Assessing the long-term impacts of forest harvesting and high intensity broadcast burning on soil properties at the Warra LTER Site

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Abstract

At the Warra Long-Term Ecological Research (LTER) Site, soil samples from 0–50 mm, 50–100 mm, 100–200 mm and 200–300 mm were taken from a clearfelled coupe (WR008B) before harvesting in 1998 and again in 2000, nine months after a high intensity regeneration burn. Analyses conducted included soil bulk density, pH, total organic C and total N and P. The effect of harvesting and burning was found to be most pronounced in the upper 50 mm of soil. Bulk density increased from 0.58 Mg/m^3 to 0.70 Mg/m^3, while there was a loss of 3850 kg C/ha and 107 kg N/ha. A total of 13 kg P/ha was added. The changes were smaller at the 50–100 mm depth, with losses of 1470 kg C/ha and 72 kg N/ha and addition of 5 kg P/ha. Only minor changes were apparent at the 100–200 mm and 200–300 mm depths.

A series of permanent sample plots was established on this coupe to assess the longer term impact of forest harvesting and burning on soil chemical and physical properties. The location of all the post-burn sampling plots has been mapped using GPS to enable researchers in the future to quickly relocate and utilise these plots.

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Introduction

Lowland wet eucalypt forest (LWEF) covers 578 460 ha and constitutes 18% of Tasmania's forested area (Forestry Tasmania 1998). The clearfell, burn and sow silvicultural system is the standard procedure for harvesting and regenerating LWEF (Forestry Tasmania 1998). Clearfelling is particularly suitable for wet forest with a dense understorey, especially if there are no younger age classes of eucalypts suitable for retention. High intensity regeneration burns remove the understorey and slash, improve nutrient status through the 'ashbed' effect (Forestry Tasmania 1993) and reduce the number of insects that may harvest the seed (Gilbert 1959).

In Australia, there has been significant research on the short-term impacts of burning on soil chemistry (Hatch 1960; Pryor 1960; Ellis *et al.* 1982; Ellis and Graley 1983; Stewart and Flinn 1985; Grove *et al.* 1986; Khanna and Raison 1986; Tomkins *et al.* 1991; Khanna *et al.* 1994; Hopmans *et al.* 1993; Guinto *et al.* 1996). It is generally accepted that high intensity burning can lead to a significant loss of organic C and total N from the upper soil layer (Hatch 1960; Ellis and Graley 1983; Dyrness *et al.* 1989; Tomkins *et al.* 1991; Baird *et al.* 1999). For example, Ellis and Graley (1983) found a loss of 7360 kg organic C and 211 kg N / ha from the upper soil layer (0–20 mm) in a wet *Eucalyptus obliqua* forest in southern Tasmania. Other chemical components such as pH, extractable P and exchangeable K, Ca and Mg have been shown to increase in the upper soil layer after fire (Ellis and Graley 1983; Stewart and Flinn 1985; Grove *et al.* 1986; Tomkins *et al.* 1991; Khanna *et al.* 1994). Ellis and Graley (1983) reported that 348 kg Ca, 282 kg Mg and 151 kg K / ha were added to the upper 20 mm soil layer from ash following a hot regeneration burn in wet *E. obliqua* forest.

A later study (P. Pennington and A. Gibbons 1998 unpublished data) reassessed the same study area as Ellis and Graley (1983). The principal objective of the later study was to assess the nutrient status of the soil below the 15-year-old regenerated stand. Analyses of the upper soil layer (0–50 mm) found that the concentrations of organic C and total N had increased since the burn, but were still below the concentrations present in the soil from the surrounding oldgrowth forest. Contrary to the results found immediately after the burn, after 15 years the concentrations of extractable Ca, Mg, K and P were similar to those found in soil of the surrounding oldgrowth forest. Because it was not possible to precisely relocate the original plots, a direct comparison with those plots was not possible.

The implementation of the Warra silvicultural systems trial (SST) (Hickey *et al.* 2001) renewed focus on research on the impact on soil properties of harvesting and regeneration burning in wet forest. In 1998, a nationally co-ordinated project was initiated to evaluate proposed Montreal soil indicators 4.1.d and 4.1.e. Four sub-projects were conducted utilising the Warra LTER Site and other forest stands throughout Tasmania.

