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** $g\ cm^{-3} \pm$ s.e.	**Total bulk density** $g\ cm^{-3} \pm$ 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

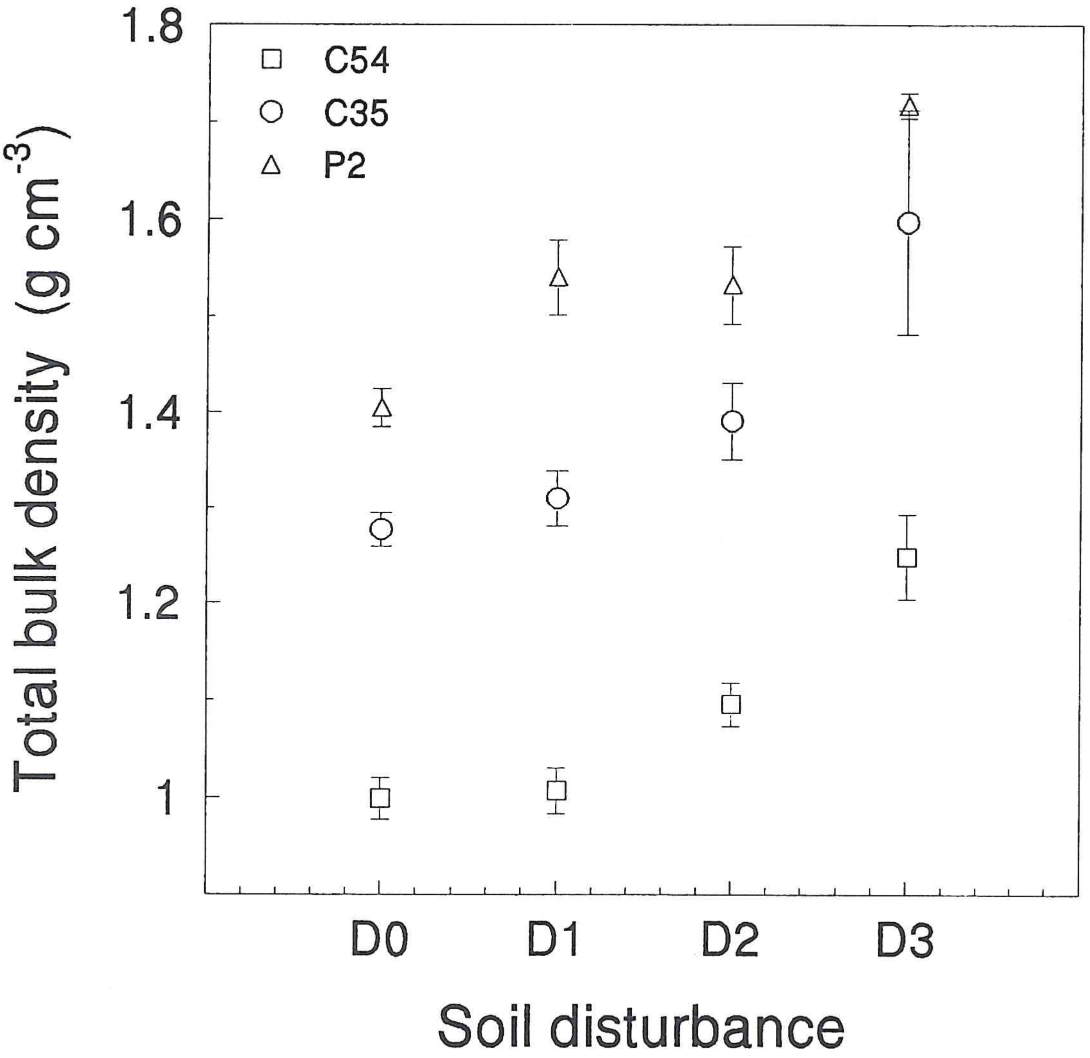


Figure 2. The mean fine earth bulk density measured on visually assessed soil disturbance classes after logging at three sites in the northern jarrah forest. Error bars are standard errors of the mean

