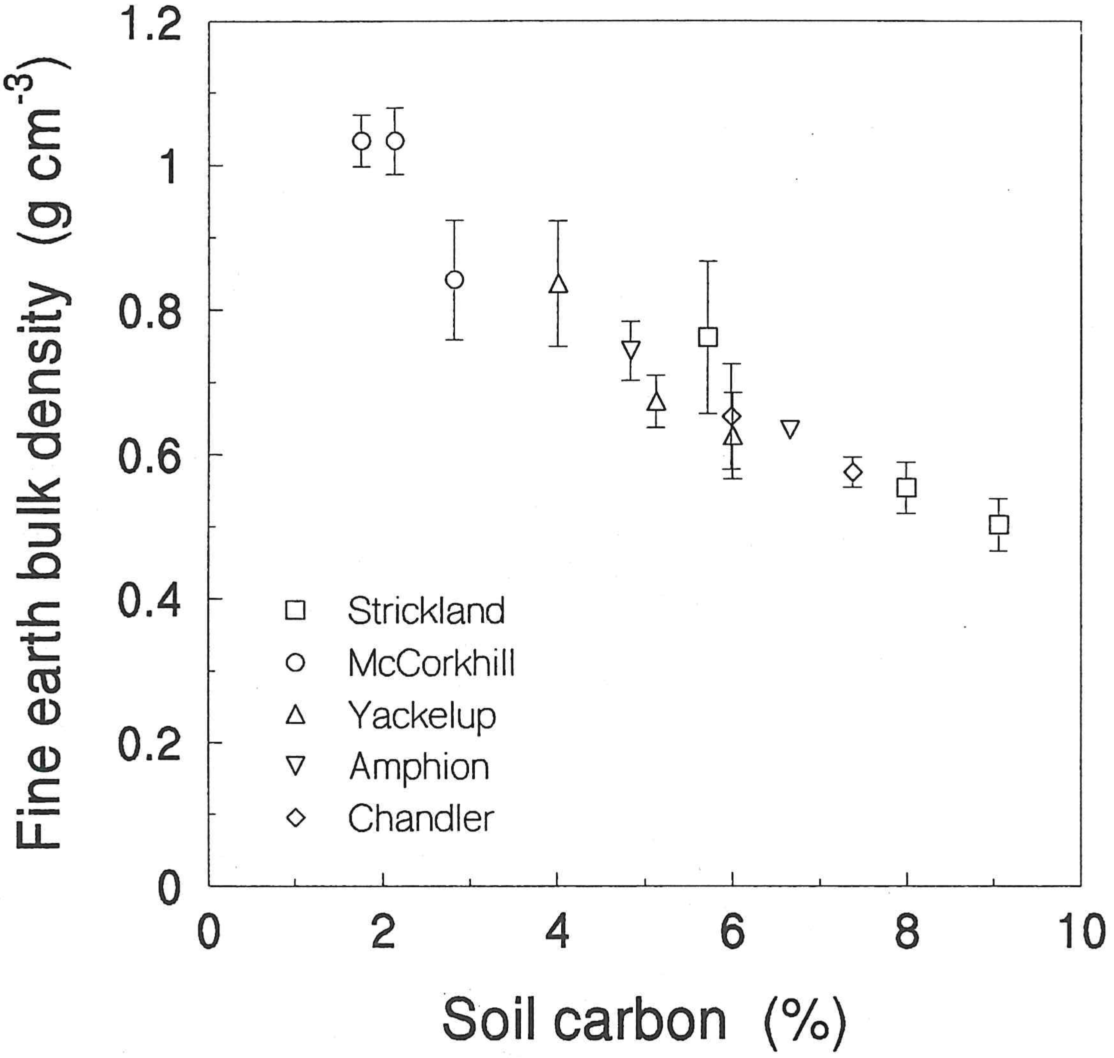
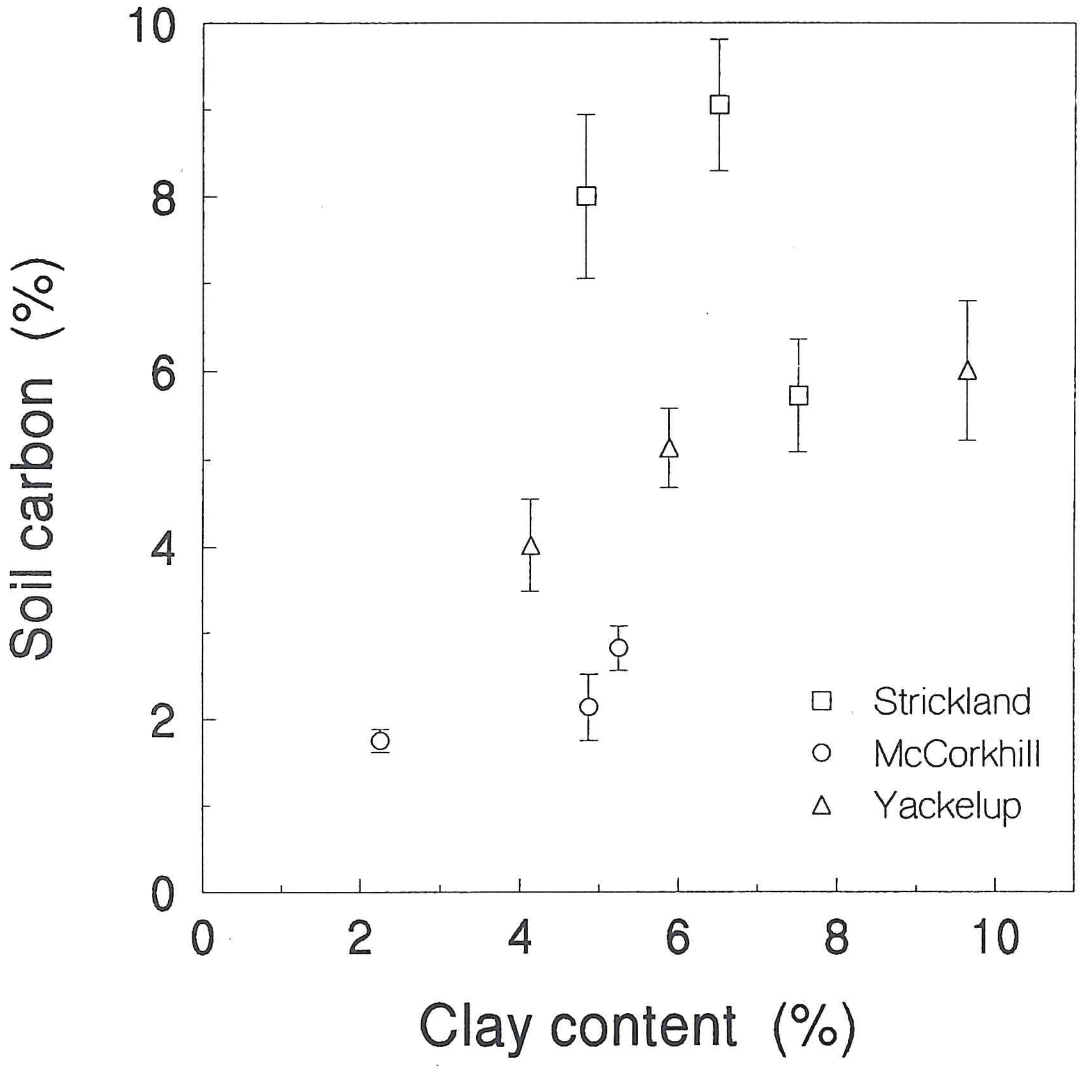


Fig. 5. Clay content and concentration of soil carbon for surface soils (0-75 mm) of plots burnt under a range of fire frequencies at three sites.