The first study examined the medium-term (17–23 years after logging) impacts of major snig tracks on stand productivity of *Eucalyptus obliqua*. The diameters, heights, densities and volumes of trees growing within the regenerating forest were compared with those of trees growing within the major snig tracks and the zones along their edges. The second study aimed to evaluate the use of Montreal interim indicator 4.1.e in wet *E. obliqua* forest. Interim indicator 4.1.e quantifies the 'Proportion of harvested forest area with significant change in bulk density of any horizon of the surface (0–30 cm) soil'. The third study aimed to evaluate a survey technique that was developed for the routine monitoring of soil disturbance associated with the harvesting of forests in Tasmania. The study was conducted on clearfelled, burnt and sown coupes at the Warra SST and at Goulds Country. Although both sites carried wet *E. obliqua* forest before harvesting, the soil type and profile varied dramatically between the two locations.

The aim of the fourth study was to assess the change in chemical properties and bulk density that were induced in the soils by forest operations. For this purpose a series of permanent plots was established within a clearfelled and burnt coupe. The plots were designed for long-term monitoring well into the future. Results from the pre-harvest sample and the initial post-burn sample are presented in this paper.

Methods

Study coupes

Pre-harvest sampling was conducted in coupe Warra 8B (WR008B) in the Warra SST (Hickey *et al.* 2001). The coupe was harvested between August and December 1998 by utilising the standard clearfell system, and a high intensity regeneration burn was conducted in March 2000. Long-term plots were established in late 2000.

Pre-harvest soil survey

Initial soil surveys utilised a network of access tracks prepared by Forestry

Tasmania. Survey points were assessed at intervals of either 25 or 50 m along all access tracks to determine the soil drainage class and to verify that all soils were formed on slope deposits derived from Jurassic dolerite. The following were recorded at each point: (1) soil parent substrate, (2) drainage class, and (3) understorey species. Soils were sampled by hand auger to depths of 0.8–1.0 m, or shallower if impeded by stones.

Pre-harvest soil sampling

Eighteen plots (0.02 ha) were selected for assessment of soil physical and chemical properties. These plots were chosen to proportionally represent the major drainage classes, which were (1) well drained and moderately well drained and (2) imperfect and poorly drained. The approximate locations of the 18 plots on WR008B were mapped through a combination of GPS and field mapping.

For the determination of bulk density, five cores from each of the 0–100 mm and 0–50 mm soil depths were collected from each plot by using a 70 mm diameter x 100 mm or a 70 mm diameter x 50 mm length steel tube. 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 transport 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 portion of cores containing large roots or large rocks was discarded and substitute cores collected.

Within a 5 m radius of the point used for sampling bulk density, at least eight cores were obtained for chemical analysis from depths of 0–50, 50–100, 100–200 and 200–300 mm. Cores were bulked according to depth, transported to the laboratory and stored at 4°C until processed. All surface cores (0–100 mm), including those for bulk density, were collected from the mineral soil layer only; leaf litter and coarse woody debris were excluded.

Long-term plots

After the completion of the high intensity burn, the coupe was surveyed for suitable points at which to establish long-term sampling plots. The following criteria were used. The plots were:

- Located in the approximate position of pre-harvest sample plots;
- Not subject to moderate to severe soil disturbance;
- Located within the harvested area and did not contain significant areas of either fire-breaks or snig tracks;
- Subject to a high intensity burn, with only a small area of very high intensity burn as indicated by orange soil oxidation;
- Approximately 20 m x 20 m in size;
- Away from regeneration survey lines used for other studies on the coupe because those areas may be subject to changes in soil properties owing to high numbers of visits.

