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Evaluation of the use of pre- and post-harvest bulk density measurements in wet *Eucalyptus obliqua* forest in Southern Tasmania

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Abstract

Criteria and indicators under the Montreal process are intended to provide a common framework for describing and evaluating progress towards sustainable forest management. In 1998 a nationally coordinated project was initiated to evaluate proposed Montreal indicators 4.1.d and 4.1.e and to provide advice to state agencies on how these indicators could be applied. Interim indicator 4.1.e quantifies '*Proportion of harvested forest area with significant change in bulk density of any horizon of the surface (0–30 cm) soil*'.

Application and evaluation of this interim indicator was conducted as part of the Warra Silvicultural Systems Trial, in Tasmania, Australia. This forest was composed of wet mixed regrowth/mature *Eucalyptus obliqua* forest with a dense rainforest understorey. Pre-harvest soil sampling was conducted in four stands followed by post-harvest sampling at two of the sites.

Pre-harvest sampling according to soil drainage class, showed that there was a high natural variation in bulk density within individual stands and between neighbouring stands.

Post-harvest sampling was stratified according to major operational areas and disturbance classes, including snig tracks (major and minor), firebreaks, harvested and unharvested areas, landings and access roads. Forest harvesting substantially increased the variability of soil bulk density. Though moderate and severe disturbance of the snig tracks and firebreaks increased average soil bulk density, changes in soil bulk density were not uni-directional. Many of the post-harvest samples showed a marked decline in soil bulk density due to the incorporation of litter and slash in the upper soil layer.

Bulk density changed most in the upper 0–100 mm layer of soil. Hence there is reasonable argument that monitoring changes in bulk density should be limited to this depth. This would substantially reduce the cost of replicate sampling to the 300 mm depth.

The high natural variation found for soil bulk density and the fact that changes are not uni-directional means that it is unlikely that the interim indicator proposed can be implemented in a practical, sensitive and cost-effective manner in the forest type examined in this study.

Keywords: Montreal process; *Eucalyptus obliqua*; Montreal indicators

1. Introduction

Montreal process criteria and indicators (C&I) have been proposed to help define sustainable forest

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management (Canadian Forest Service, 1995). The Ministerial Council on Forestry, Fisheries and Aquaculture (MCFFA) has endorsed the use of these C and I, as part of Australia's commitment to the sustainable management of its native forest estate. It is envisaged that a number of these indicators will be used at a regional level to assess the impacts of forestry practices, and to monitor the outcomes from the Regional Forest Agreements (RFAs).

Montreal Criterion 4 encompasses the conservation of soil and water. Indicator 4.1.e is the area and percent of forested land with significant compaction or change in soil physical properties resulting from human activities. The rationale behind this indicator is that soil physical change induced by forest activities may adversely affect soil fertility.

It has been recognised that it would be impractical to utilise or evaluate all the possible measures for determining change in soil physical properties (bulk density, hydraulic conductivity, porosity or soil strength) at an operational level. In response to this recognition, the Montreal Process Implementation Group (MIG) has proposed an interim indicator (MIG, 1998), which states, 'Proportion of harvested forest area with significant change in bulk density of any horizon of the surface (0–30 cm) soil.'

A national strategy was developed to phase the introduction of Montreal indicators according to the level of current knowledge. Indicator 4.1.e (and the interim indicator) was listed in category C, those indicators where significant research and development was required to assess if there was a practical, sensitive and cost-effective means of implementation.

Under the Wood and Paper Industry Strategy (WAPIS), a national research program on soil indicators was established to study soil indicators 4.1.e and 4.1.d (changes in soil chemical properties). One of the major objectives of this program was to 'determine the effects of forest management practices on soil organic matter and soil bulk density in a range of contrasting environments'. Collection of data at a series of well-planned and implemented case studies were considered to be the best option for evaluating this and many other indicators. A joint study was undertaken between CSIRO Forestry and Forest Products, Forestry Tasmania, Tasmanian Forest Research Council and Forest and Wood Products Research and Development Corporation at the Warra Long-term Ecological Research (LTER) Site in Southern Tasmania. The principal objective was to evaluate Montreal indicator 4.1.e, particularly the proposed interim indicator, and if possible develop guidelines for monitoring changes in soil bulk density in harvested native forests.

2. Methods

2.1. Study area

The Warra LTER Site was established by Forestry Tasmania to study the ecology of the cool temperate (*Eucalyptus obliqua* L'Herit) wet forest ecosystem in Tasmania. This forest community is widespread throughout the state in both designated conservation and wood production areas. The 15,900 ha site is located in Southern Tasmania. Its approximate central position (Mt Fredrick) is at 43°3′S, 146°39′E (Hickey et al., 1999a). Analysis of vegetation, geology, climate and topography has shown that the Warra site is broadly representative of wet *E. obliqua* forests in the wider Tasmanian landscape (Neyland et al., 2000).

The Warra LTER Site Silvicultural Systems Trial (Warra SST) was established in 1997 on a 200 ha area of mixed regrowth/mature *E. obliqua* forest to compare a range of potentially feasible alternative harvesting and regeneration systems with the conventional clearfell, burn and sow system. The conventional system is routinely applied in Tasmania to regenerate over 90% of harvested lowland wet eucalypt forests. Silvicultural treatments listed in Table 1 were planned for the Warra SST, after a review of past silvicultural trials in both Tasmania and Victoria by Forestry Tasmania, and consultation with numerous stakeholders. Even though some treatments may be sub-optimal in terms of cost and wood production, these alternative treatments may improve maintenance of non-wood values: e.g. biodiversity, soil productivity or aesthetic values (Hickey et al., 1999b).