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

Final report - Part 2.

The impact of logging on soil physical properties at three sites in the northern jarrah forest.

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Abstract

Survey techniques advocated in the draft protocol for Montreal Indicator 4.1e (Rab, 1998) were used to compare the extent and intensity of disturbance on three faller's blocks in the northern jarrah forest of south-west WA. I used this process to examine techniques of measuring bulk density in gravelly forest soils, to determine the effects of corer size on the measured fine earth and total bulk density, and to examine the relationship between soil disturbance class, bulk density, and soil strength. I found relatively low levels of disturbance on logged jarrah coupes with 12 - 14% of the area covered by snig tracks, and 12 - 16% of the area classified as disturbed under draft Montreal Indicator 4.1.e (Rab, 1998). Bulk density was successfully measured with small corers in these highly gravelly soils (36%-70% gravel). Fine earth bulk density was a more informative measure than total bulk density with these soils. Both bulk density measurements were expensive and time consuming to collect. 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 did not provide a meaningful assessment of soil disturbance.

I found high variability between three methods of surveying snig track area. The source of this variability is unclear. Photo-interpretation was unsuccessful as a method of determining snig track area and GPS ground traverse was the most efficient and reliable method for snig track surveys

A modified version of the visual disturbance classification system of the draft protocol (Rab, 1998) 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.

Introduction

Research into soil physical disturbance in the forests of south-west Western Australia has focussed on disturbance in the soils of the wet sclerophyll karri forests which occur across the high rainfall areas of the lower south-west. Schuster (1979) examined the vertical extent of soil compaction, the effect of compaction on root growth, and the value of various rehabilitation techniques in the karri forests. Bradshaw (1978) discussed the extent, causes, and impacts of soil disturbance in the karri forests. Wronski (1984) reported on the impact of karri thinning operations on soil physical properties and root damage and Maher (1992) examined the relationship between penetrometer resistance and karri seedling growth. Soil disturbance in karri coupes can be extensive and difficult to control given the constraints of current logging activities. The existing work on soil physical properties provides background but is not directly applicable to the development of the Montreal Indicator 4.1e.

This current work on soil physical properties adapts and applies the national measurement protocol for Montreal Indicator 4.1e. to the south-west forests, with the aim of developing appropriate measurement techniques and sampling strategies for monitoring the impacts of logging on soil physical properties. Part 3 of this project examines the effect of soil compaction on karri regrowth.

Specifically, in this component of the research project we:

- Establish some base data on the degree and extent of soil disturbance in the jarrah logging coupes using a nationally agreed survey protocol for estimating soil disturbance on logged coupes.
- Examine the commonly expressed assumption that only minor soil compaction and disturbance occur in jarrah logging. Surveys will be conducted on one highly disturbed

jarrah faller's block that has been logged in winter, and for comparison two more typical jarrah faller's blocks.

- Use these surveys as a basis for the development and refinement of survey techniques proposed in the national protocol.
- Examine techniques for measuring bulk density in gravelly forest soils and identify appropriate measurement technique for these soils.
- Examine the effects of corer size on the measured fine earth and total bulk density, and determine if this is affected by soil gravel content.
- Examine the relationship between soil disturbance class, bulk density, and soil shear strength
- Compare survey techniques for determining snig track area
- Report and compare the extent of disturbance on three faller's blocks in the northern jarrah forest of south-west WA.

Methods

Sites

Table 1 gives details of the study sites for all soil disturbance measurements. The Curara 54 site (C54) had low gravel content, relatively high slopes for the jarrah forest and was logged under wet conditions in winter. This site was selected to represent the extreme end of soil disturbance in the northern jarrah forest. The Plavins 2 site (P2) represented a more typical example of soil disturbance in the jarrah forest, and the Curara 35 site (C35) was a site with extensive but relatively low levels of disturbance. This range of sites was selected to provide descriptive information of the range of disturbance seen in the Northern Jarrah forest, and as a basis for the development of these survey techniques across this range of disturbance types.

Table 1. Location, size, and descriptive information for three faller's blocks in the jarrah forest surveyed for soil disturbance, bulk density, and soil shear strength.

Site	**AMG**	**Coupe Area**	**Mean slope degrees**	**Gravel content**
Curara 54	MJ273701	16.12	7	36%
Curara 35	MJ289669	25.42	2	65%
Plavins 2	MJ204747	12.93	10	70%

Soil disturbance survey

All three sites were surveyed for soil disturbance using the transect-intercept-quadrat method described by Rab (1998) and a modification of the soil disturbance classification system used by Rab (1998), (Table 2). Soil disturbance was assessed as the disturbance class covering the most area of a 1m x 1m quadrat. Quadrats were located at intersections spaced at 7.5m along transects spaced at 50m (C54 and C35) and 30m (P2) across the entire faller's blocks. Approximately 400 transect-intercept points were classified on each faller's block.

Table 2. A system for classifying soil impacts following timber harvesting and site preparation (After Rab 1998).

A: Operation categories:

Harvested Area	(HA)	General logging within which trees are felled
Unharvested Area	(UA)	Areas of retained forest within the coupe boundary
Firebreak	(FB)	Perimeter boundary
Snig Tracks	(ST0)	Major snig track into landing
	(ST1)	Major snig tracks, Primary
	(ST2)	Minor snig tracks, Secondary
	(ST3)	Minor snig track Tertiary
	(OST)	Old Snig track
Landing	(LL)	Area where logs are snigged for sorting and loaded for transportation
	(OL)	Old landing from previous logging
Access Roads	(AR)	Temporary forest roads falling with the coupe boundary

B: Soil disturbance categories:

Soil profile disturbance	Classification		Type of mixing/removal	Dominant horizon
Undisturbed	(D0)	(LI)	Litter layer intact	O
Lightly disturbed	(D1)	(LR)	Litter layer broken/partially removed	O
Moderately disturbed	(D2)	(TE)	Litter completely removed and topsoil exposed	A
		(LM)	Litter mixed with topsoil	A
		(TD)	Topsoil disturbed	A
		(TM)	Topsoil mixed with subsoil	A
		(TR)	Topsoil partially removed	A
Severely disturbed	(D3)	(SE)	Topsoil completely removed and subsoil exposed	B
		(SM)	Topsoil mixed with subsoil	B
		(SD)	Subsoil disturbed	B
		(SC)	Subsoil mixed with parent material	B
		(SR)	Subsoil partially removed	B
Very severe disturbance	(D4)	(PE)	Subsoil removed and parent material exposed or mixed with subsoil parent material	C or R

Non soil	(t)	Tree stump	*Qualifiers*	(d)	Obvious soil displacement
	(r)	Rock		(p)	Obvious soil compaction
	(w)	Fallen large tree or log		(a)	Animal digging

C: Soil, and slash piling categories

Soil or soil and slash piling	(S0)		No soil or slash piling	
	(S1)	(S2)	Soil piling < 0.3m,	Soil piling > 0.3m
	(SS1)	(SS2)	Soil and slash piling < 0.3m,	Soil and slash piling > 0.3m
Slash and/or bark piling	(SR)		Scrub rolled	
	(B1)	(B2)	Slash and/or bark piling <0.3m	Slash and/or bark >0.3m

D: Fire intensity categories

Unburned	(F0)	Litter, soil, vegetation unburned
Low intensity	(F1)	Partial burn of slash and litter up to a diameter of 20 mm. Litter O2 horizon, where present, predominantly unburned.
Moderate intensity	(F2)	Near-complete burn of slash and litter up to a diameter of 20 mm, partial burn of branches greater than 20 mm. Some soil oxidation present, but generally charcoal or ash-seedbed
High intensity	(F3)	Near-complete burn of slash and litter up to a diameter of 70 mm, partial burn of branches greater than 70 mm. Soil oxidation (orange ash-bed) predominant.

