SOIL CHEMICAL PROPERTIES AND FOREST FLOOR NUTRIENTS UNDER REPEATED PRESCRIBED-BURNING IN EUCALYPT FORESTS OF SOUTH-EAST QUEENSLAND, AUSTRALIA

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ABSTRACT

The long-term impacts of repeated prescribed-burning on surface (0–30 cm) soil chemical properties and forest floor nutrients in two contrasting native eucalypt forests in south-east Queensland, Australia were assessed. Most effects were confined to the topsoil (0–10 cm). At the dry sclerophyll site, more than 40 years of annual burning had not led to any loss in topsoil total nitrogen and organic carbon but had significantly increased topsoil acid-extractable phosphorus. At the wet sclerophyll site, biennial burning (10 burns) resulted in decreases in topsoil total nitrogen and potentially mineralisable nitrogen despite a shorter experimental period (22 years). The increase in acid-extractable phosphorus with burning on this latter site was not significant.

The varying impacts of prescribed-burning on soil chemical properties at the two sites may be partly explained by differences in site quality and in the number of times the forests have been subjected to various burning regimes. These changes may have implications for tree growth in the long term. Repeated burning reduced the weight, organic matter, and nutrient contents of the forest floor at both sites, the decreases being directly proportional to the frequency of burning.

Keywords: fuel reduction burning; forest soils; soil fertility; eucalypt forests.

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INTRODUCTION

Low-intensity (< 500 kW/m) prescribed-burning has been a standard landscape management tool for reducing wildfire occurrence in both native and plantation forests of Australia since the 1960s. Besides its role in protecting timber resources from wildfires, other major benefits cited include: reduction of pests and diseases, improvement of the grazing value of forest lands, ease of access for logging and silvicultural treatments, and enhancing the regeneration of some native eucalypt species (Queensland Department of Forestry 1984). In Queensland, current prescribed-burning practices in eucalypt forests vary according to forest type. In dry sclerophyll forests (classification according to Beadle & Costin 1952), broadscale prescribed-burning is normally done on a cycle of 3–4 years and might also be carried out before logging. When the logging is finished, the debris will also be burned and then the block will revert to the normal burning cycle. In wet sclerophyll forests (Beadle & Costin 1952), burning is restricted to those sections which can be burned safely during winter and is normally conducted on no less than a 5-year cycle (Taylor 1989, 1994).

At present, it is a common view that the long-term ecological consequences of such practices are uncertain (Florence 1994; Noble 1986). A major concern with recurrent prescribed-burning relates to its disruption of mineral nutrient cycling which may have long-term negative cumulative effects on forest productivity (Guinto *et al.* 1999; Monleon *et al.* 1997; Richards & Charley 1983; Turner *et al.* 1997). Since soil properties are strongly influenced by living vegetation and accumulated dead organic matter, both of which are removed to a variable degree by burning (Kimmins 1987), fire has the potential to change the chemical, physical, and biological properties of mineral soil by heating, altering, and removing these substances, and exposing the soil surface (Giovannini & Lucchesi 1997; Guinto *et al.* 1999, 2000; Lynham *et al.* 1998). The nature and degree of alteration depend on fire intensity and duration, and the amount of organic matter consumed, which in turn are influenced by the amount of fuel available, its spatial distribution and moisture content, and prevailing weather conditions. Because these factors are variable and the processes involved are complex, the effects cannot be predicted accurately and sometimes appear contradictory (Wells *et al.* 1979). While the apparent conflict in research results could well stem from variations in experimental methodology, much of the variation in observed results may reflect the actual range of potential fire effects (Christensen 1987). It is therefore important to understand site-specific changes in soil properties as a result of prescribed burning and their implications for long-term forest productivity. The nutrient elements such as nitrogen and phosphorus are of most concern here because they usually limit the productivity of many forest ecosystems (Bubb *et al.* 1998a, b, 1999; Hall & Matson 1999; Xu *et al.* 1995a, b) and are subject to volatilisation losses during the burning of litter and surface soil (Raison *et al.* 1985). Thus, most studies on the impacts of fires on soil fertility have focused on these nutrients, particularly nitrogen (Binkley *et al.* 1992; McKee Jr. 1982; Wells 1971).

In this study, two experimental forest sites being maintained by Queensland's Department of Primary Industries Forestry (DPI Forestry, formerly Queensland Department of Forestry) as part of their research programme on the ecological and silvicultural effects of repeated prescribed-burning (House 1995; Taylor 1989) were selected primarily because they represent south-east Queensland's commercially important native eucalypt forests and because their long-term burning histories (> 20 years) were known. They also provided an interesting ecological contrast. The objectives of this study were to examine the cumulative impacts of repeated prescribed burning on: (1) surface soil chemical properties and forest floor nutrient pools in these two forest types, and (2) their implications for sustainable forest management.