Of the original 18 pre-harvest sample plots, a number were lost owing to severe disturbance (snig tracks, landings or fire-breaks). A total of 14 plots proximate to those originally selected were identified. The number of plots required to detect a given difference in the means between the pre- and post-harvest data can be calculated from the formula:

$$m_1 - m_2 = \pm t_{0.05}\, \check{s}s^2(1/n_1 + 1/n_2)$$

where $m_1 - m_2$ is the difference between the means that one wishes to detect with $t = 0.05$ or 95% confidence, and with an estimated variance of s^2 (Ellis 1995). Montreal indicator 4.1.d assesses the 'area and per cent of forest land with significantly diminished soil organic matter and / or changes in other chemical properties' (Commonwealth of Australia 1998), but it does not indicate what level of change is considered significant. Rab (1999) suggested a 30% decrease in organic matter content in the 0–100 mm depth from the undisturbed site should be considered as significant. The pre-harvest data were used to determine the number of plots required to detect a ± 30% difference in organic carbon between the pre- and post-harvest results, with a 95% probability that the true difference exceeds ± 5%. Nine plots would be required to detect such a change in the 0–100 mm depth and six plots for the 0–300 mm depth. Hence, nine plots were permanently marked. The location of each was fixed by GPS. Each plot was divided into sixty-four 2 m x 2 m subplots, and disturbed soil, unburnt areas, stumps and downers were

