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

Final report - Part 1.

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

K. R. Whitford
Science Division, Dwellingup
Western Australian Department of Conservation and Land Management

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Abstract

I examined the impact of fire frequency on soil organic carbon and nitrogen, and bulk density using a retrospective study of five sites in the high, intermediate, and low rainfall zones of the jarrah and karri forests. The soil carbon content ranged from 2% to 9% at these sites. The greatest response of carbon and nitrogen was observed in the surface soils. Across all sites, regular burning reduced the concentration of carbon and nitrogen in the surface soils and increased the bulk density. Within a site the total mass of carbon and nitrogen in the surface soil layer was unaffected by fire frequency, however changes in bulk density of the soil altered the concentration of carbon and nitrogen in this layer. Soil carbon concentrations were highly correlated with fine earth bulk density across all sites (r = -0.96). This correlation implies that fire alters the biological processes in the soil, and at the soil/litter interface. These changes increased the bulk density of the soil and reduced the carbon and nitrogen concentration on regularly burnt sites.

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

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

Introduction

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

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

Indicator 4.1d :

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

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

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

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

Methods

Sites

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

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

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

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

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

[2] Estimated values from ESOCLIM or Data-drill

Table 2. Fire treatments studied at each site.

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

Field procedures

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

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

Chemical analyses

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

Physical analysis

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

Bulk density was estimated for surface soils at all sites by taking the mean bulk density from cores collected at ten locations systematically located across each plot. Corers had a 66.9 mm inside diameter, a sampling depth of 100 mm, and a total volume of 348 ml. Soils were dried at 105° C for 48 hours, sieved through a 2 mm mesh, the mass of both <2 mm and >2 mm fractions determined and the volume of the coarse fraction (>2 mm) determined by displacement. The bulk density of the fine earth fraction (<2 mm) and bulk density of the undisturbed sample were calculated.