MATERIALS AND METHODS

Sites and Fire Treatments

Bauple State Forest (lat. 25°48' S, long. 152°37' E) is approximately 260 km north of Brisbane, at about 60 m above sea level. It is classified as a dry sclerophyll forest or an open forest (Specht 1970) dominated by spotted gum (*Corymbia variegata* F. Muell., formerly *Eucalyptus maculata* Hook.) and grey ironbark (*E. drepanophylla* F. Muell. ex Benth.). The understorey vegetation includes wattles (*Acacia* spp.), brush box (*Lophostemon confertus* (R. Br.) P.G. Wilson & Waterhouse), swamp box (*L. suaveolens* (Solander ex Gaertn.) P.G. Wilson & Waterhouse), red ash (*Alphitonia excelsa* (Fenzl.) Reisseck ex Benth.), and lantana (*Lantana camara* L.) (Henry 1961). Average annual rainfall in the area is 1131 mm, with over half of this occurring between December and March, and a marked dry period from July to September. The topography is one of broad flat ridges separated by shallow gullies. Brown and red Kurosols (Isbell 1996) cover most of the area, with red Kandosols appearing on some hill tops and gullies. The soils have loamy surface textures and are generally shallow with clay loam to clay textures at 30–40 cm depth. In 1952, two compartments were set aside by DPI Forestry to investigate the long-term effects of two fire regimes—namely, no burning and annual burning in late winter or early spring (August to September). In 1973, periodic burning every 2 to 3 years was added as the third treatment in another compartment to simulate the Department's current routine practice of prescribed burning in this forest type. There were six plots per treatment, with each plot measuring 100 × 40 m. It is significant to note that the spatial arrangement of treatments (i.e., plots within a compartment receive only one burning treatment) resulted in an experimental design which may be termed segregated (Hurlbert 1984) and was therefore strictly non-randomised, an acknowledged limitation of the experiment. Nevertheless, within a compartment, plot locations were spread evenly and the average distance between two nearest neighbouring plots was about 0.7 km. This situation may weaken any spatial dependence of soil properties that could exist between neighbouring plots. One rationale behind the one-compartment/one-treatment approach to experimentation in this forest was to ensure protection of the experiment from unscheduled burns (Queensland Department of Forestry unpubl. data), a major consideration at the time when prescribed burning techniques were in their infancy. Due to logistical constraints, only three out of the six replicate plots of each treatment were sampled in this study. Plots were selected based on similarity of soil types and vegetation. Because of high fuel moisture content and/or unfavourable weather conditions, scheduled burns sometimes could not be achieved. At the time of sampling (September 1994) there had been 41 burns in the annually burnt treatment (last burned in 1992) and nine burns in the periodically burnt treatment (last burned in 1989). The control treatment has remained unburnt since 1946 when this forest land was first acquired by DPI Forestry. Prior to acquisition, however, the site would have likely been burned quite frequently by graziers while it was freehold land.

Peachester State Forest (lat. 26°50' S, long. 152°53' E) is situated about 100 km north of Brisbane in the Sunshine Coast hinterland at 137 m above sea level. It is a wet sclerophyll forest or a tall open forest (Specht 1970) dominated by blackbutt (*E. pilularis* Smith). Other canopy tree species include *E. microcorys* F. Muell., *E. resinifera* Smith, *Lophostemon confertus* (R. Br.) P.G. Wilson & Waterhouse, and *Syncarpia glomulifera* (Smith) Niedenzu. The understorey vegetation is variable and species-rich, in places dominated by grasses (e.g., *Imperata cylindrica* (L.) Rauschel, *Digitaria ciliaris* (Retz.) Koeler), ferns (*Blechnum cartilagineum* Sw.), or shrubs (e.g., *Dodonaea triquetra* Andr., *Hibiscus heterophyllus* Vent., *Hovea acutifolia* Cunn. ex G. Don). The average annual rainfall in the area is 1711 mm. The topography is undulating to rolling (2–16% slopes). The sandstone geology of the area has produced deep sandy soils with no perceptible increase in clay content to a depth of 60 cm. The soils are classified as red to yellow Kandosols (Isbell 1996).