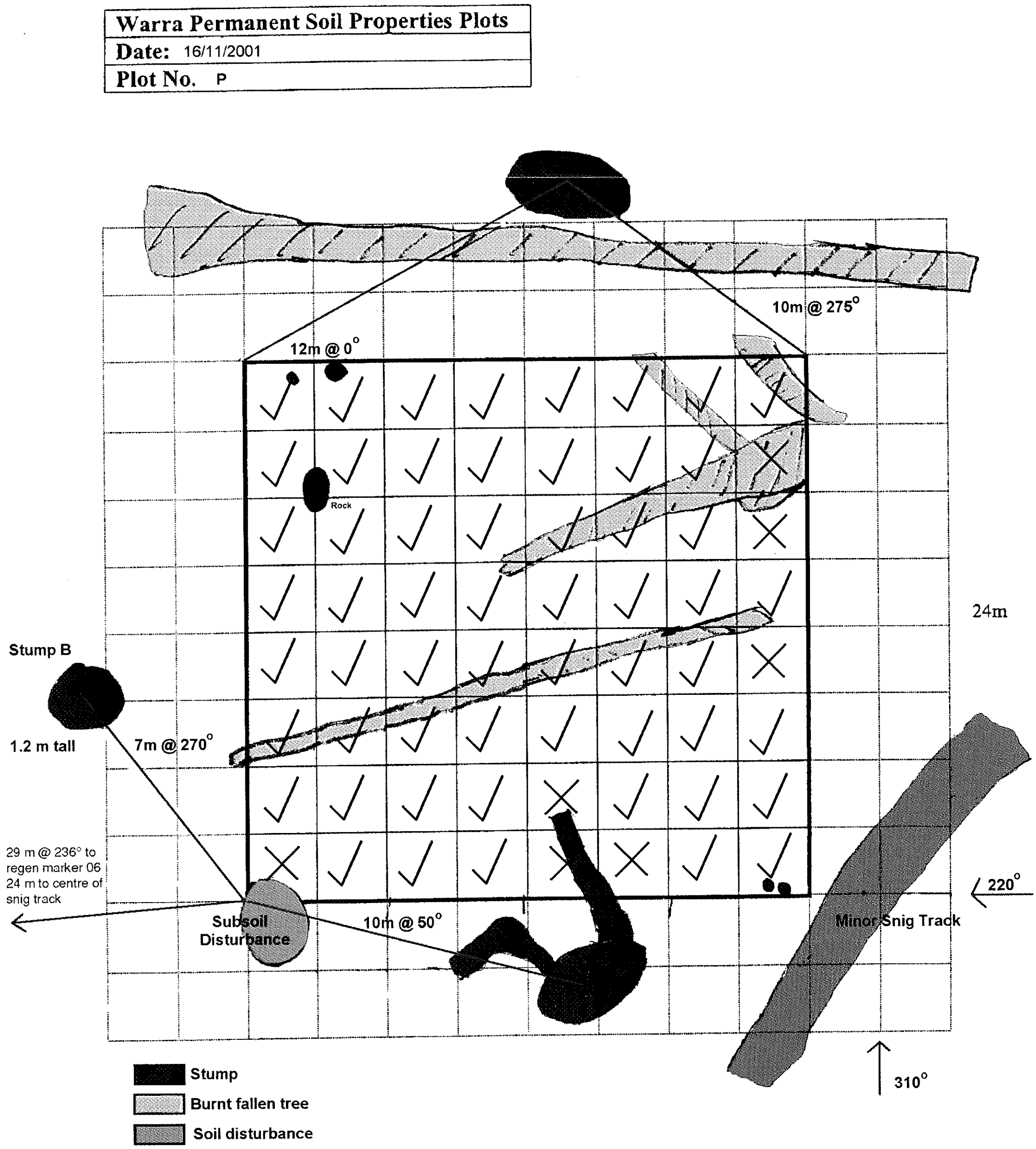

Figure 1. Layout of the long-term plot in WR008B.

mapped (Figure 1). The locations of neighbouring large stumps were also recorded. Each subplot was numbered consecutively from 1 to 64. All plots were photographed from each corner in order to facilitate relocation (Photo 1).

Post-burn soil sampling

The first post-burn soil sampling was completed nine months after the burn. During this period, a total of 935 mm of rain had fallen. Low rainfall during sampling (December 2000 to January 2001) meant that the upper soil was relatively dry. Three subplots were sampled at each of the nine plots. The subplots were selected from a randomly generated number series between 1 and 64. If a subplot could not be sampled owing to soil disturbance or other factors, another randomly allocated subplot was chosen.

In line with the pre-harvest sampling protocol, bulk density samples were collected from four depths: 0–50 mm, 0–100 mm, 100–200 mm and 200–300 mm. Three cores within the 2 m x 2 m subplot were taken at each depth and three additional cores at each depth were collected for chemical analysis.

Soil analysis

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 has been shown to be very low (Pennington *et al.* 1999) so no correction for gravel content was made. Bulk density for the 50–100 mm depth was calculated from the data obtained for the 0–50 and 0–100 mm depths.

Chemistry.—Soil samples were initially air-dried at 25°C, then passed through a 2 mm sieve. Gravel (> 2 mm), root material and soil invertebrates were discarded. Sieved samples were then fully air-dried. After air-drying, a 30 g subsample was ground and passed through a 0.5 mm sieve. Soils were analysed by methods published in Rayment and Higginson (1992) for pH (4A1), organic C (6A1) and total N and P (7A2).

Analysis of results

Analysis of variance between pre-harvest and post-burn results was conducted by using Genstat 5 Release 3.2. Percentage concentrations were converted to kilograms per hectare by using the mean bulk density for the individual plots (pre-harvest) and individual subplots (post-burn) and allowing for the depth of samples.

Photo 1. Long-term chemistry Plot P, looking from the eastern corner towards the starting point at the southern corner. Note stumps A and B shown in the layout of the plot. Such photographs and maps should enable these plots to be accurately relocated in the distant future.

Table 1. Pre-harvest and post-harvest soil bulk densities (Mg/m³) at WR008B. Pre- and post-harvest means are significantly different (P < 0.05). (STD = standard deviation)*

Depth		Pre-harvest (18 sites)	Post-harvest (9 sites)	*P* values
0–50 mm	Mean (± STD)	0.58 (0.13)*	0.70 (0.08)*	*P* = 0.024
	Minimum	0.24	0.55	
	Maximum	0.76	0.82	
50–100 mm	Mean (± STD)	0.84 (0.22)	0.92 (0.15)	*P* = 0.335
	Minimum	0.43	0.64	
	Maximum	1.25	1.11	
100–200 mm	Mean (± STD)	1.00 (0.11)	1.01 (0.12)	*P* = 0.761
	Minimum	0.76	0.80	
	Maximum	1.15	1.13	
200–300 mm	Mean (± STD)	1.02 (0.12)	1.04 (0.12)	*P* = 0.611
	Minimum	0.85	0.83	
	Maximum	1.18	1.17	