Carbon mass

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

Litter

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

Statistical analysis

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

Results

Site descriptions

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

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

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

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

Litter weight and nutrient levels

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Bulk density

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

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

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

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

Soil carbon and nitrogen stores

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

Clay content

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

Discussion

General trends in soil carbon and nitrogen

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

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

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

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

Clay as a covariate

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

Carbon concentration, carbon store, and fine earth bulk density

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

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

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

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

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

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

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

Litter

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

Conclusion

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

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

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

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

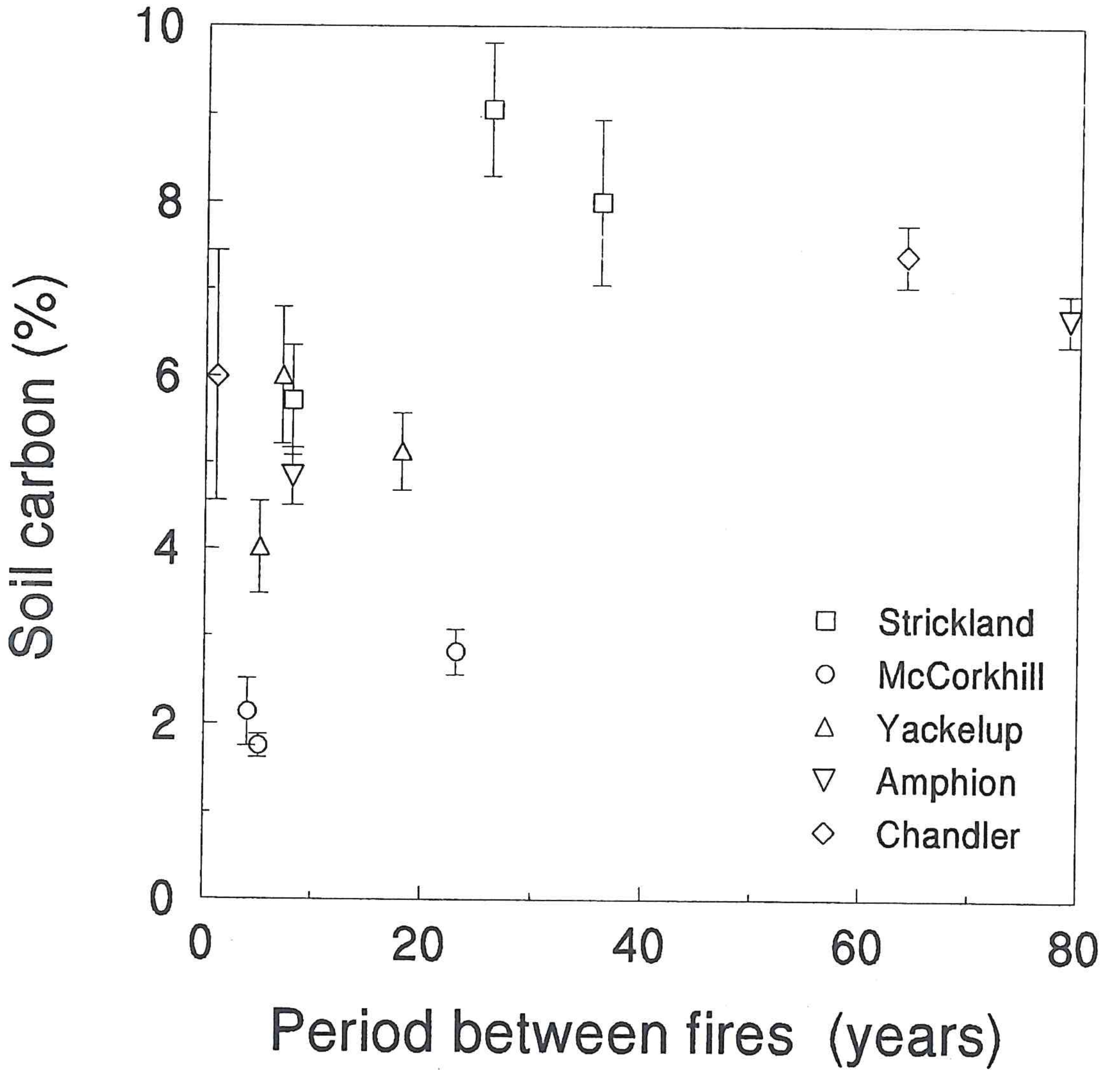


Fig. 2. The fine earth bulk density of surface soils (0-75 mm) for plots burnt under a range of fire frequencies at five sites.