Pre-harvesting soil and site surveys and sampling were restricted to two of the silvicultural treatments; clearfell, burn and sow coupes (WR008B and WR008H) and the dispersed retention (WR001B and WR008C). On the coupes studied, all soils were derived from Jurassic dolerite (Laffan, 2001), the

Table 1
Silvicultural treatments for the Warra Silvicultural Systems Trial and their perceived advantages

Treatment	Potential benefits	Coupes	Soil sampling	
			Pre-harvest	Post-harvest
Clearfell, burn and sow (CB and S)	Seedbed for eucalypts Safe harvesting Low costs of supervision Reduced fuel loads Maximises eucalypt growth	WR008B WR008H	Yes Yes	Yes No
CB and S with understorey islands	>Biodiversity	WR008B WR008H	Yes Yes	Yes No
Stripfell (cable harvested) (250 m by 80 m strips; low intensity burn, natural seedfall Patchfelling (cable harvested) (250 m by 200 m patch; low intensity burn, natural seedfall)	>Natural seed <Soil damage >Rainforest species			
Dispersed Retention (10% basal area retention, low intensity burn, natural seedfall)	>Natural seed >Biodiversity (hollows) >Aesthetics >Large logs	WR001B WR008C	Yes Yes	Yes No
Aggregated Retention (30% basal area retention, log one tree length either side of snig tracks, retain aggregates of 0.5 to 1.0 ha, low intensity burn, natural seedfall)	>Natural seed >Biodiversity (hollows) >Aesthetics >Safety			
Single tree/small group selection logging (permanent snig tracks, harvest 40 m^3 ha^{-1} every 20 years, scarification, natural seedfall)	>Natural seed >Biodiversity >Advance growth retention >Rainforest species >Structural diversity			

most common substrate under wet forest in Tasmania. Area of wet sclerophyll and mixed forest occurring on dolerite substrate is 226,500 ha or 23% of the wet forest (eucalypt and mixed) estate throughout the State (Forestry Tasmania, 1998). Chemical analysis of pre-harvest soil samples indicated that for a given soil depth soil chemistry was similar for all coupes. The pH of the upper 0–50 mm soil layer was 4.8 ± 0.4, increasing to 5.0 ± 0.4, 5.1 ± 0.4 and 5.2 ± 0.4 for the 50–100 mm, 100–200 mm and 200–300 mm depths, respectively. The upper 0–50 mm layer contained 7.7 ± 2.3% organic carbon which decreased to 4.0 ± 0.9%, 2.6 ± 0.7 and 1.9 ± 0.6% for the other layers. Similar trends were seen for total N (0.28% at 0–50 mm decreasing to 0.10% at 200–300 mm) and total P (0.015% at 0–50 mm decreasing to 0.009% at 200–300 mm).

Post-harvest survey and soil sampling was restricted to WR008B and WR001B. The dispersed retention coupe (WR001B) was harvested between November 1997 and March 1998; with a low intensity burn conducted during April 1998. The clearfell coupe (WR008B) was harvested between August 1998 and December 1998. A high intensity burn was originally planned for the spring of 1999, but wet conditions delayed this burn until April 2000. During the logging of WR008B, four habitat islands were established. These islands were approximately 40 m × 20 m in size and occupied less than 2% of the coupe. These areas were excluded from post-harvest sampling.

All the above four coupes were logged by ground-based machinery. Most snig tracks were corded to reduce soil degradation and maintain trafficability and water quality. On the major snig tracks, this comprised layers of understorey and non-commercial trees intermixed with copious quantities of bark from the landing. On the minor snig tracks, the cording was generally composed of understorey slash only.

2.2. Site surveys

A random transect method was recommended for pre-harvest sampling of Australian native forest in the original protocol developed for the soil indicator project (WAPIS Soil Indicators Project- Soil Sampling Sub-Group, 1998). Unfortunately, the very dense understorey present on the study coupes severely limited the ability of field staff to move rapidly and safely through the forest. For this reason, a stratified sampling procedure was adopted and initial soil surveys limited to access tracks. Sampling points were assessed at intervals of either 25 or 50 m along all access tracks. At each point the following observations were recorded; (1) soil substrate, (2) drainage class and (3) understorey species. Soil observations were made using a hand auger to depths between 0.8 and 1.0 m or shallower if impeded by stones.

Drainage class was used to stratify the soils, since it has been found to be an important indicator of soil fertility and potential site productivity (Laffan, 1997). Uniform red, reddish brown and yellowish brown colours in the B horizon usually indicate aerobic conditions due to good drainage, whereas pale grey, bluish or olive-green colours reflect anaerobic conditions due to poor drainage. A mixture of colours usually indicates seasonal waterlogging due to imperfect drainage (Grant et al., 1995). In the study, area well-drained soils are characterised by thin (<10 cm) dark brown clay loam topsoils (A1 horizons) overlying yellowish-brown light and medium clay subsoils with moderately to strongly developed subangular blocky structure. Imperfectly drained soils are characterised by thin, very dark greyish brown humic clay loam topsoils overlying mottled yellowish-brown and grey clayey subsoils.