1. *Randomly locate first quadrat along transect*
2. *Assess the soil disturbance category that occupies the majority of area of the 1m x 1m quadrat.*
3. *If dense slash, bark or soil does not allow soil disturbance to be accurately assessed, score soil disturbance according to surrounding area and most likely soil disturbance category.*
4. *Topsoil is* A_1, A_2 *&* A_3 *horizons except where* A_2 *is conspicuously bleached whereby* A_2 *&* A_3 *are regarded as subsoil.*
5. *Subsoil includes* B_1 *&* B_2 *horizons and* A_2 *and* A_3 *if* A_2 *is conspicuously bleached.*

Snig track area survey

I compared the results and the efficacy of four different techniques for estimating the area of snig tracks on each faller's block. These were the transect-intercept-quadrat method, and the transect based line intercept method, both systematic surveys, and the direct measurement techniques of interpreting aerial photographs, ground traverse using compass and hip-chain, and GPS. I assumed that the ground traverse was the most accurate means of determining snig track area and compared other methods to this. Table 3 lists the various methods used on each faller's block. Snig tracks were classified into one of four operational classes (Table 2) based on an assessment of the relative amount of traffic and the location within the dendritic network of tracks. With the transect-intercept-quadrat-method, each transect-intercept point on the survey was classified into its operational category. The area of snig track in each snig track category was determined as the product of the proportion of all transect-intercept points in each snig track category and the faller's block area. The line intercept survey was conducted along the transect lines that make up the soil disturbance survey. Along these transects the length of transect that intersected each snig track category was recorded, and the area of each snig track category determined from the proportion of the total transect length in each snig track category and the area of the faller's block. In the ground traverse methods (hip-chain and compass, and GPS) snig tracks and the faller's block boundary were walked and mapped. The area of the faller's block and the total length of snig track in each operational category were determined. Snig track area in each operational category (ST0, ST1, ST2, ST3) was determined from the mean snig track width and the total snig track length.

Table 3. The methods used to estimate the area of snig tracks on each faller's block.

Method	**Faller's block**		
	C54	**C35**	**P2**
Aerial photointerpretation	X		
Transect-intercept-quadrat survey	X	X	X
Line intercept survey	X	X	
Hipchain and compass survey	X	X	
GPS survey			X

Bulk Density

The national protocol for measurement of Indicator 4.1e nominates bulk density as the primary measure of soil physical properties. Few measurements of bulk density have been collected in the northern jarrah forest and little is known of the natural range and variability of bulk density in these forests. In addition, the lateritic soils of the jarrah are noted for their exceptionally high gravel content, which ranges up to 80% (Hingston et al., 1980; Sharma et al., 1987). It is generally stated that core based methods of determining bulk density are unreliable in gravelly soils and displacement methods are commonly proposed as a superior alternative for measuring bulk density in gravelly soils. Any method selected for assessing this indicator needs to be accurate, practical, efficient, and suited to rapid measurement in locations accessible only on foot. I examined several methods (nuclear densiometers, the sand replacement technique as per AS1289, water replacement techniques, a modified excavation technique using polyurethane foam, and a range of corer sizes) and determined that core based methods were the only methods likely to meet the practical constraints of this working environment. As corer size is a known source of variability in gravelly soils I examined the effect of corer size on bulk density measurements.

Table 4. The stratification of soil shear strength and bulk density measurements across soil disturbance classes at transect-intercept points on three faller's blocks (C54, C35, P2) in the northern jarrah forest. Table 2 gives detailed definitions of the disturbance classes: D0 = undisturbed, D1 = lightly disturbed, D2 = moderately disturbed, D3 = severely disturbed.

Soil disturbance class	Soil disturbance class transect points n			Bulk density sample points n			Soil strength sample points n		
	C54	C35	P2	C54	C35	P2	C54	C35	P2
D0	289	266	288	74	150	144	89	80	144
D1	80	75	28	37	75	28	80	75	28
D2	68	41	64	68	41	64	68	41	64
D3	14	8	3	14	8	3	14	8	3
Total	451	390	383	193	274	245	251	204	239

Bulk density was determined for surface soils (0-100mm) on three soil disturbance strata, and measured with one of three corer sizes (Table 5). Soils were dried at 105 C for 48 hours, sieved through a 2 mm mesh, the volume of the course fraction (>2 mm) determined by displacement. The fine earth (<2 mm) was weighed, and fine earth and total bulk density calculated. Bulk density was analysed to examine its relationship with soil disturbance class, to determine the variation within undisturbed sites, and to determine the area of the faller's block that exceeds a 20% increase in bulk density. Analysis followed Rab (1998).

Comparison of corer size

Within the undisturbed soil class (D0) at C54 and P2 I compared measurements of mean fine earth bulk density, total bulk density and gravel content determined with three different sized corers. All corers were the same length and sampled the 0-100 mm soil depth. Corer inside diameters were 66.9, 95, and 108 mm (Table 5). Approximately 25 cores were collected with each corer from undisturbed transect-intercept points distributed across each of the faller's blocks.

Table 5. The diameters and volumes of three bulk density corers used in a comparison of the effect of corer size on measured bulk density. All corers had a sampling depth of 100 mm.

Nominal bore of SS tube	**Outside diameter (mm)**	**Internal diameter (mm)**	**Cross sectional area**	**Nominal corer volume (ml)**	**Actual sample volume of corer (ml)**
63.5	73	66.9	35.2	352	348
90	101.6	95	72.2	722	720
100	114.3	108	92.1	921	932

Soil shear strength

Soil shear strength and moisture content were measured on soil disturbance strata within the faller's blocks (Table 4). Measurements of surface soil strength were collected with a Geonor H-60^2 field inspection vane. Strength measurements are reported in t m^{-2}. Multiplying these values by 9.807 converts them to kPa. Measurements were taken under moist soil conditions, and soil moisture measurements were taken across the measurement period to determine the range of soil moisture during measurement. The relationships between soil disturbance class and soil shear strength, and between shear strength and bulk density were examined.

Results

Comparison of Corer size

I compared measurements of fine earth bulk density, total bulk density, and gravel content for undisturbed soil collected with three different sized corers on one high gravel content site and one low gravel content site (Table 6). None of these measures: fine earth bulk density, total bulk density, or gravel content, were significantly different between the three corer sizes (Tukey studentized range with $p = 0.05$). In addition, all corer sizes showed similar amounts of variability about the estimated mean, with the standard errors of these means being comparable and showing no trend with corer size (Table 6).

Table 6. The effect of corer size on measured values of fine earth bulk density, total bulk density, and gravel content of undisturbed soils at one high and one low gravel content jarrah forest site: Plavins 2, gravel content 70% and Curara 54, gravel content 36%. Values are means ± standard errors for undisturbed soils. Within each site neither the fine earth bulk density, the total bulk density or the gravel content were significantly different between different corer sizes (Tukey test, $p = 0.05$).