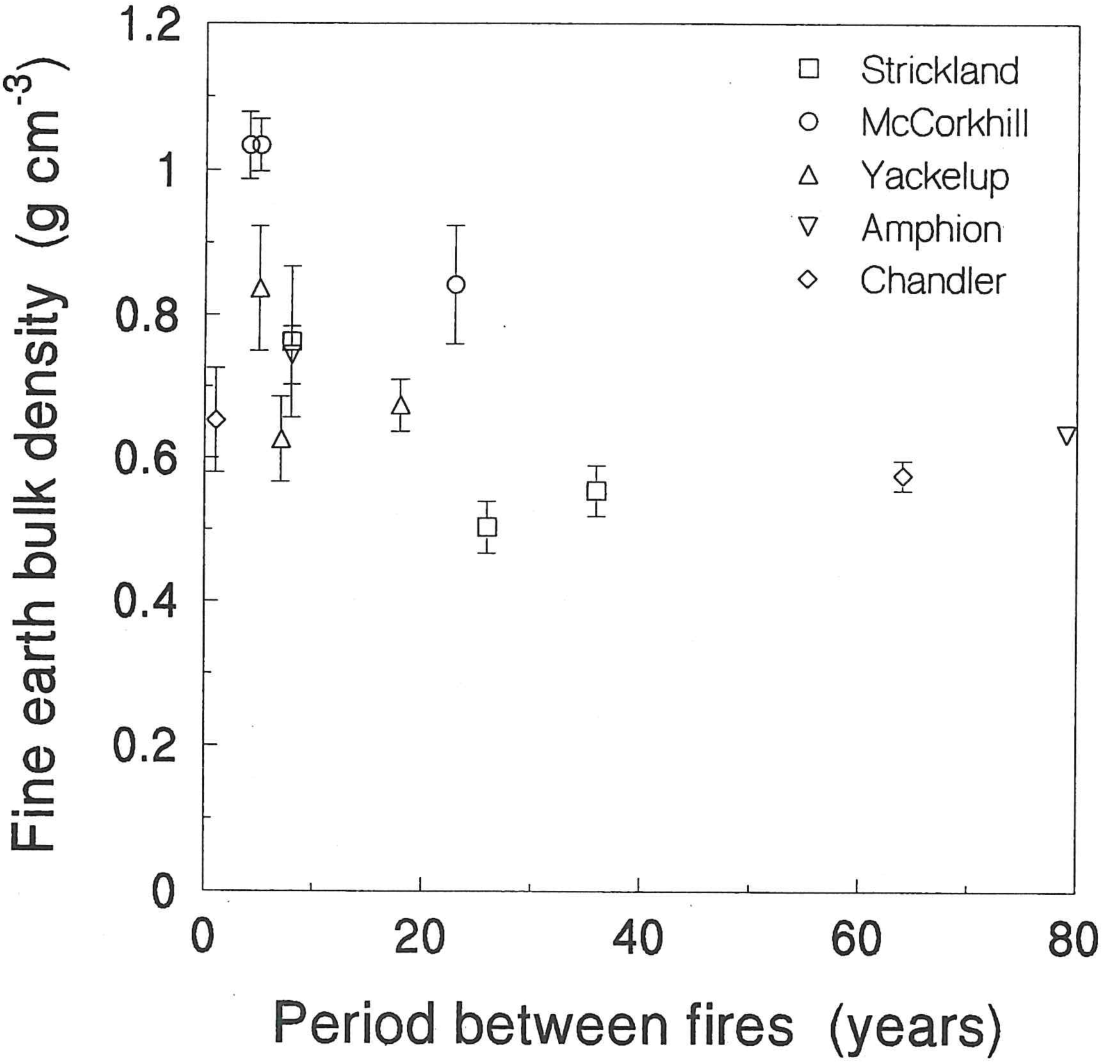


Fig. 3. The carbon store (g cm^{-3}) of surface soils (0-75 mm) for plots burnt under a range of fire frequencies at five sites.