Post-harvest surveys assessed the extent of major disturbance features such as snig tracks, firebreaks and subsoil disturbance. Each coupe was divided by the following categories: operational area (e.g. snig track, firebreaks etc.); disturbance (e.g. undisturbed, light, moderate or severe); soil and slash piling; and fire intensity. The degree of disturbance is dependent upon the soil horizon disturbed and the various disturbance types were designed to take account of both soil disturbance and compaction. Appendix A outlines the “Rab” technique (WAPIS Soil Indicators Project- Soil Sampling Sub-Group, 1998) used to survey WR001B after the low intensity burn. This technique, with its numerous soil disturbance categories, was found to be relatively cumbersome to use in the field. It did not have an adequate category to cover the major corded snig tracks. WR008B was surveyed using a modification (Pennington/Laffan system) of the technique (Appendix B). It was considered that the high intensity burn planned for this coupe was likely to mask some of the soil disturbance, so the survey was conducted prior to the burn.

2.3. Soil sampling

Prior to harvest 10 sites in each coupe were selected for more detailed assessment of both soil physical and chemical properties. These sites were selected on the basis of the proportional representation of the major drainage classes; (1) well and moderately-well-drained, (2) imperfect and poorly drained. An additional eight sites on coupe WR008B were sampled for bulk density only.

In mature *E. obliqua* forest in Southern Tasmania it is difficult to extract a single 0–300 mm core from the clay soils. Bulk density cores were collected using a 70 mm diameter × 100 mm length steel tube driven into the soil profile. Five replicates were collected from 0 to 100 mm. After extracting the tube from the soil without disturbing the core, the ends were trimmed as required and the soil transferred to a plastic bag for transportation to the laboratory. A fresh working surface as close as practical to the original five surface cores was cut at 100 mm depth and three cores were taken from the 100–200 mm depth. This process was repeated for the 200–300 mm layer. A small percentage of cores containing large roots or rocks were discarded and substitute cores collected.

Post-harvest different bulk density sampling strategies were adopted for the two coupes sampled (WR001B and WR008B). For WR001B samples were collected from systematically allocated sample points, on the following operational areas: (1) major corded snig tracks; (2) minor snig tracks; (3) firebreaks and (4) harvest area (undisturbed to moderate disturbance only). On major snig tracks sampling was restricted to those areas where the cording and bark have been lifted to expose mineral soil. The occurrence of severely disturbed sites in the harvested area was less than 3%, and these were not sampled. Surveys after the low intensity burn show that the bulk of this coupe was left unburnt. Hence sampling was restricted to unburnt areas. For WR008B a total of 333 points were surveyed for disturbance. For each disturbance type a randomly selected sub-set of sites ($n = 149$) were tagged prior to the high intensity burn, and of these 96 were sampled post-burn.

To compare the stratified sampling procedure used for this study to the recommended random transect method, each was compared on coupe WR008H. A series of transects at 100 m spacing were located at 250°MN roughly parallel to the contours of the coupe. Bulk density samples were collected along these transects at 10 m intervals. Under the random transect method; bulk density sampling was restricted to the 0–100 mm depth only.

2.4. Bulk density

Bulk density was determined by oven drying cores at 105 °C for 40 h. The gravel (>2 mm) content of soils on all coupes was low but to confirm the exact proportion approximately 20% of samples taken from coupe WR008B were assessed for gravel content. Dried soil samples (of known dry weight) were shaken overnight in 1% solution of Calgon. The slurry was washed through a 2 mm sieve. Gravel >2 mm was collected and dried overnight at 105 °C prior to weighing. This confirmed gravel contents of 2.0, 1.3 and 0.9% for the 0–100, 100–200 and 200–300 mm depths, respectively. Because of these low levels and little variation between depths no attempt was made to correct bulk density results for gravel content. Significant changes in bulk density were assessed utilising Genstat 5 Release 4.1 and included Chi-Square analysis and analysis of variance (ANOVA).

3. Results

3.1. Site survey

The pre-harvest survey confirmed that all soils were derived from Jurassic dolerite. A total of 150 points were assessed with the percentage of each drainage class listed in Table 2. Statistical analysis indicated that there was a significant difference between coupes (Chi-square $P < 0.002$). WR008H and WR001B had a higher proportion of well-drained soil than WR008B and WR008C, and WR001B (17%) had a higher proportion of poorly drained soils than WR008H (5%).

For WR008H a total of 44 observations were made which led to an absolute error of 3% for the recorded 5% of poorly drained soils, 7% for the recorded 27% imperfectly drained soils, and 7% for the recorded 68% of well-drained soils. To halve these errors would require an increase in the sampling intensity by a factor of 4.

The Rab system used for post-harvest survey initially divides the coupe into operational areas, and then by disturbance class (Table 3). Area assessed as harvested was 72.0%, snig tracks 13.7% (6.2% major corded snig tracks and 7.5% minor snig tracks), firebreaks 11.2%, unharvested 1.6%, and access road and landing 1.6%. The high level of firebreaks was due in part to the small area of the coupe (18 ha), compared to the standard operational coupe (>40 ha).

The Pennington/Laffan system also divides the coupe into operational areas and then secondly by disturbance class (Table 3). Area assessed as harvested was 62.2%, snig tracks 17.4% (6.2% major

Table 2
Percentage of different soil drainage classes

Drainage class	Coupe			
	WR001B	WR008C	WR008B	WR008H
Well and moderately-well-drained	68 ± 8	39 ± 7	47 ± 9	68 ± 7
Imperfectly drained	15 ± 6	49 ± 8	38 ± 9	27 ± 7
Poorly drained	17 ± 6	12 ± 5	15 ± 6	5 ± 3

Data are means ± absolute error.