Site	**Corer size**	**Corer volume** (ml)	**n**	**Fine earth bulk density** g cm^{-3} ± s.e.	**Total bulk density** g cm^{-3} ± s.e.	**Gravel content** % ± s.e.
Curara 54	Small	348	26	0.667 ± 0.028	0.943 ± 0.027	35.0 ± 3.2
	Medium	720	23	0.657 ± 0.024	0.933 ± 0.015	36.5 ± 2.7
	Large	932	25	0.660 ± 0.030	1.119 ± 0.044	35.3 ± 3.1
	All corers		74	0.662 ± 0.016	0.999 ± 0.021	35.6 ± 1.7
Plavins 2	Small	348	25	0.585 ± 0.082	1.421 ± 0.104	70.7 ± 2.1
	Medium	720	25	0.594 ± 0.074	1.440 ± 0.095	70.9 ± 1.5
	Large	932	25	0.633 ± 0.081	1.460 ± 0.120	67.5 ± 3.0
	All corers		75	0.604 ± 0.020	1.440 ± 0.027	69.7 ± 1.3

Soil disturbance

Of the three faller's blocks C54 had a greater proportion of disturbance (36% disturbed) than both C35 (32% disturbed) and P2 (25% disturbed) (Table 7). The amount of disturbance was significantly different between faller's blocks (Chi-square $p<0.005$). P2 with its high gravel content (70%) had the least amount of disturbance. The distributions of disturbance also showed that the disturbed areas on C54 had greater proportions of moderately and severely disturbed soil than either C35 or P2 (Table 7).

Table 7. The distribution of soil disturbance classes within three faller's blocks in the Northern jarrah forest of south-west Western Australia, and the fine earth bulk density, total bulk density, and soil shear strength for these soil disturbance classes. Means with different letters are significantly different (Tukey test, p=0.05). Table 2 gives detailed definitions of the disturbance classes: D0 = undisturbed, D1 = lightly disturbed, D2 = moderately disturbed, D3 = severely disturbed. Total disturbed = D1+D2+D3.

Site	**Soil disturbance classification**	**% of faller's block area**	**Fine earth bulk density** g cm^{-3} ± s.e.	**Total bulk density** g cm^{-3} ± s.e.	**n bulk density**	**Soil shear strength** t m^{-2} ± s.e.	**n soil strength**
C54	D0	64.1	0.662 ± 0.016^{a}	0.999 ± 0.021^{a}	74	27.44 ± 0.98^{a}	89
C54	D1	17.7	0.694 ± 0.024^{a}	1.007 ± 0.023^{a}	37	33.43 ± 1.89^{a}	80
C54	D2	15.1	0.834 ± 0.024^{b}	1.095 ± 0.022^{a}	68	60.68 ± 5.83^{b}	68
C54	D3	3.1	1.012 ± 0.043^{c}	1.248 ± 0.045^{b}	14	74.43 ± 8.94^{b}	14
	Total disturbed	35.9					
C35	D0	68.2	0.620 ± 0.016^{d}	1.277 ± 0.018^{c}	150	20.59 ± 0.64^{c}	88
C35	D1	19.2	0.635 ± 0.024^{d}	1.310 ± 0.029^{c}	75	21.60 ± 1.09^{c}	75
C35	D2	10.5	0.764 ± 0.029^{d}	1.391 ± 0.040^{c}	41	25.07 ± 1.93^{c}	41
C35	D3	2.1	0.755 ± 0.061^{d}	1.597 ± 0.116^{d}	8	22.25 ± 4.70^{c}	8
	Total disturbed	31.8					
P2	D0	75.2	0.583 ± 0.014^{e}	1.405 ± 0.020^{e}	144	22.23 ± 12.00^{d}	144
P2	D1	7.3	0.689 ± 0.017^{e}	1.540 ± 0.039^{ef}	28	21.79 ± 5.29^{d}	28
P2	D2	16.7	0.697 ± 0.023^{e}	1.532 ± 0.040^{ef}	64	25.53 ± 8.00^{d}	64
P2	D3	0.8	0.743 ± 0.128^{e}	1.717 ± 0.013^{f}	3	24.00 ± 1.73^{d}	3
	Total disturbed	24.8					

Table 8 shows the proportion of soil disturbance classes within each operational category. C54 has only an intermediate amount of disturbance within the harvested area but has a relatively high amount of disturbance on snig tracks. Although P2 had a relatively low amount of disturbance, Table 7 shows that P2 had a large proportion of disturbance on snig tracks and relatively little disturbance within the harvested area.

Table 8. The distribution of operational classes within three faller's blocks in the northern jarrah forest of south-west Western Australia. See Table 2 for descriptions of operational classes. Total disturbed = D1+D2+D3.

Operational Category	**Soil Disturbance**	**C54 %**	**C35 %**	**P2 %**
HA	D0	61.9	67.4	74.9
HA	D1	11.1	16.2	3.9
HA	D2	5.1	4.1	1.0
HA	D3	0.2	1.0	0.3
HA	Total disturbed	16.4	21.3	5.2
ST	D0	0.2	0.3	0.3
ST	D1	6.7	3.1	3.4
ST	D2	10.0	6.4	15.9
ST	D3	2.7	1.0	0.3
ST	Total disturbed	19.4	10.5	19.6
LL	D2	0	0	1.0
LL	D3	0.2	0	0.3
UA	D0	1.3	0	0
OST	D0	0	0.5	0
OL	D0	0.7	0	0

Snig track areas

Snig tracks covered between 11.6% and 14.2 % of the total area of the three faller's blocks I surveyed (Hip chain and compass, and GPS values). Estimates determined with the three methods varied widely (Table 9). No estimate was determined from the aerial photo-interpretation as snig tracks were not clearly visible.

Table 9. Comparison of estimates of snig track areas determined by transect-intercept-quadrat, line intercept, and traverse (hip-chain and compass or GPS) survey methods. The total snig track area and areas for four orders of snig track (ST0, ST1, ST2, ST3) on faller's blocks C54, C53, and P2. Areas are expressed as m^2 and as a percentage of the total area of the faller's block.

Faller's block (area) and survey method	**ST0** m^2 (%)	**ST1** m^2 (%)	**ST2** m^2 (%)	**ST3** m^2 (%)	**Total** m^2 (%)
C54 (16.122 ha)					
Hip-chain	1,158	2,528	4,571	12,227	20,485
	(0.70)	(1.57)	(2.80)	(7.60)	(12.67)
Transect-intercept-quadrat	2,145	6,435	6,435	13,584	28,598
	(1.33)	(3.99)	(3.99)	(8.43)	(17.74)
Line intercept	363	3,614	6,698	13,453	24,127
	(0.23)	(2.24)	(4.15)	(8.34)	(14.97)
C35 (25.421 ha)					
Hip-chain	1,283	5,586	16,398	12,714	35,981
	(0.50)	(2.20)	(6.45)	(5.00)	(14.15)
Transect-intercept-quadrat	639	4,471	7,665	14,052	26,826
	(0.25)	(1.76)	(3.02)	(5.53)	(10.55)
Line intercept	967	4,445	7,328	14,819	27,559
	(0.38)	(1.75)	(2.88)	(5.83)	(10.84)
P2 (12.938 ha)					
GPS	570	3,667	3,868	6,858	14,963
	(0.44)	(2.83)	(2.99)	(5.30)	(11.57)
Transect-intercept-quadrat	1,689	4,391	6,418	11,485	23,984
	(1.31)	(3.39)	(4.96)	(8.88)	(18.54)

Bulk Density

Fine earth bulk density was significantly different between soil disturbance classes on C54 but not on C35 or P2 (Table 7). Total bulk density was significantly different between soil disturbance classes on all sites. Fine earth bulk density was significantly different between operational categories on C54 and C35 but not on P2. The total bulk density was significantly different between operational categories on C35 and P2 but not on C54.