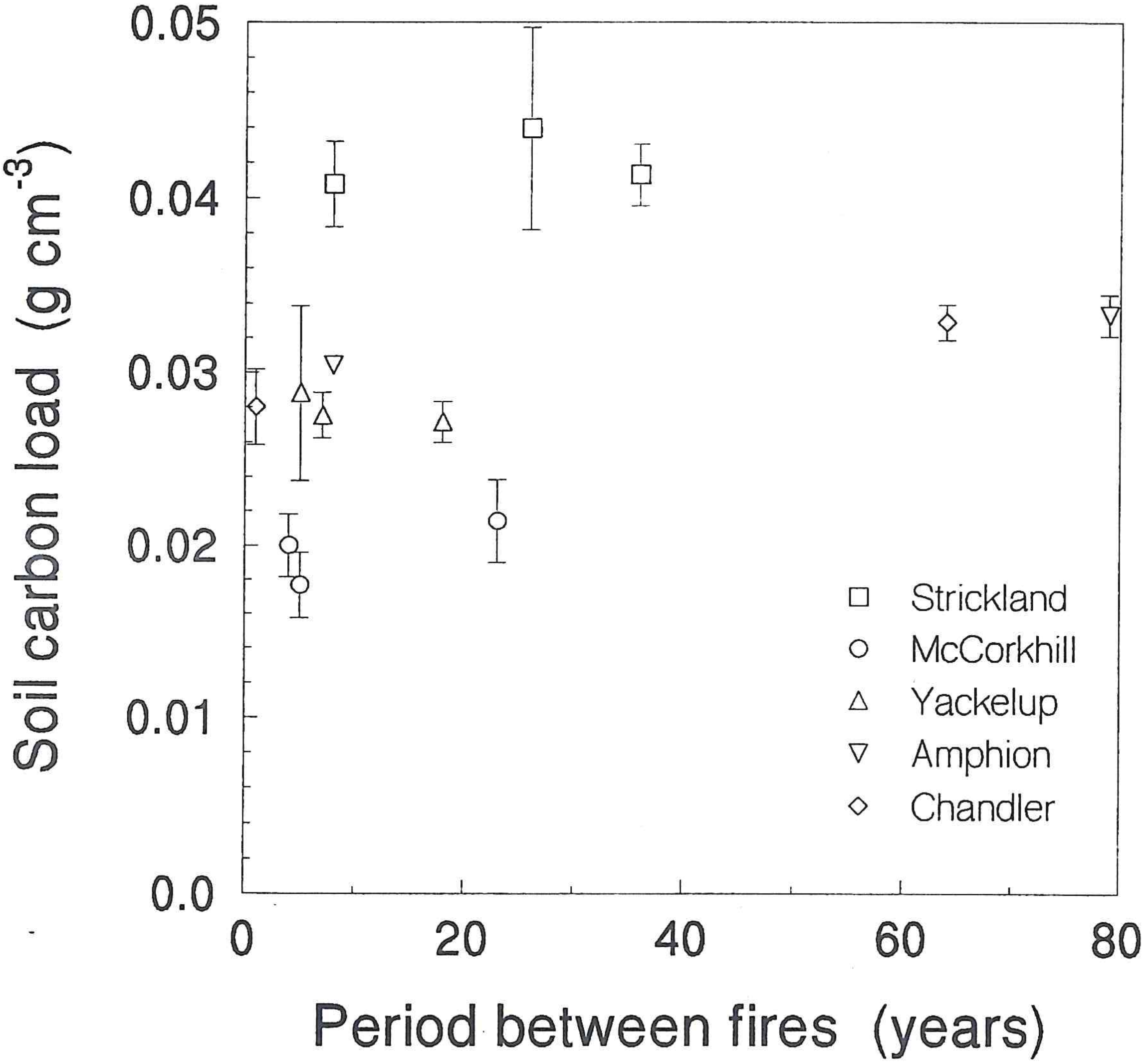


Fig. 4. The relationship between mean carbon concentration (%) and fine earth bulk density of surface soils (0-75 mm) for plots burnt under a range of fire frequencies at five sites.