Table 3
Post-harvest soil disturbance survey of coupe WR001B and WR008Bassification system

Disturbance level	Rab classification (Appendix A)			Pennington/Laffan classification (Appendix B)		
	Count	(%)	Category total (%)	Count	(%)	Category total (%)
Access road and log landing						
Undisturbed						
Light						
Undistrubed/light						
Moderate	1	0.3				
Severe	4	1.2	1.6 ± 1.4	9	2.7	2.7 ± 1.8
Firebreaks						
Undisturbed						
Light	3	0.9				
Undist/light				17	5.1	
Moderate	14	4.4		13	3.9	
Severe	19	5.9		24	7.2	
Not assessed			11.2 ± 3.6	4	1.2	17.4 ± 4.2
Snig tracks						
Undisturbed						
Light	15	4.7				
Undist/light				5	1.5	
Moderate	28	8.7		36	10.8	
Severe	1	0.3	13.7 ± 3.8	17	5.1	17.4 ± 4.2
Unharvested						
Undisturbed	5	1.6		1	0.3	
Light						
Undist/light						
Moderate						
Severe			1.6 ± 1.4			0.3 ± 0.6
Harvested						
Undisturbed	35	10.9				
Light	152	47.4				
Undist/light				158	47.4	
Moderate	33	10.3		29	8.7	
Severe	11	3.4		6	1.8	
Not assessed			72.0 ± 5.8	14	4.2	62.2 ± 5.3
	321			333		
	Count	(%)	Absolute Error	Count	(%)	Absolute Error
Undisturbed	40	12.5	3.7			
Light	170	53.0	5.6			
Undisturbed/light				181	54.4	5.4
Moderate	76	23.7	4.7	78	23.4	4.6
Severe	35	10.9	3.5	56	16.8	4.0

Count: The number of sample points within a given operational area with the specified level of disturbance. (%): Percentage of total sites sampled ($n = 321$ WR001B and $n = 333$ WR008B). Sub-total: Percentage of a given operational category. Abs Err: Absolute error of sub total calculated according to McMahon (1995).

corded snig tracks and 10.8% minor snig tracks), firebreaks 17.4%, unharvested 0.3%, and access road and landing 2.7%.

There were a number of notable differences between the coupes. First was the level of firebreaks. The higher level in WR008B was due to wider firebreaks installed to allow for a high intensity regeneration burn, plus the firebreaks around the habitat islands, which accounted for 2.4% of the coupe area. Both decreased the area classified as harvested. Secondly, there was a higher level of snig tracks due to an increase in the area of minor snig tracks. The area of major tracks was 6.2% on both coupes. WR008B was surveyed prior to burning when minor tracks are clearly obvious while WR001B was surveyed after burning when it is more difficult to differentiate minor tracks from the surrounding area.

3.2. Bulk density

The 100 mm × 70 mm diameter steel cores used for sampling at Warra were both highly portable and effective to use. Presence of surface or sub-surface rocks, large roots and fallen trees can make the task of collecting an adequate number of samples to 300 mm very time consuming. Components of variance analysis indicated that the location within the coupe accounted for 61% of the variance in observed bulk density. While only 17% of the variance was due to variation within a site for a given depth. This components of variance analysis indicated that reducing replication at a given site but increasing the number of sites sampled on a coupe would improve the precision of the result.

Only 10 sites (for three coupes) or 18 sites (for one coupe) were sampled for detailed assessment of pre-harvest soil bulk density and chemistry. The number of pre-harvest samples taken will directly affect the level of accuracy of the calculated mean and in turn the assessments based on that mean. The number of samples (N) required to estimate the mean with a given confidence level can be calculated as $N = 4\sigma^2/L^2$ (Snedecor and Cochran, 1967) for a mean with a 95% confidence interval, $L = 5\%$ of the mean, and σ^2 is the variance. The relationship leads to a curve of diminishing returns (Downes et al., 1997). With 10 sampling sites on coupe WR001B the calculated mean (0.86 Mg/m^3) has an accuracy of ±10.2%. To improve the accuracy to 8 or 5%, the number of sampling plots increases to 17 and then to 42. Ten sites were considered to be a compromise that provided a result with an acceptable error (±10%).

With only one sample per site the random transect sampling procedure was less accurate for a given number of plots. With 10 sampling sites on coupe WR008H, the calculated mean bulk density (0.66 Mg/m^3) has an accuracy of ±16%. To improve the accuracy to 10 or 5% the number of sampling points would need to increase to 26 and then to 102. Allowing for sites that could not be sampled due to obstructions (surface and sub-surface rocks) approximately 35–40 sites would be visited to achieve the necessary 26 samples for an accuracy of ±10%.

As expected, soil bulk density was highly dependent upon soil depth; consequently all bulk density data are presented according to depth of sampling (0–100, 100–200 and 200–300 mm). The mean bulk densities for each coupe and the SST overall are summarised in Table 4. The overall mean for the 0–100 mm depth was 0.74 Mg/m^3, but the minimum was 0.40 Mg/m^3 or 46% below the mean, while the maximum was 1.12 Mg/m^3 or 51% above the mean value. The means for the 100–200 and 200–300 mm depths were 1.02 and 1.07 Mg/m^3, respectively, each also having a wide range.

ANOVA confirmed there was a significant difference between coupes at all depths (0–100 mm $P = 0.0080$, 100–200 mm $P = 0.0037$, 200–300 mm $P = 0.019$). For the 0–100 mm depth samples, mean bulk density varied from 0.67 Mg/m^3 for WR008H to 0.86 Mg/m^3 for WR001B.

Table 5 shows the results of post-logging bulk density measurements from the major operational areas of minor snig tracks, major corded snig tracks, and firebreaks, along with the harvested area on WR001B. In both the major and minor snig tracks, and firebreaks the mean bulk density in the 0–100 mm depth had increased by 16% (1.00 Mg/m^3), 14% (0.98 Mg/m^3) and 8% (0.93 Mg/m^3), respectively. At the 5% level there had been a significant increase in bulk density only on the major snig tracks. There was no significant difference in bulk density of the major and minor snig tracks and firebreaks.