Results

The pre-harvest soil survey confirmed that all soils were derived from Jurassic dolerite. Approximately half (47%) of WR008B was found to be well-drained to moderately well-drained, with 38% imperfectly drained and 15% poorly drained. Laffan (2001) gives detailed profile descriptions of well-drained and poorly drained dolerite soils within the Warra SST. Of the 18 pre-harvest samples, nine were collected from the well-drained to moderately well-drained class, six from imperfectly drained, and three from poorly drained sites. Of the post-harvest samples, five were from well- to moderately well-drained sites, and the remaining four were from imperfectly to poorly drained classes.

Soil bulk densities at WR008B were highly dependent upon soil depth (Table 1). The means for the pre-harvest sampling were 0.58 Mg / m³, 0.84 Mg / m³, 1.00 Mg / m³ and 1.02 Mg / m³ for the 0–50 mm, 50–100 mm, 100–200 mm and 200–300 mm depths respectively. At the 0–50 mm depth, values ranged from 0.24 to 0.76 Mg / m³ and, at the 200–300 mm depth, from 0.85 to 1.18 Mg / m³. Post-harvest, the corresponding mean bulk densities were 0.70 Mg / m³, 0.92 Mg / m³, 1.01 Mg / m³ and 1.04 Mg / m³ for the 0–50 mm, 50–100 mm, 100–200 mm and 200–300 mm depths respectively. The range from the 0–50 mm depth was greatly reduced at 0.55 to 0.82 Mg / m³. The change in bulk density was statistically significant only at the 0–50 mm depth (P = 0.024).

Pre-harvest sampling showed that there was a high variation in each of the chemical components measured. For example, the coefficient of variation (CV) for the 0–50 mm depth was 24%, 26% and 38% for organic C, total N and total P respectively.

At all depths, the post-harvest pH was significantly higher ($P < 0.01$) than that of pre-harvest samples (Table 2). At the 0–50 mm, 50–100 mm, 100–200 mm and 200–300 mm depths, the mean pH rose by 0.9, 0.7, 0.6 and 0.6 of a pH unit respectively. For organic C, levels declined significantly ($P < 0.001$) in the upper 0–50 mm from 8.0% to 5.4%. The decline at the 50–100 mm depth was less (4.1–3.4%) but still significant (P = 0.047). No decline in organic C was recorded at the lower depths. The decline in total N was also significant at the two upper depths (P = 0.004 for 0–50 mm and P = 0.029 for 50–100 mm), while there was a slight but

Table 2. Pre-harvest and post-harvest soil chemical data at WR008B. Pre- and post-harvest means are significantly different (P < 0.05, ** P < 0.01).*

	Organic C (%)		Total N (%)		Total P (%)		pH	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
0–50 mm	8.04 **	5.40 **	0.31 **	0.22 **	0.0156	0.0164	4.58 **	5.71 **
50–100 mm	4.12 *	3.41 *	0.18 *	0.15 *	0.0110	0.0112	4.65 **	5.43 **
100–200 mm	2.56	2.55	0.12	0.12	0.0092	0.0098	4.81 **	5.43 **
200–300mm	1.91	1.86	0.10	0.09	0.0083	0.0086	4.92 **	5.43 **

Table 3. Pre-harvest and post-harvest soil chemistry data at WR008B expressed in kg/ha. There were no significant differences.

	Organic C (kg / ha)		Total N (kg / ha)		Total P (kg / ha)	
	Pre	Post	Pre	Post	Pre	Post
0–50 mm	22 735	18 884	872	765	45	58
50–100 mm	17 063	15 592	760	688	48	53
100–200 mm	25 287	25 595	1236	1154	95	100
200–300mm	19 077	19 034	980	913	88	92
Total 0–300mm	84 162	79 105	3848	3520	276	303

insignificant decline at the 100–200 mm and 200–300 mm depths. No significant changes in concentration of total P were found at any depth.