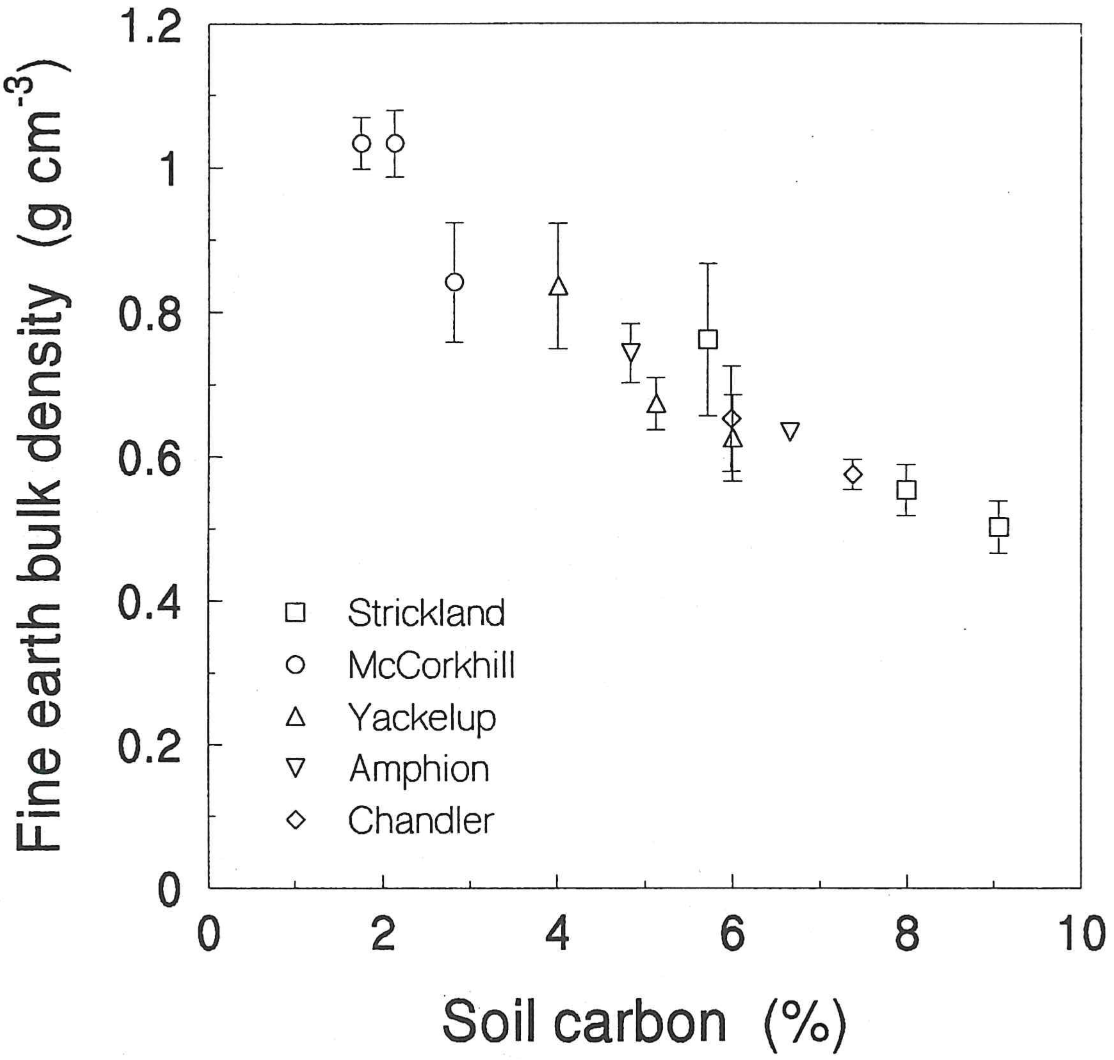
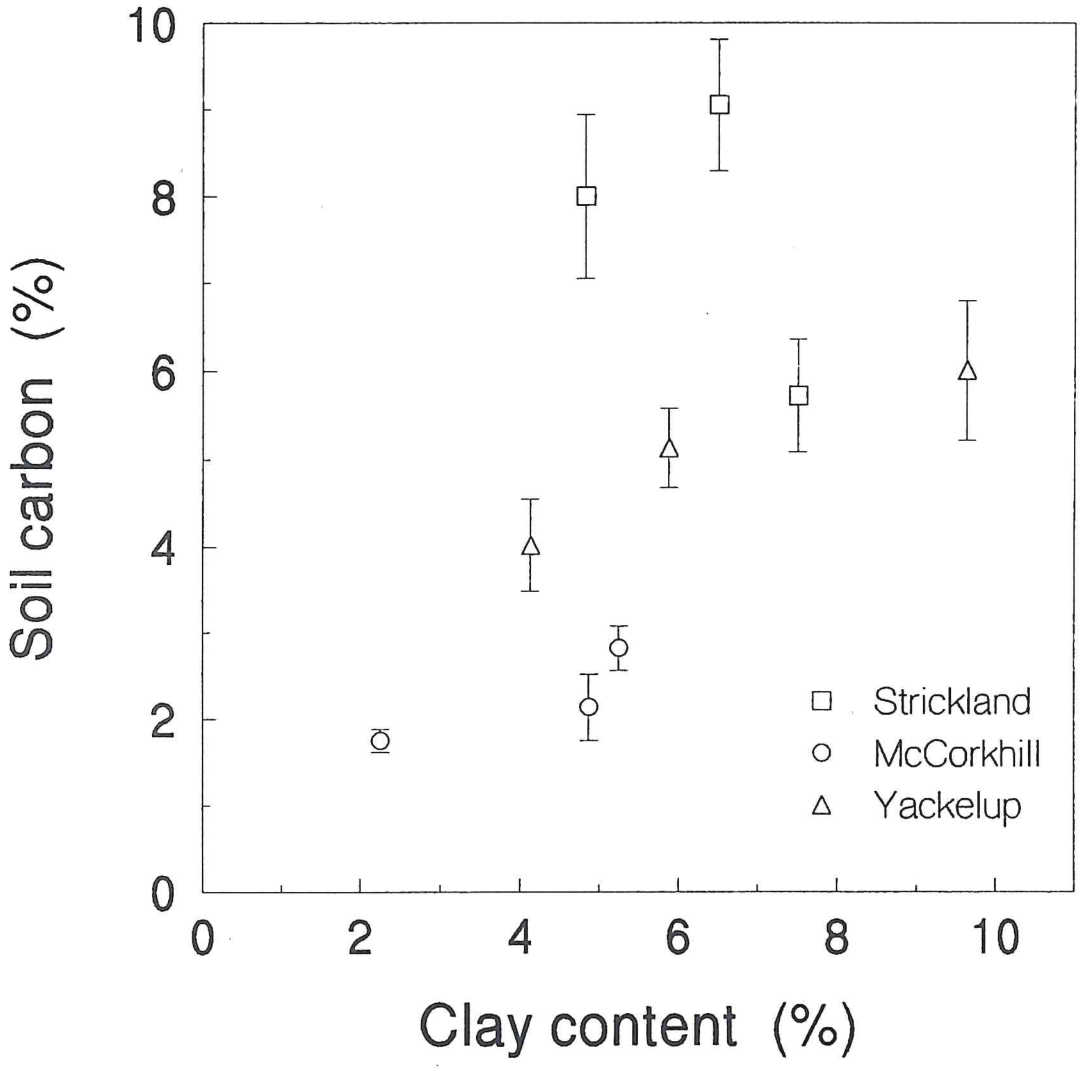


Fig. 5. Clay content and concentration of soil carbon for surface soils (0-75 mm) of plots burnt under a range of fire frequencies at three sites.



FOREST & WOOD PRODUCTS
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DEPARTMENT OF
Conservation
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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)

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K. R. Whitford

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K. R. Whitford, M. R. Williams, M. A. Maxwell and B. MacArthur

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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.