Surprisingly, there was a significant ($P = 0.015$) decrease in soil bulk density on the harvested area from 0.86 to 0.67 Mg/m^3. Notably, three of the 15 samples had very low bulk densities (0.28, 0.41 and

Table 4
Soil bulk density (Mg/m^3) for the individual Silvicultural Systems Trial unharvested coupes and the four coupes combined (10 sites per coupe)

Soil depth	Statistic	Bulk density (Mg/m^3)				
		WR001B	WR008C	WR008B	WR008H	Overall
		10 Sites	10 Sites	18 Sites	10 Sites	40 Sites
0–100 mm	Mean ± S.D.	0.86 ± 0.14	0.74 ± 0.10	0.71 ± 0.14	0.67 ± 0.12	0.74 ± 0.14
	Minimum	0.64	0.64	0.40	0.42	0.40
	Maximum	1.12	0.95	0.89	0.80	1.12
	C of Variance	16.2%	13.5%	17.1%	17.9%	18.6%
100–200 mm	Mean ± S.D.	1.16 ± 0.16	0.98 ± 0.14	1.04 ± 0.11	0.98 ± 0.10	1.02 ± 0.14
	Minimum	0.93	0.81	0.76	0.83	0.76
	Maximum	1.48	1.19	1.15	1.12	1.48
200–300 mm	Mean ± S.D.	1.19 ± 0.17	1.03 ±0 .17	1.02 ± 0.12	1.07 ± 0.07	1.07 ± 0.14
	Minimum	0.95	0.87	0.85	0.95	0.85
	Maximum	1.47	1.42	1.18	1.18	1.47

0.46 Mg/m^3) due to the incorporation of litter and fine slash in the upper soil layer.

Changes in bulk density were limited to the upper 0–100 mm layer with no significant differences in the bulk density between the major disturbance features (major and minor snig tracks, and firebreaks) and the pre-harvest samples at either the 100–200 mm, $P = 0.41$ or 200–300 mm, $P = 0.34$ depths.

Table 6 shows the results of the post-logging soil bulk density measurements on WR008B. Sampling for this coupe was restricted to 0–100 mm only. Of the 149 sites tagged prior to the burn, samples could only be obtained from 96 (65%). Surface or sub-surface rocks were the major reason for preventing bulk density samples being obtained. Other reasons included the site being waterlogged, occupied by stump or old logs, or covered by dense mixture of soil and slash. A number of the sampling points were still covered by a dense mat of bark (~1 m deep) on the major corded snig tracks. These mats proved too difficult and time consuming to remove.

For the major operational areas, the measured changes in bulk density were a 17% increase for the major snig tracks, a 1% decrease for the minor snig

Table 5
Soil Bulk Density (Mg/m^3) prior to harvesting and for the major operational categories following harvesting at WR001B (dispersed retention)

Soil Depth	Statistic	Bulk Density (Mg/m^3)				
		Pre-harvest	Major snig	Minor snig	Firebreaks	Harvested
		10 Sites	8 Sites	9 Sites	7 Sites	15 Sites
0–100 mm	Mean ± S.T.D.	0.86 ± 0.13	1.00 ± 0.11	0.98 ± 0.22	0.98 ± 0.15	0.67 ± .20
	Minimum	0.64	0.88	0.62	0.68	0.28
	Maximum	1.12	1.14	1.26	1.09	1.09
	C of Variance	15.1%	11.0%	22.4%	15.3%	29.8%
100–200 mm	Mean ± S.T.D.	1.16 ± 0.16	1.14 ± 0.11	1.17 ± 0.12	1.05 ± 0.17	
	Minimum	0.93	1.00	0.95	0.81	
	Maximum	1.48	1.29	1.28	1.33	
200–300 mm	Mean ± S.T.D.	1.19 ± 0.17	1.13 ± 0.10	1.21 ± 0.11	1.09 ± 0.16	
	Minimum	0.95	1.02	1.02	0.87	
	Maximum	1.47	1.30	1.34	1.36	

Table 6
Soil Bulk Density (Mg/m^3) prior to harvesting and for the major operational categories following harvesting at WR008B (clearfell)

Soil depth	Statistic	Bulk density (Mg/m^3)				
		Pre-harvest	Major Snig	Minor Snig	Firebreaks	Harvested
		18 Sites	15 Sites	25 Sites	21 Sites	35 Sites
0–100 mm	Mean ± S.T.D.	0.71 ± 0.14	0.83 ± 0.15	0.70 ± 0.23	0.71 ± 0.18	0.63 ± 0.14
	Minimum	0.40	0.60	0.19	0.28	0.36
	Maximum	0.89	1.11	1.15	1.01	0.91
	C of Variance	17.1%	18.1%	32.9%	25.4%	22.2%

tracks, no change for the firebreaks and 11% decrease in the harvested area. For both the minor snig tracks and firebreaks the most notable change was the increase in the range of bulk density recorded. For the minor tracks, measured bulk density ranged from 0.19 Mg/m^3 (on a site where a great deal of bark had been incorporated into the upper soil surface) to 1.15 Mg/m^3 (where there was no cording and the topsoil had been disturbed and compacted by obvious vehicle tracks).

4. Discussion

The aim of the research was to evaluate the Indicator 4.1.e and in particular the interim indicator that has been proposed. There are three important components of the proposed interim indicator to consider and they are highlighted below.