Expressing the content of organic C, total N and total P on a kilogram per hectare basis allows for changes in soil bulk density attributable to harvesting and burning to be taken into consideration. There was a decrease in organic C of 16.9% and 8.6% at the 0–50 and 50–100 mm depths respectively, though neither of these changes was significant (Table 3). There was also a decrease in total N at all depths but again none was significant. The largest relative changes were in the content of total P. There was a 28.9% increase in total P at the 0–50 mm depth and a 11.1% increase at the 50–100 mm depth, but neither of these increases was significant.

Discussion

The changes in soil bulk density and chemistry were similar to those previously recorded. Ellis and Graley (1983) compared the soil from a harvested stand of wet *E. obliqua* forest to an adjacent unlogged stand in the Picton Valley, 12 km south of the Warra LTER Site. They reported marked increases in bulk density in the upper 0–20 mm and 20–50 mm soil depths two days after a high intensity burn on the harvested site. Ellis and Graley (1983) located their plots in relatively undisturbed areas. Although part of the bulk density increase was due to forest harvesting, they attributed most of the increase to the high intensity burn. Tomkin *et al.* (1991), in a study of the effects of fire intensity alone on soil chemistry in eucalypt forest, also reported significant increases in bulk density in the 0–20 mm depth of soil, and little change at greater depths.

The loss of a significant proportion of soil organic C after high intensity burning has been reported in several studies (Hatch 1960; Ellis and Graley 1983; Dyrness *et al.* 1989; Tomkin *et al.* 1991; Baird *et al.* 1999; Rab 1999). Ellis and Graley (1983) reported decreases from 19.0 to 11.2 % and 9.9 to 6.5%

in the 0–20 mm and 20–50 mm depths respectively. A small, non-significant decrease from 4.9 to 4.0 % was reported for the 50–100 mm depth. Tomkin *et al.* (1991) found decreases in organic C at all depths to 100 mm, though this was significant only at the 0–20 mm depth. Contrary to these findings, Stewart and Flinn (1985) and Grove *et al.* (1986) reported a slight increase in organic C, but these changes were not significant. Stewart and Flinn indicated their result might have been an artefact of sampling, while Grove *et al.* included the fine ash deposited on the soil surface, which was not the case in the other studies.

Hatch (1960) and Ellis and Graley (1983) reported large decreases in the total N content of the upper soil layers. After a slash burn in Karri forest in Western Australia, Hatch (1960) showed decreases in total N of 59% (0.22–0.09%), 44% (0.18–0.10%), 31% (0.13–0.09%) and 29% (0.07–0.05%) for the 0–25 mm, 25–75 mm, 75–150 mm and 150–300 mm depths, respectively. In the current study, there was a 29% decrease in total N for the 0–50 mm depth. Grove *et al.* (1986) reported a 19% increase in total N in the upper 0–30 mm of soil one day after the burn, but their sampling included the fine ash.

Changes in the levels of total P following burning have been variable. Ellis and Graley (1983) reported no significant change in concentration of total P in the upper soil layers (0–20 mm and 20–50 mm) two days after a high intensity burn, but in stands burnt more than 12 months previously there was an apparent increase (Ellis *et al.* 1982; Ellis and Graley 1983). Tomkin *et al.* (1991) also found only a small but insignificant increase in the soil total P just after the burn but, after major rainfall and input from the ash, that had increased to more than double the pre-harvest levels. These results are consistent with those found in this study.

An immediate increase of between 1.5 and 2.0 pH units in the upper 0–20 mm of soil is a general feature of high intensity burns. This is followed, after three months, by a measurable decline (Hatch 1960; Ellis and Graley 1983; Tomkin *et al.* 1991). The increase in the 20–50 mm depth is lower, 0.5 to 0.7 pH units (Ellis and Graley 1983; Tomkin *et al.* 1991). Thus, the increase of 0.9 pH units nine months after the fire for the 0–50 mm depth sampled in this study is consistent with these previous studies. Hatch (1960) reported an increase of 0.5 pH units at a depth of 150–300 mm after slash burning. Similar increases were also reported by Smith (1970) who found that at various depths between 180 and 420 mm peak pH values were not reached until between six weeks to 13 months after the burn.