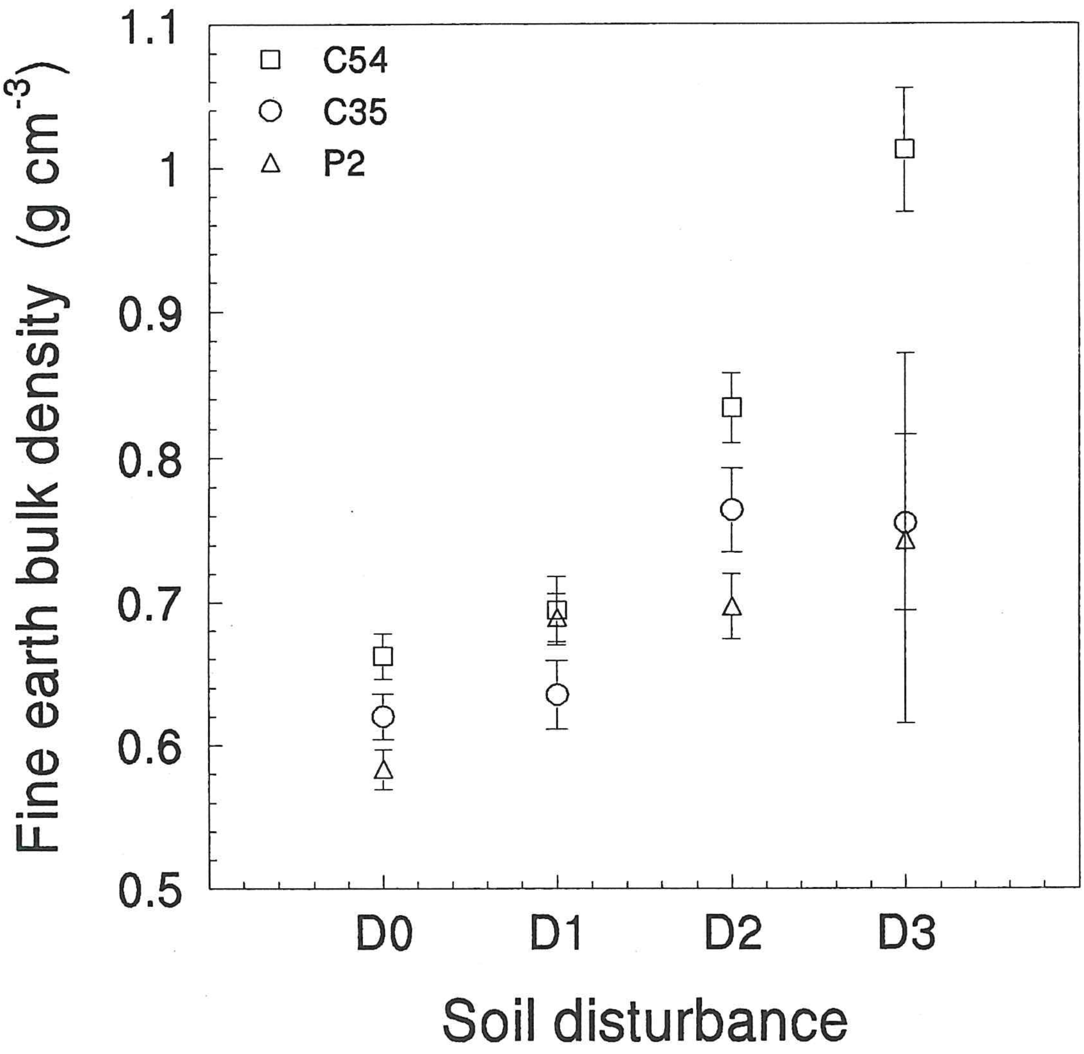
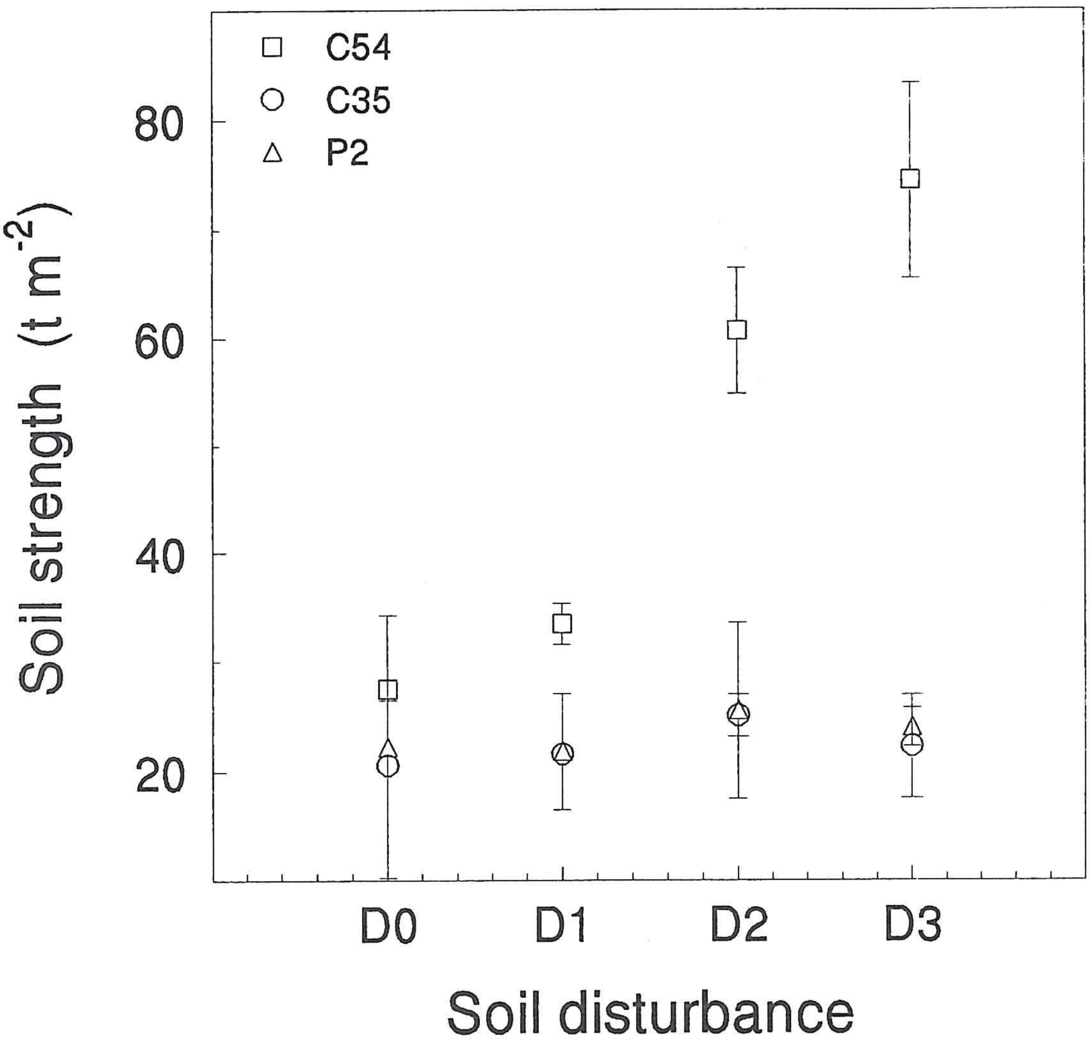


Figure 3. The mean soil shear strength measured on visually assessed soil disturbance classes after logging at three sites in the northern jarrah forest. Error bars are standard errors of the mean



FOREST & WOOD PRODUCTS
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DEPARTMENT OF
Conservation
AND LAND MANAGEMENT
Conserving the nature of WA

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

K.R. Whitford

Final Report

PROJECT NUMBER: PN99.802

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

CONTENTS

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SUMMARY

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

Part 1

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

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

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

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

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

Part 2

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

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

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

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

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

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

Part 3

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

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

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