> Proportion of harvested forest area with *significant change* in *bulk density* of any horizon of the surface (0–30 cm) soil.

Are changes in bulk density a useful measure to meet the requirements of this indicator? Of bulk density, shear strength and penetration resistance, Lacey et al. (1994) considered both bulk density and shear strength the more sensitive means of detecting changes in soil physical properties. Rab (1999) proposed a 10% increase in aeration porosity in the 0–100 mm soil depth as a suitable measure. Each method has its advantages or disadvantages in different applications. Shear strength or penetration resistance are relatively quick to use but the results can be highly dependent upon moisture content. Also, for the dolerite soils, the presence of surface and sub-surface rock would make the interpretation of the results from these techniques difficult. Aeration porosity is a very informative measure but the processing of samples can be very time consuming.

Accepting that bulk density is currently the most appropriate and practical method to use, this technique still presents numerous difficulties in dense wet *E. obliqua* forests. The application of the stratified pre-harvest sampling procedure was only possible due to the presence of pre-cut tracks to allow repeated access, but it still took a two-person team ~36 h to conduct the initial survey of soil type, soil drainage class and vegetation summary, and the collection of bulk density and chemistry samples (three depths for bulk density and four for chemistry) from 10 selected sites. This time did not include down time or travelling time.

Restricting both the initial survey and soil sampling to areas adjacent to the access tracks may introduce bias, especially on coupes where vegetation, slope, aspect and soil type changes significantly. The authors felt that the network of access tracks within the small coupes of the SST trial adequately cover all variations within the coupe even though this was not a statistically unbiased sample. In a normal commercial operation it is highly unlikely that similar patterns of access tracks will be available.

The random transect method of sampling also proved to be very time consuming. It was estimated it would take approximately 26 h for a two-person team to visit ~45 potential sampling points and collect a single 0–100 mm sample from ~30 of these points. The random transect system recommended for the assessment of changes of soil physical properties (MIG, 1998) was a modification of that adopted by Lacey et al. (1994) and used by Rab (1999). Lacey et al. (1994) assessed a range of native forest types as well as pine plantations though their plots were only approximately 2 ha in size. Rab worked in 1939 regrowth *Eucalyptus regnans* but of the 26 coupes assessed post-harvesting only one was assessed prior to logging. This latter, was also a relatively small coupe (∼10 ha). In these two studies the soil sampling was restricted to the upper 100 mm. Either sampling to 300 mm or sampling a larger operational coupe (∼40 ha) would increase dramatically the time taken to carry out the sampling.

The mean bulk density for the four coupes varied from 0.67 to 0.86 Mg/m^3 for the upper 100 mm of mineral soil. Ellis et al. (1982) and Williamson (1990) found bulk densities for two mature stands of *E. obliqua* forests within the Picton Valley (10 km South of the SST) to be 0.63 and 0.54 Mg/m^3, respectively. Both these forests were more mature than the forest present in the SST area, so the accumulation of both soil organic carbon and decomposing organic matter could possibly explain the lower bulk density of the upper soil layer. More notable was the very wide range, 0.40–1.12 Mg/m^3, of soil bulk density recorded in the upper 0–100 mm of soil. Such high variance will diminish the utility of this soil physical property as a tool for assessing the impact of forestry operations.

What depth of soil should be sampled? With both the soil physical and chemical properties changing dramatically down through the 0–300 mm layer multiple depths of sampling are required. The heavy clay soils and wet conditions present on the study site made the collecting of a single 0–300 mm sample impossible. The current study clearly shows that most changes are associated with the upper 0–100 mm layer. Restricting both pre- and post-harvest sampling to a single depth of 0–100 mm would allow the intensity of sampling to be increased.

The extent of changes in soil physical properties can be affected by a number of factors. These include soil moisture content at the time of harvesting, gravel content, soil type, slope of the coupe and the type and operation of the machinery (Greacen and Sands, 1980; Howard et al., 1981; Butt and Rollerson, 1988; Wronski et al., 1989; Williamson, 1990; Soane, 1990; Rab, 1992; Lacey et al., 1994).

What constitutes a 'significant change'? The current study has found that significant change measured by ANOVA is only seen on the major snig tracks. Increases in mean bulk density on major snig tracks of 16 and 18% for WR001B and WR008B, respectively are less than values reported in other studies within Australia. Incertia et al. (1987) reported an increase of 27% and Rab (1994) an increase of 64% in the bulk density of snig tracks compared to undisturbed areas. Lacey et al. (1994) reported increases between 18 and 69% in the bulk density of snig tracks over the pre-harvest result. The results for WR001B and WR008B suggest that cording reduces the impact of traffic on soil bulk density.

However, these results must be treated cautiously. On WR001B, only sites where the cording had been lifted and the soil easily accessible were sampled. On WR008B, some major snig track sites were not sampled because they carried a dense mat of bark and timber that was too difficult to remove. The use of cording (an operation to minimise soil deformation) made sampling of major snig tracks difficult and often involved a team of three and the use of chainsaws and crowbars. Such effort could not be applied in a practical, sensitive and cost-effective manner operationally.

Although the use of corded snig tracks appears to have reduced soil compaction and, erosion and loss of nutrients, an additional note of caution must be given. Visual observations made on coupes 3–5 years after regeneration (Pennington and Lewis, unpublished data) have shown that the corded snig tracks suffer both poor recruitment and growth of seedlings in areas where the cording has not been lifted.