The Indicator

Following Rab (1998) an approximation of Montreal indicator 4.1e is given by the area of D1 and D2 affected by a greater than 20% increase in bulk density over the mean of the undisturbed (D0), and the area affected by subsoil disturbance (D3). Areas classified D0 and known to be undisturbed are not considered in the estimate of the Indicator. Table 10 gives these areas for all sites calculated using firstly total bulk density and secondly fine earth bulk density. On all sites, fine earth bulk density produces a much higher estimate of the proportion of the block affected by soil disturbance than does total bulk density. The estimate based on total bulk density indicates C35 has the greatest area of soil disturbance, and C54 the least. Using fine earth bulk density C54 has the greatest area of soil disturbance, and P2 the least.

Table 10. The proportion of each disturbance class where the post logging bulk density was 20% greater than the mean of the undisturbed areas on the faller's block, and an estimate of the proportion of the faller's block that exceeded the first approximation of Montreal indicator 4.1e proposed by Rab (1998).

Site	**Disturbance class**	**Measurement points n**		**Percentage of block area with >20% increase in bulk density**	
		Soil disturbance	**Bulk density**	**Total bulk density**	**Fine earth bulk density**
C54	DO	289	74	9.5	12.1
C54	D1	80	37	1.0	4.3
C54	D2	68	68	4.7	8.2
C54	D3	14	14	2.2	2.9
C54	Indicator 4.1e			8.7	15.6
C35	DO	266	150	8.2	19.1
C35	D1	75	75	4.4	5.1
C35	D2	41	41	2.8	5.9
C35	D3	8	8	0.8	1.0
C35	Indicator 4.1e			9.2	13.1
P2	D0	288	144	11.5	18.3
P2	D1	28	28	2.3	3.7
P2	D2	64	64	5.5	7.6
P2	D3	3	3	0.8	0.3
P2	Indicator 4.1e			8.6	12.1

Soil shear strength

Soil strength was significantly different between soil disturbance classes on C54 (GLM p=0.0001) (Table 7). Tukey's test (p=0.05) identifies two soil disturbance classification groups, D0, D1, and D2, D3 (Table 7). On C35, soil disturbance class was not significantly related to soil strength (GLM p=0.0764), and there was little variation in soil strength between the disturbance classes on this site. On P2 soil strength was significantly related to soil disturbance classes (GLM p=0.005) however the differences in soil strength between disturbance classes were not significant (Table 7).

Soil moisture at the time of the soil strength measurements was much higher on C54 than on C35 and P2. There was little or no difference in moisture content between measurement days on C54 and C35 (Table 11). Strength measurements at P2 were completed in a single day. The moisture content of soils on harvested areas of C54 was higher than that on snig tracks with much less moisture in the compacted soils.

Table 11. Soil moisture content at three jarrah forest sites at the time of soil strength measurements

Date	**Faller's block**	**n**	**Operational category**	**Soil moisture content % ± s.e**
7/09/00	C54	10	HA	37 ± 2.5
8/09/00	C54	5	HA	38 ± 1.8
7/09/00	C54	5	ST1	23 ± 1.7
28/09/00	C35	10	HA	12 ± 1.0
29/09/00	C35	10	HA	13 ± 1.4
4/06/01	P2	5	HA	16 ± 3.3
4/06/01	P2	1	ST2	10
4/06/01	P2	1	ST3	22

Discussion

Comparison of heavily disturbed and typical jarrah faller's block

Faller's block C54 had relatively steep slopes for a jarrah forests site, low soil gravel content, and was logged under wet conditions in winter. These are all atypical conditions for logging in the northern jarrah forest. This site was studied as it represented an extreme in soil disturbance intensity for the jarrah forest. By comparison both C35 and P2 were regarded as more typical examples of logging operations in the northern jarrah forests. Both the total amounts of disturbance and the distribution of disturbance classes across the three faller's blocks confirm these general observations regarding the amounts of disturbance on these faller's blocks.

The Indicator

Approximately 20% to 30% of the undisturbed sample points had fine earth bulk densities that were more than 20% above the mean fine earth bulk density for that site. This gives an indication of the variability that occured naturally within these faller's blocks. These undisturbed sample points are not included in the estimate of the area affected by soil disturbance.

The estimate of the Indicator based on total bulk density shows little difference between the three sites, with all sites having approximately 9% of the block disturbed (Table 10). This is in contrast to the results from the soil disturbance survey, which clearly identified a greater intensity and extent of soil disturbance on C54 than on C35 and P2, and is contrary to what would be expected from the differences in soil, topography, and moisture conditions that affected these three logging operations. However the estimate of the Indicator calculated from fine earth bulk density yields clear differences between the sites ranging from 12% to 16%, and shows C54 as the most disturbed site. This exercise indicates that on these gravelly soils, fine earth bulk density, though more difficult to measure than total bulk density is superior for interpreting the Indicator.

Time required for surveys

Table 12 gives the mean times taken to complete the soil disturbance surveys, bulk density measurements of the surface soil, and soil strength surveys. For a mean of 400 transect intercept points spread over a faller's block of 18 ha the time required for the soil disturbance survey and bulk density measurements is 41 man days or 8.2 man weeks. This does not include the time required for data entry and processing. This is clearly a substantial commitment of time to collect this information. The majority of time (29 man days) is devoted to bulk density sample collection and processing. The remaining 12 man days is devoted almost equally to the soil disturbance survey and snig track mapping. Substantial efficiencies could be achieved by replacing the bulk density measurements with some other measurement, such as soil strength, and using more efficient snig track mapping methods (eg. GPS).

Table 12. Time required for field and laboratory components of the soil disturbance surveys and bulk density measurements of surface soil.

Task	**Time per transect intercept point** (minutes)	**Time per ha**	**Time for 400 points or 18 ha** (minutes)	**Time for 400 points or 18 ha** (hours)
Soil disturbance survey	6.5	2 hrs 30 mins	2600	43.33
Snig track survey and mapping		2 hrs 35 min	2790	46.50
Soil strength measurements	7			
Bulk density sample collection	14		5600	93.33
Laboratory processing of bulk density samples	13.5		5400	90
Gravel volume analysis for bulk density	5.25		2100	35
Total time			18490	308.17

Bulk density measurement methods

The jarrah forest soils of WA have extremely high gravel contents (eg. 80% gravel) and it is generally considered difficult to accurately measure bulk density in gravelly soils (Blake, 1965; Vincent and Chadwick, 1994; Page-Dumroese et al., 1999). Avery (1974) gives general guidelines for the sizes of samples needed for gravelly soils of various types. A number of techniques have been proposed for this measurement (Blake, 1965; Flint and Childs, 1984; Erbach, 1982; Andraski, 1991; Muller and Hamilton, 1992; Page-Dumroese et al., 1999). These can be grouped under three headings: corer techniques, displacement techniques, or nuclear densiometry. I examined and considered nuclear densiometers, the sand replacement technique (as per AS1289), water replacement techniques, a modified excavation technique using polyurethane foam, and core sampling with a range of corer sizes. The aim of this work was to identify an efficient, accurate, and cost-effective technique suited to field use in the jarrah forest.

Of the displacement techniques the Australian standard sand replacement technique (AS1289) is accurate, but excavation and measurement is slow and sand replacement requires large volumes of heavy sand which cannot be readily transported into the forest. Similar problems occur with water displacement techniques, with the added inconvenience of ruptured membranes (I have never tested any of the balloon and pump measurement devices that appear to provide a sound solution, although they are rarely used as they are regarded as problematic). I trialed the foam mould displacement technique proposed by Muller and Hamilton (1992) and Page-Dumroese et al. (1999). This was found to be slow, and required revisiting the site. I experienced problems in obtaining accurate moulds. Too much or too little foam produced poor moulds, and water in the soil and soil/air temperature affected the foam expansion. Nuclear densiometry is not suited to uneven heterogeneous surfaces found in forests, gives total bulk density, and requires a core sample to calculate fine earth bulk density. The requirement for a core sample almost rules out nuclear densiometry other than as an independent calibration for core samples. For these reasons I focused on developing an accurate coring technique and identifying an appropriate corer size.