The experiment was arranged in a split-plot design with fire regimes as the main plot treatment and slope position (lower and upper slopes) as subplot treatment. The plots were established in 1969 but the first burn was not conducted until about 1972. Since that time, the fire treatments had included: unburnt, biennial burning, and quadrennial burning during late winter or early spring (August to September). There were three blocks, two of which were adjacent to each other while the third block was about 6 km away from the others. Plots in the two adjacent blocks measured 30 × 27 m while plots in the third block measured 40 × 20 m. The third block had soils with sandier texture and considerably less organic matter, classified as red Kandosols (Isbell 1996). There was also a marked change in the vegetation with the presence of grass trees (*Xanthorrhoea* spp.), banksias (*Banksia* spp.), and different grass species (*Entolasia stricta* (R. Br.) Hughes and *Eremochloa bimaculata* Hackel) in the understorey. There were a total of 18 plots for the experiment. As at the dry sclerophyll site, high fuel moisture content and/or unfavourable weather conditions resulted in burns that were either poor or completely unsuccessful and varied from plot to plot. This illustrates the difficulty of applying quantitative levels of treatments as well as repeated application of treatments in designed fire experiments (Binkley *et al.* 1993). At the time of sampling (August 1994), there had been, on average, 10 burns in the biennially burnt treatment (last burned in 1991) and seven burns in the quadrennially burnt treatment (last burned in 1989).

Soil and Forest Floor Sampling and Analysis

At both sites, surface soil samples (0–10, 10–20, and 20–30 cm depth increments) were collected from six randomly selected points within each plot using a 7.5-cm-diameter auger and then bulked by depth increments to give a single composite sample per plot. The samples were air-dried, homogenised, sieved to less than 2 mm, and analysed for total nitrogen, organic carbon, acid-extractable phosphorus, bicarbonate-extractable phosphorus, total phosphorus, pH, exchangeable basic cations (potassium, calcium, magnesium, and sodium), exchangeable aluminium, potentially mineralisable nitrogen, and particle-size distribution. Total nitrogen was determined by semimicro-Kjeldahl digestion of a 1.0-g sample and the ammonia released was determined by steam distillation (Bremner & Mulvaney 1982) and potentiometric titration. Organic carbon was determined by the modified Walkley-Black procedure (Jackson 1958). Acid-extractable phosphorus was determined by extracting 5.0 g soil with 50 ml 0.1 *M* sulphuric acid solution (MacLeod & Clarke 1975). Bicarbonate-extractable phosphorus was determined by the method of Colwell (1963). Total phosphorus was extracted with constant boiling hydrochloric acid and determined colorimetrically using the reduced molybdenum blue method (MacLeod & Clarke 1975). Soil pH was measured on a 1:5 soil water suspension. Exchangeable basic cations were extracted with 1 *M* ammonium acetate (pH 7) and determined by atomic absorption spectrophotometry (Chapman 1965), and exchangeable aluminium was extracted with 1 *M* KCl and determined by atomic absorption spectrophotometry (Barnhisel & Bertsch 1982). Particle-size distribution was determined by a combination of wet sieving and hydrometer methods employing pre-treatment with hydrogen peroxide to remove soil organic matter (Day 1965). Freshly collected topsoil (0–10 cm) samples were assayed for potentially mineralisable nitrogen using a 7-day/40°C waterlogged incubation (Waring & Bremner 1964). The ammonium-nitrogen produced (mineralised) was extracted with 1 *M* KCl and determined by steam distillation and potentiometric titration. Potentially mineralisable nitrogen was computed as the difference between ammonium-nitrogen concentrations obtained at Day 7 and Day 0.

Forest floor samples at both sites were collected from 10 randomly selected spots using a 20-cm square frame and bulked to give a single composite sample per plot. The samples were dried at 60°C for 48 hours, weighed, and ground to pass a 0.5-mm sieve. Total nitrogen was determined by the semimicro-Kjeldahl method. For phosphorus, potassium, calcium, and magnesium analyses, a 1.0-g sample of the material was digested in concentrated nitric acid (Jones & Case 1990) and nutrient concentrations were measured using inductively-coupled plasma atomic emission spectroscopy (ICP-AES). A separate subsample was dry ashed at 500°C for 5 hours to determine mineral content which was subtracted from the total dry weight to yield organic matter content.

Statistical Analysis

For forest floor weights and nutrients, comparison of prescribed burning treatments within each site was made by analysis of variance (ANOVA).

Because the experiments were not originally designed to assess soil nutritional changes after burning, none of the sites had detailed soil analyses before the imposition of the treatments. At the wet sclerophyll site, 1972 pre-treatment surface soil pH, organic carbon, total nitrogen, total phosphorus, and exchangeable potassium values were available. However, the measurements included only two of the three blocks. Thus, only 12 of the 18 plots can be included in the analysis. An alternative analysis was sought which would include all the plots, soil properties, and sampling depths considered in this study. At this site, it was found that there were soil textural differences between plots. Because this variation might have an effect on the retention and movement of soil nutrients, it was decided to use analysis of covariance (ANCOVA) with clay content as covariate for soil properties with significant correlations ($p < 0.10$) with clay, for comparing burning treatments at this site. It is widely known that clayey soils have higher total nitrogen content than coarse-textured soils (Stevenson 1982). This assumes, of course, that clay content is not significantly affected by burning—a reasonable assumption given that texture is a stable soil property and that the fires were of low intensity. This analysis of covariance should be able to adjust for soil property differences not directly attributable to burning so that a valid interpretation of treatment effects could be made. Soil properties with no significant correlations with clay were compared by ANOVA. For soil properties with significant correlations with clay, but where clay was not significant as a covariate, ANOVA was also employed. At the dry sclerophyll site, only plain ANOVA was employed because of similarity of textures across burning treatments.