Although some marked bulk density changes were apparent on the minor snig tracks and firebreaks, overall there were no significant changes. The most marked changes was the increase in the range of bulk densities recorded. On the harvested area post-harvest soil bulk density declined on both coupes. This change was only significant on WR001B where three of the 15 samples taken had very low bulk densities (0.28, 0.41 and 0.46 Mg/m^3) due to the incorporation of both litter and fine slash into the upper soil layer. On WR008B, five of the 35 sites sampled had been subject to a very high intensity burn, which was clearly evident by the presence of orange soil indicating soil oxidation. All these sites had bulk densities below the mean with one site having a bulk density of 0.36 Mg/m^3. Lacey et al. (1994) reported declines in soil bulk density on both displaced soil and under waste heaps, and they also found that there was a general increase in the variance in the bulk density of post-harvest samples. A notable increase in variance was found on both coupes sampled. This result highlights the potential problem associated with comparing different disturbance features after logging only, as it may be difficult to locate and sample undisturbed areas that accurately reflect the pre-harvest site.

One other means of measuring 'a significant change' is to determine the portion of harvested area with a post-harvest bulk density above a percentage of the pre-harvest mean. Rab (1999) suggested as a first approximation, Indicator 4.1.e may be determined by adding the area affected by a 20% increase in bulk density (compared to the pre-harvest value) in the 0–100 mm soil depth and the area affected by subsoil disturbance. The high coefficient of variance apparent for bulk density data in this and many other studies means that a large number of pre-harvest samples are required to achieve a pre-harvest mean with an adequate level of confidence. With 10 sites (and five cores per site) the confidence interval was approximately ±10%, but to reduce this interval the number of samples required escalates rapidly. This problem is not limited to soil physical data. Ellis (1995) highlighted the large number of plots required (∼50) to detect significant changes in total nitrogen in the upper 100 mm following forestry operations.

There is also a lack of knowledge on what effect a 20% increase in bulk density will have on recruitment, early growth, and productivity. A number of researchers have examined the effect of soil bulk density upon seedling performance and have found it dependent upon the soil texture and plant species (Daddow and Warington, 1984). For example, Williamson (1990) showed that when taking the mean results from five different sites the total dry weight of *Eucalyptus globulus* seedlings decreased by 22% as the bulk density of the soil was increased from 0.69 to 0.86 Mg/m^3. However, if the data for the sites are examined individually a different picture emerges. For the dolerite soil taken from the Picton site by Williamson, there was a 58% decrease in seedling dry weight as the soil bulk density increased from 0.39 to 0.53 Mg/m^3 (36% increase in bulk density). For the basalt soil from Gads Hill there was no change in seedling weight as bulk density increased from 0.54 to 0.69 Mg/m^3 (26%). For the granite soil from Goulds Country there was a 43% decrease in seedling weight as bulk density increased from 0.79 to 1.04 Mg/m^3 (32%). For the mudstone soils from Sumac there was a 23% increase in seedling dry weight as the bulk density increased from 0.66 to 0.89 Mg/m^3 (34%).

One final option for assessing a significant change is a threshold value. Rab (1994) reported that a 50% reduction in height and diameter growth for 13-month-old seedlings occurred when soil bulk density reached 0.91 and 0.96 Mg/m^3, respectively. Mitchell et al. (1982) found significant reductions in height growth at a density of 1.6 Mg/m^3. The threshold level would be highly dependent upon the soil texture. Daddow and Warington (1984) speculated that for a clay soil (68% clay, 12% silt and 20% sand) the growth-limiting bulk density would be in the order of 1.4 Mg/m^3, but for a sandy loam (10% clay, 12% slit and 80% sand) the growth-limiting bulk density would be 1.75 Mg/m^3.

There has been significant debate concerning the linking of soil physical changes and their impact on future productivity (Greacen and Sands, 1980; Lockaby and Vidrine, 1984; Miller and Sirois, 1986; Farrish, 1990; Williamson, 1990; King et al., 1993a,b; Raison and Khana, 1995; Senyk and Craigdallie, 1997; Lacey and Ryan, 2000). Williamson (1990), in a study of the impacts of mechanised harvesting on a range of soil types in Tasmania, reported a marked decline in the productivity of primary snig tracks, but also indicated that the stocking and growth of seedlings on secondary snig tracks were as good as or better than those on undisturbed areas. Pennington et al. (in press) also have found a significant decline in standing volume on compacted major snig tracks compared to undisturbed or lightly disturbed control areas in 17 to 23-years-old regenerating stands. They also found that the loss of productivity on the snig track area was partly compensated by increased productivity in the adjacent areas. In a review of measures and operating standards for assessing Montreal soil sustainability indications, Rab (1999) stated that 'at this stage, it is not possible to relate the measures and operating standards with the long-term changes in forest ecological processes including productivity.'

5. Conclusions

As indicated by the MIG (1998), Indicator 4.1.e. requires long-term R&D to determine if there is a practical, sensitive and cost-effective means of its implementation at forest operational scales. Lowe (1995) warned against an over-optimistic opinion of the potential of criteria and indicators to contribute to sustainable forest management. It must be questioned whether an indictor based on bulk density change can be implemented in a practical, sensitive and cost-effective means. The high natural variability found in the Warra SST coupes and probably many forest ecosystems in Australia means that a high sampling intensity is required to achieve a result with the required level of confidence. Bulk density measures are also time consuming and expensive.

Use of a standard 0–300 mm depth for determining the indicator needs to be critically reviewed. The authors believe that substantial changes below 100 mm can be adequately assessed by visual procedures (Pennington et al., in review). Taking a single sample to 300 mm in the medium/heavy clay soils below wet forests has been shown to be impractical. Incremental sampling to 300 mm is very time consuming and a better result may be achieved by increased sampling intensity at the 0–100 mm depth only.