Corer size

No significant differences were found in either fine earth or total bulk density measurements collected with three different sized cores, and measurement variability did not differ substantially or in a consistent manner with corer size (Table 6). Variability about the mean was greater on the high gravel content site than on the low gravel content site. On the low gravel content site the standard error for fine earth bulk density was approximately 4% of the mean for all corers (n = 25, gravel content 36%), compared with approximately 13% of the mean for the high gravel content site (n = 25, gravel content 70%). The standard error for total bulk density was approximately 3% of the mean on the low gravel content site (n = 25) and approximately 7% of the mean on the high gravel content site (n = 25). This variability is relatively small for soils with such high gravel contents. It is likely that the small, round and consistently sized gravels that occur in these soils do not introduce as much error into these measurements as is seen in soils with more angular and irregularly sized gravels. I conclude that carefully collected cores are an accurate and practical method of determining bulk density on these soils, and that measurements obtained with small corers (volume = 348 ml) do not contain any greater error than those obtained with large corers (volume = 932 ml).

Errors in operational class surveys

The three methods used to estimate the area of snig tracks yielded very different estimates within each of the three faller's blocks. The three methods were the transect-intercept-quadrat method, the line intercept method, and compass and hip-chain or GPS survey of snig track lengths and widths. On two of the three faller's blocks both the line intercept and transect-intercept-quadrat methods substantially over estimated the snig track area when compared to the survey methods. On the third faller's block these two methods both underestimated the snig track length.

There are a several potential sources of these errors. Misclassification of snig tracks occurred too frequently. It is very difficult in the transect-intercept-quadrat or line intercept survey to correctly classify snig track order because only a small section of the snig track is considered and snig track order is only clear when the branching structure and the condition of a larger area of snig track is known. Often the area crossed by the transect or line survey has atypically high or low localized disturbance and misclassification of the snig track occurs. Error is also introduced when the transect runs along or parallel to a snig track, as the transect-intercept-quadrat survey method assumes that the transects are crossing the major axis of the snig tracks. A third source of error is the spacing of sample quadrats along the transect in the transect-intercept-quadrat survey. The national protocol for this survey method allows for transect-intercept sample spacings which are greater than the width of the snig tracks. Published work on this technique (e.g., Murphy, 1984; McMahon, 1995a; McMahon, 1995b) relies on estimates from surveys with transect-intercept sample spacings that are smaller than the snig track width (e.g. McMahon uses approximately 1000 survey points per coupe, aiming for 3% error). The wide transect-intercept sample spacings used in this work may be a source of error in estimating snig track area. Williamson (1990) found that his grid based survey of snig tracks over estimated snig track area when compared to a mapping survey.

I examined aerial photography as a means of identify the length and layout of snig tracks in the jarrah forest. It was not possible to produce maps of the snig track layout from aerial photo interpretation, as snig tracks were obscured by trees, understory, and ground vegetation.

Guidelines for monitoring bulk density

Fine earth bulk density samples are more expensive to process than total bulk density samples. Should fine earth or total bulk density be used to monitor soil disturbance? Fine earth bulk density is more meaningful than total bulk density as it is the fine earth component of the soil that undergoes compaction. Gravel typically has a higher bulk density than fine earth. Consequently soils with high gravel content have high total bulk density. Increases in the gravel content increase the total bulk density yet this increase does not reflect compaction of the soil. Consequently difference between sample points and between sites may be driven by variations in gravel content rather than variations in soil compaction. Removing the gravel from the calculation brings all sites to a common basis and enables better comparisons to be made between sites (see Figs. 1 and 2), and should also enable more meaningful comparison within sites. Consequently, although total bulk density identified significant differences between disturbance classes at all three sites, and fine earth bulk density only identified significant differences between disturbance classes at one site (Table 7), the distinctions made by the fine earth bulk density measurements should be more meaningful. Consistent with the previous findings regarding the Indicator, I conclude that fine earth bulk density should be used to monitor soil disturbance.

There was an increase in both fine earth and total bulk density with soil disturbance class on all sites (Figs. 1 and 2) indicating that the visual disturbance classes provide meaningful classifications of soil disturbance. Although I was unable to detect any significant difference in either the fine earth or total bulk density of jarrah forest soils classified as undisturbed, and those classified as lightly disturbed, both fine earth bulk density and total bulk density were higher on the lightly disturbed areas at all sites. The absence of significant differences between the bulk densities of the disturbance classes is due to both the size of these differences and the variation of bulk density within the disturbance classes. From this work it appears that increasing the sample size beyond 75 does little to reduce the size of the standard error of the measured bulk density. Standard errors were large where sample numbers were less than fifteen, and a sample size of forty appears to provide a measurement with relatively low errors at a low cost.

This work demonstrates that small corers can be successfully used to measure bulk density in gravelly soils. Bulk density was significantly related to disturbance classes indicating the value of visual assessment. Fine earth bulk density was superior to total bulk density with these soils, but both measures were expensive to collect.

Soil shear strength

Powers et al. (1998) asserted that the simplest and most practical means of assessing soil physical properties that are related to productivity is by measuring soil strength. Lacy et al. (1998) similarly acknowledged the sensitivity of soil shear strength measurements in monitoring soil disturbance. Our experience supports the utility and sensitivity of this instrument on some sites. The gravelly soils on the sites I studied are an extreme environment in which to use this measurement technique, which is better suited to sand or clay soils. However the Geonor H-60[2] field inspection vane did produced meaningful discrimination between the soil disturbance classes on the block with relatively low gravel content (C54), relatively high soil moisture content and a high degree of soil disturbance. Soil strength did not provide meaningful separation of the disturbance classes on the sites with high gravel content (Fig. 3). This lack of separation on sites with high gravel contents (65% - 70%) indicates that soil shear strength measurements have little or no value on these high gravel content sites.

The difficulty in using soil shear strength measurements as a basis for the Montreal Indicator is in establishing threshold values that can be used to define significant soil disturbance in individual soil types.

Conclusions

I examined a variety of displacement and coring techniques for measuring bulk density in gravelly soils and found that displacement techniques 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 introduced errors equivalent to those present in coring techniques in these gravelly soils. No significant difference existed between estimates of the mean fine earth bulk density, total bulk density, or gravel content from three different corer sizes. The efficiencies of using the smallest corer (internal diameter = 66.9 mm) indicated this as the best method of measuring bulk density in these soils.

Large differences in estimates of snig track area occur between transect-intercept-quadrat, line intercept, and traverse techniques. 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. Using GPS to map snig tracks is 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.

Within the jarrah forest approximately 30% of the total area of logging coupes show visual signs of soil disturbance, however relatively small areas of these logging coupes (12%-16%) exceeded the 20% increase in bulk density proposed by Rab (1999) as a threshold for Montreal Indicator 4.1e. Fine earth bulk density provides a more meaningful basis for interpreting the indicator than total bulk density. Bulk density measurements are time consuming and costly to collect, and soil strength and visual classification provide a simpler and more efficient means of identifying disturbed soil.

Although it is a valuable and meaningful measure of soil disturbance, the expense of collecting bulk density 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.