In percentage terms, the changes in the various soil components were marked and agreed with previously published data. However, harvesting and burning induces many other changes. There is an apparent increase in soil bulk density during harvesting (Ellis and Graley 1983) and a further increase due to burning (Ellis and Graley 1983; Tomkin *et al.* 1991). Ellis and Graley (1983) pointed out that such increases in bulk density may distort conclusions drawn on simple comparisons between fixed intervals of soil depth. Thus, J. Bauhus (pers. comm.) found that an apparent large decrease in the concentration (%) of C in soil from severely disturbed snig tracks was much reduced when the amount of carbon per unit of soil volume was calculated. In this study, the decreases in organic C and total N in the upper soil layers (Table 2) were not significant when the data were expressed as kg C / ha or kg N / ha. However, though not statistically significant, the 16.9 and 12.3% decrease in organic C and total N, respectively, in the upper 0–50 mm was still substantial and corresponded to a loss of approximately 3850 kg C / ha and 107 kg N / ha. Total P increased, especially at the 0–50 mm and 50–100 mm depths, but again neither of these increases was significant.

Ellis (1995) highlighted the potential problems of detecting statistically significant change in soil properties following forest operations. He concluded that the number of plots used in most studies (and similar to the number used in this study) would be sufficient to detect a minimum difference of 30% in the pre- and post-harvest means for soil components such as total N and organic C. But to detect a difference of 20% would require an average of 50 plots. The decrease in total N detected at WR008B was 8.5% and 11.0% for the 0–300 mm and 0–100 mm depths respectively. To detect this level of change would require 64 and 37 plots respectively. For organic C, the number of plots required was similar at 57 to detect a 6.0% change in the 0–300 mm depth and 24 to detect a 13.4% change in the 0–100 mm depth. For total P, where the coefficient of variation for the pre-harvest data was greater than 50%, the number of plots required to statistically prove the 10% difference in pre- and post-harvest means would be over 200.

Although there is a loss of organic carbon and nitrogen following a high intensity burn, levels of P, Ca, Mg and K are all increased in the surface soil (Ellis and Graley 1983; Tomkins *et al.* 1991). Disturbed seedbeds (burnt or mechanical) provide better conditions for germination and growth of eucalypt seed than undisturbed seedbeds (Cunningham 1960; Stoneman 1994). Because a seedbed created by mechanical disturbance is significantly more expensive to produce than one created from slash burning (King 1991), high intensity burning is considered an important and beneficial management tool. The positive 'ashbed' effect of fire was recognised by Pryor (1960) who reported accelerated tree growth in the areas where windrowed logs had been burnt. This amelioration of soil condition by fire may be due to a direct effect such as the increase in the mineralisation of N and P (Bauhus *et al.* 1993), or indirectly through effects on soil microflora and microbial processes (Florence 1996). Lockett (1999), in a study of the implication of slash burning on regeneration in Tasmania, found that on wetter sites slash burning had consistently doubled the growth rate of seedlings three years after the burn. Although this effect of burning progressively declines, the net result may be a reduction of five years in the rotation length (Lockett 1999).

Conclusions

Large changes in soil bulk density and chemistry occur in the short-term after clearfelling and high intensity burning of wet *E. obliqua* forest. The way the results are expressed affect the interpretation made from the data. With significant changes in soil bulk density associated with harvesting and high intensity burning, it is critical that soil bulk density data be considered and that the results are expressed in terms of kilograms per hectare. Unless the changes in soil properties are very great, the highly variable nature of the results make it difficult to detect any statistically significant changes. This problem could be overcome with increased sampling intensity, but the number of plots required (> 50) is beyond the scope of this study. For this reason, trend data are most likely to give more useful information.

Studies by Ellis and Graley (1983) and P. Pennington and A. Gibbons (unpublished data) suggested that these large changes were reversed with time. The current plots have been designed for long-term sampling and should lead to firm conclusions. Long-term storage of the plot information, including layout and location (determined by GPS), long-term maintenance of the site (available under Forestry Tasmania's commitment to the Warra LTER Site) and the storage of both pre-harvest and post-burn soil samples should greatly improve the interpretations made in future.

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