For the reasons stated above it is not practical to operationally monitor changes in soil bulk density after the harvest of wet *E. obliqua* forests in Tasmania. In terms of both practicality and cost-effectiveness, we conclude that detecting changes in soil physical properties in an operational system cannot be achieved by using Interim Indicator 4.1.e. An alternative approach could be related to a visual soil disturbance classification. The visual system will need to be calibrated for different soil types, climatic conditions, forest types and silvicultural systems. The measurement of soil bulk density should be limited to research and calibration applications in the forest type studied.

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Appendix A. System (WAPIS Soil Indicators Project- Soil Sampling Sub-Group, 1998) for classifying soil impacts following timber harvesting and site preparation

A: Operation categories:

Harvested area (HA)	General logging within which trees are felled
Unharvested area (UA)	Areas of retained forest or vegetation within the coupe boundary
Firebreak (FB)	Perimeter boundary
Snig tracks (ST)	Tracks created by towing or winching logs to landing
Landing (LL)	Area where logs are snigged for sorting and loaded for transportation
Access roads (AR)	Temporary forest roads falling with the coupe boundary

B: Soil disturbance categories:

Degree of soil profile disturbance	Type of mixing/removal	Dominant horizon
Undisturbed (S0)	Forest intact (FI)	O1
	Understorey intact (UI)	O1
	Litter layer intact (LI)	O1
Lightly disturbed (S1)	Litter layer broken (LD)	O2
	Litter layer partially removed (LR)	O2
Moderately disturbed (S2)	Litter completely removed and topsoil exposed (TE)	A

Appendix A (*Continued*)

	Litter mixed with topsoil (LM)	A
	Topsoil disturbed (TD)[a]	A
	Topsoil mixed with subsoil (TM)	A
	Topsoil partially removed (TP)	A
Severely disturbed (S3)	Topsoil mixed with subsoil (SM)	B
	Subsoil disturbed (SD)[b]	B
	Subsoil mixed with parent material (SC)	B
	Topsoil removed and subsoil exposed (SE)	B
	Subsoil partially removed (SR)	B
	Subsoil removed and parent material exposed (PE)	C
C: Soil and slash piling categories		
Soil piling (SP)	Soil piled at a height >0.3 m	
Soil and slash piling (SS)	Soil and slash piled at height >0.3 m	
Slash and/or bark piling (SB)	Slash and/or bark piling at height >0.3 m	
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.	

[a] Topsoil consists of A1, A2, and A3 horizons except where A2 is conspicuously bleached whereby A2 and A3 are regarded as subsoil.

[b] Subsoil includes B1 and B2 horizons and conspicuously bleached A2 horizon (and any other A-horizon below the A2).

Appendix B. Pennington/Laffan system for classifying soil impacts following timber harvesting and site preparation

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	(ST)	Tracks created by towing or winching logs to landing
	(SAT)	Major snig tracks
	(SIT)	Minor snig tracks

Appendix B (*Continued*)

Draglines	(DL)	Disturbance created by dragging tree by cable harvesting system.
Landing	(LL)	Area where logs are snigged for sorting and loaded for transportation
Access roads	(AR)	Temporary forest roads falling with the coupe boundary

B: Soil disturbance categories: (2 & 3)

Degree of soil profile Disturbance	Classification	Type of mixing/removal	Dominant horizon
Undisturbed/Light (D0)	(S0.1)	Litter layer intact	O
	(S0.2)	Litter layer broken/partially removed	O
	(S0.3)	Litter completely removed and topsoil exposed	A
Moderate disturbed (D2)	(S2.1)	Topsoil (4) mixed with litter/slash	A
	(S2.2)	Topsoil disturbed/partially removed/mixed with subsoil	A
Severe disturbed (D3)	(S3.1)	Subsoil (5) mixed with topsoil or litter	B
	(S3.2)	Subsoil exposed/disturbed/partially removed	B
Very Severe disturbance (D4)		Parent material or parent rock exposed/mixed with subsoil parent material	C or R
Non soil	Tree stump (t)	Rock (r)	Fallen large tree (w)

C: Soil, slash piling and cording categories (6)

Soil and slash piling	
(S)	Soil and slash piled at height <0.3
(SS)	Soil and slash piled at height 0.3–1.0 m
(SSS)	Soil and slash piled at height >1.0 m
Slash and/or bark piling	
(B)	Slash and/or bark piling at height <0.3 m
(BB)	Slash and/or bark piling at height 0.3–1.0 m
(BBB)	Slash and/or bark piling at height >1.0
Cording (6)	
(C)	Cording <0.3 m deep, <300 mm in diameter
(CC)	Cording >0.3 m deep, piece size <300 mm in diameter
(CCC)	Cording >0.3 m deep, piece size >300 mm in diameter. Additional bark added to snig track.

Appendix B (*Continued*)

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. Intensive survey or small coupe, plots located every 10 m on transects spaced at 50 m. Large coupes, plots located every 30 m on transects spaced at 100 m. 2. Assess dominant soil disturbance category on a 1 m × 1 m plot. 3. If dense slash, bark or soil does not allow soil disturbance to be accurately assessed, score 0, 2 or 3 according to surrounding area and most likely soil disturbance category. 4. Topsoil consists of 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 B1 and B2 horizons and conspicuously bleached A2 horizon (and any other A horizon below the A2). 6. Cording-slash and bark layed over soil to form snig track. May be impossible to classify soils under major corded snig tracks. Assume S2 under CC and S3 under CCC, unless there is clear evidence to the contrary.

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