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Figure 1. The mean total bulk density measured on visually assessed soil disturbance classes after logging at three sites in the northern jarrah forest. Error bars are standard errors of the mean

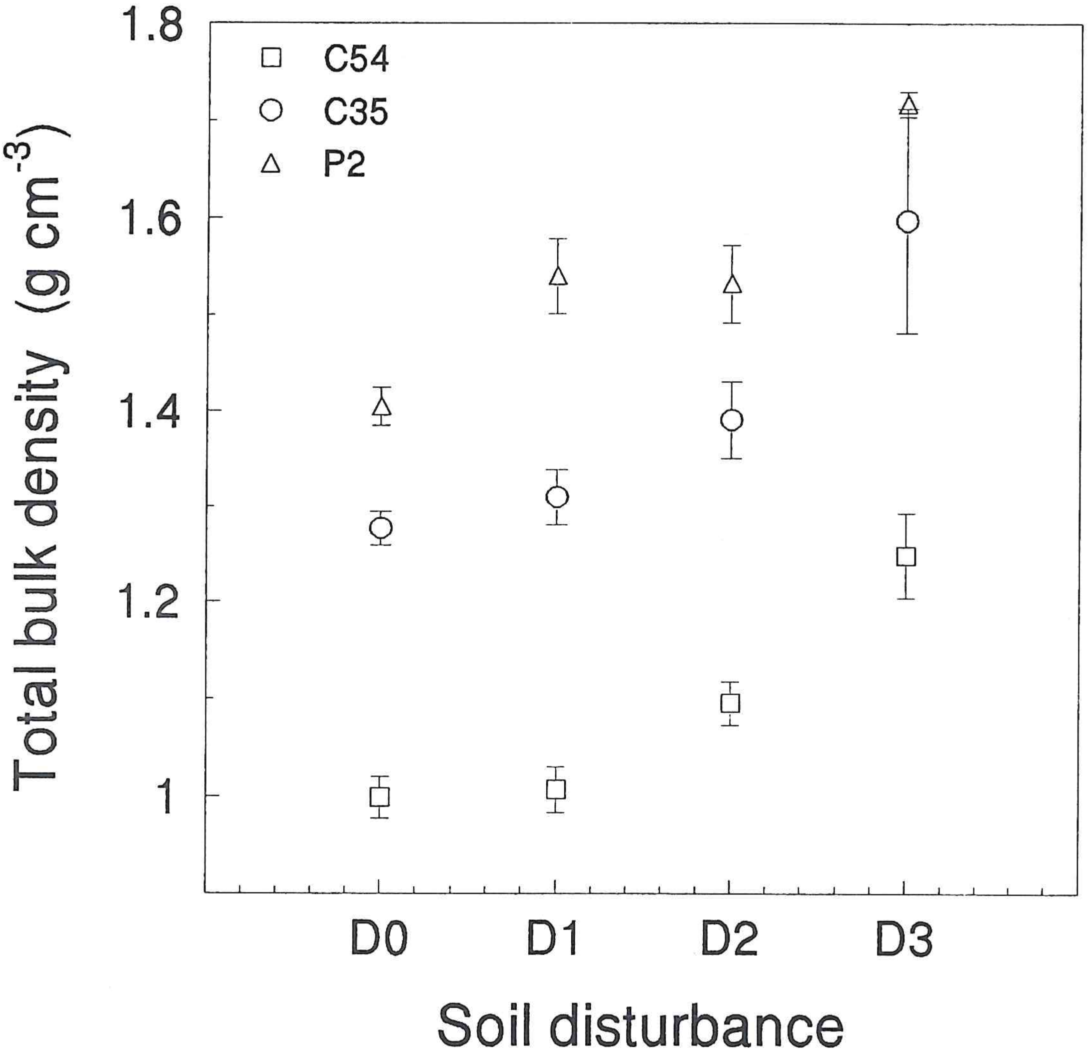


Figure 2. The mean fine earth bulk density measured on visually assessed soil disturbance classes after logging at three sites in the northern jarrah forest. Error bars are standard errors of the mean

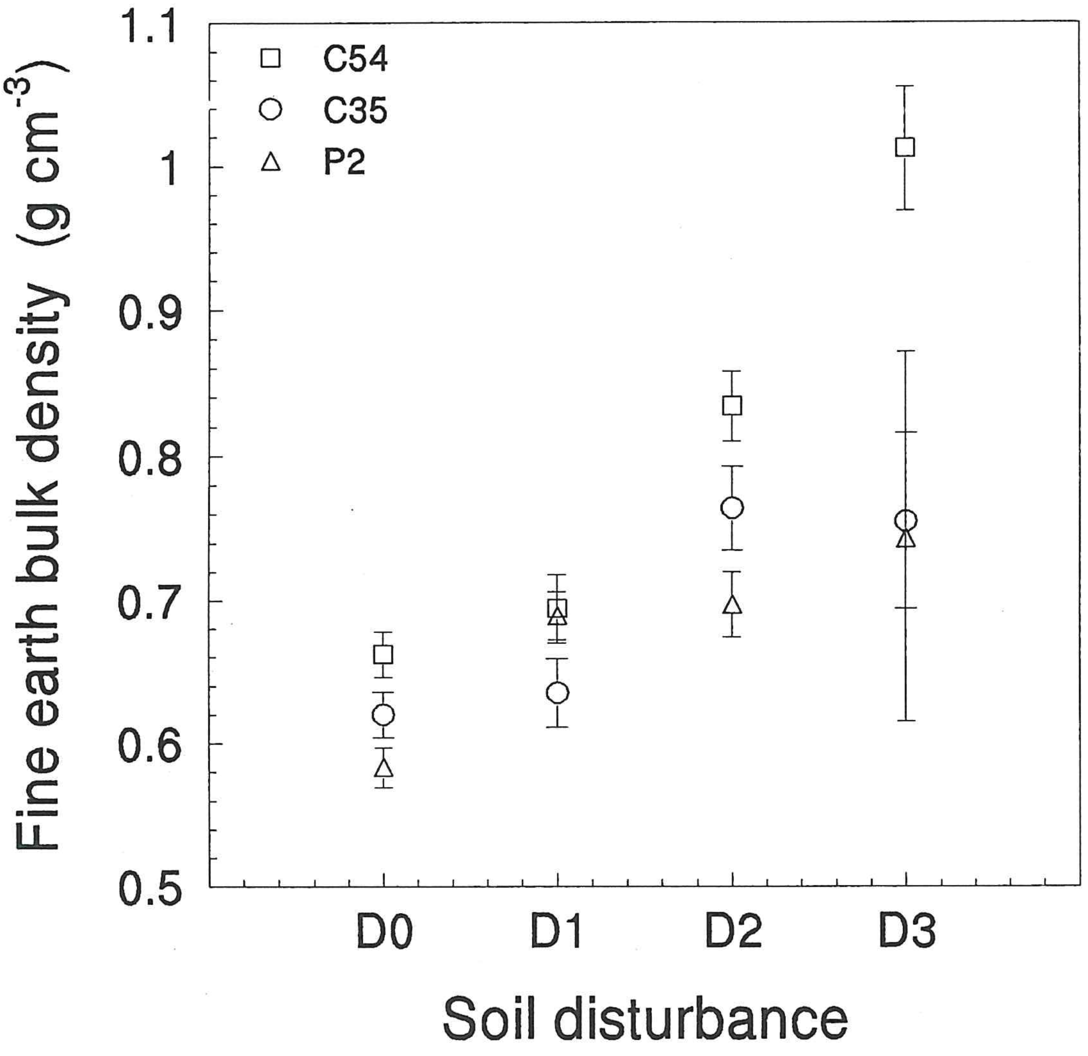
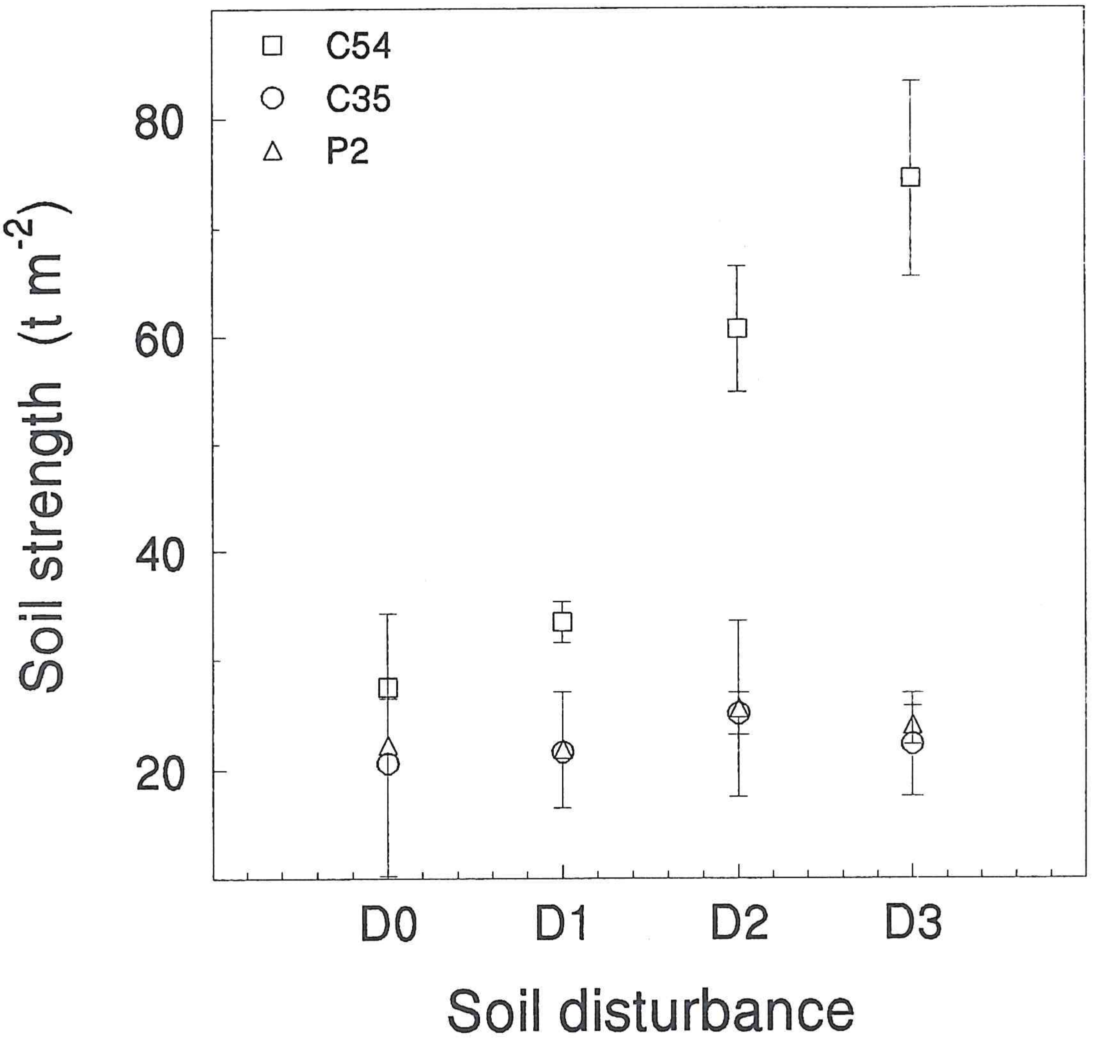


Figure 3. The mean soil shear strength measured on visually assessed soil disturbance classes after logging at three sites in the northern jarrah forest. Error bars are standard errors of the mean



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

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** ($m^3ha^{-1}yr^{-1}$)	**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.

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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).

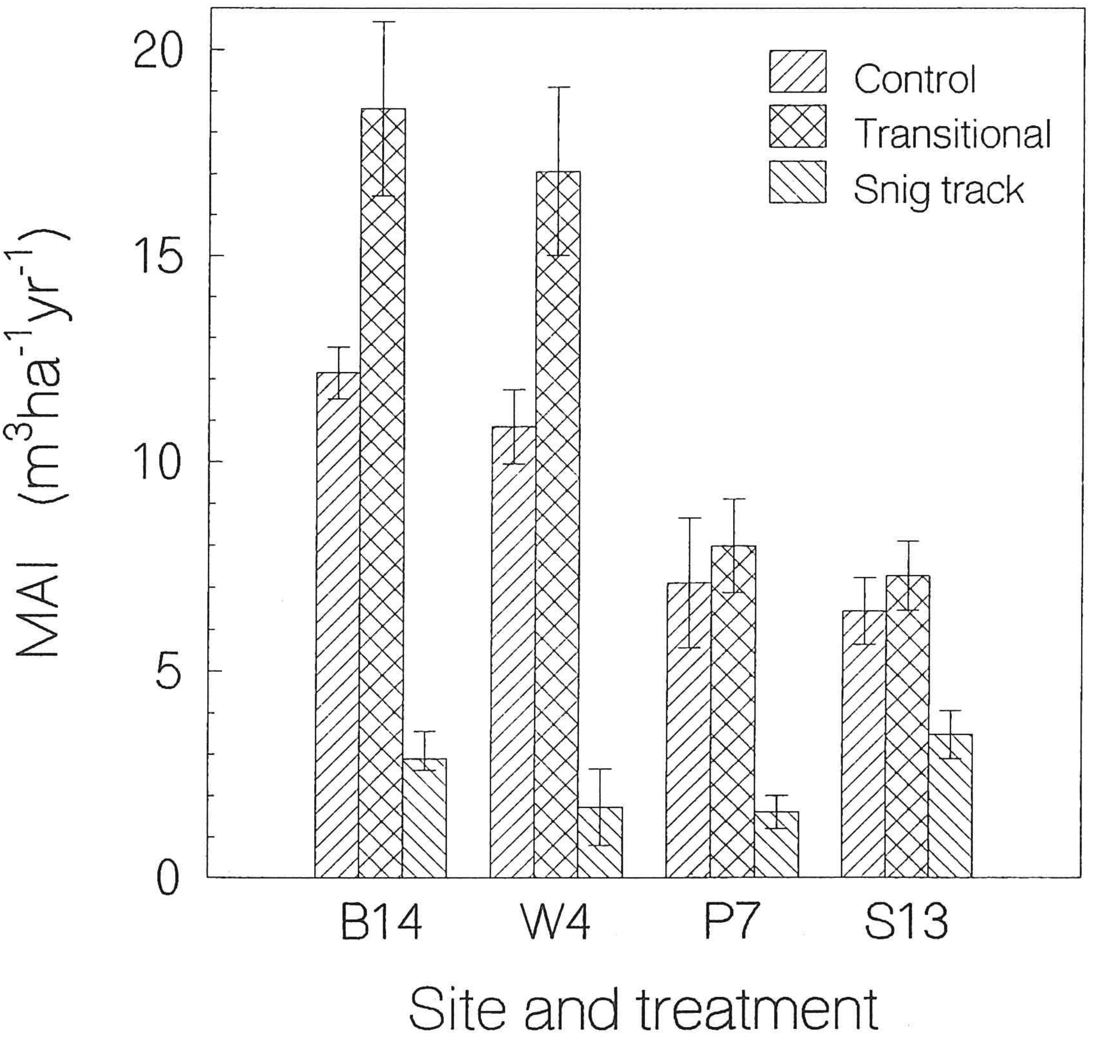

Figure 2. The mean fine earth bulk density of control, transitional, and snig track plots on two sites in the karri forests.