ANOVA and ANCOVA were performed using the PROC GLM module of SAS (SAS Institute Inc. 1987). Significant differences between treatments for each site and soil depth were identified using Fisher's LSD procedure at $p = 0.10$. Steel *et al.* (1997) suggested using $p = 0.10$ in experiments with low replication rather than the more stringent $p = 0.05$ because detection of treatment differences may not be possible unless there are large real differences.

Preliminary statistical analysis of all variables in the wet sclerophyll site had revealed that slope position (lower or upper slope) had no influence on soil and litter properties. Thus, it was decided to consider only the fire factor to analyse the experiment as a randomised block design with six replicates per treatment.

RESULTS AND DISCUSSION

Particle-size Distribution of Soils

Average clay content, and organic carbon, total nitrogen, total phosphorus, and extractable inorganic phosphorus concentrations of the soils, grouped according to treatment and depth, are given in Table 1. At the dry sclerophyll site, ANOVA revealed that, regardless of depth, there were no statistically significant differences in clay content among the treatments. At the wet sclerophyll site, ANOVA showed that there were significant differences in clay content among treatments in the 0–10 cm depth ($p = 0.038$), with the biennially burnt plots having the least clay content. There were no significant differences in clay content in the sub-surface layers but the biennially burnt plots still had the lowest clay content. This could lead to biased assessment of treatment effects on soil properties if only plain ANOVA was employed in the study. Therefore, it is important to take into account these inherent differences so that they do not become confounding factors in the assessment of burning effects on soil properties. Organic carbon, total nitrogen, potentially mineralisable nitrogen, and exchangeable basic cations correlated significantly with clay content and were thus adjusted using clay content as a covariate.

Organic Carbon and Total Nitrogen

Prescribed burning effects on soil chemical properties were confined mostly to the topsoil (0–10 cm) layer (Table 1). At the dry sclerophyll site, annual burning did not significantly reduce soil organic carbon levels, although periodically burnt soils tended to have slightly higher organic carbon than unburnt soils. Burning did not result in any significant loss of total nitrogen in the topsoil. Wells (1971), McKee (1982, 1991), and Waldrop *et al.* (1987) observed that total nitrogen in loblolly pine (*Pinus taeda* L.) soils of South Carolina, USA, was not reduced by periodic burning but was increased slightly by annual burning in winter or summer. They attributed the increase to a greater number of herbaceous leguminous plants invading burnt sites and their ability for symbiotic nitrogen fixation. Fixed nitrogen becomes incorporated into the topsoil thus improving soil fertility. This process may equally be in operation at this site because of the presence of acacias in the understorey (Guinto *et al.* 2000). Similarly, in a comparison between two adjacent jarrah (*E. marginata* Donn ex Smith) stands in Western Australia, one of which had been protected from fire for 45 years and the other burned periodically approximately every 2.6 years (17 burns), Abbott *et al.* (1984) also found slightly higher total nitrogen in soils of burnt stands. If it can be assumed that the increase in total nitrogen at the dry sclerophyll site was not due to chance alone, Pritchett

TABLE 1—Clay content, organic carbon, total nitrogen, potentially mineralisable nitrogen, total phosphorus, acid-extractable phosphorus, and bicarbonate-extractable phosphorus (± SE) of soils under long-term prescribed burning in two native eucalypt forests of south-east Queensland*

Soil depth and fire treatment	Clay (%)	Organic C (%)	Total N (%)	Potentially mineralisable N (mg/kg)	Total P (mg/kg)	Acid-P (mg/kg)	Bicarb-P (mg/kg)
Dry sclerophyll site							
0–10 cm							
Unburnt	17±2	2.16±0.19	0.105±0.012	10.3±5.3	117±7	3.8**b**±0.4	4.9±0.7
Periodic (9)†	17±5	2.54±0.64	0.134±0.038	17.7±7.2	197±59	4.7**b**±0.5	6.6±1.6
Annual (41)	17±4	1.98±0.35	0.122±0.025	14.4±4.8	167±41	6.6**a**±0.7	6.6±0.4
10–20 cm							
Unburnt	21±5	1.36±0.12	0.080±0.006	nd‡	109±7	2.5±0.1	3.0±0.6
Periodic (9)	22±9	1.44±0.40	0.083±0.026	nd	158±43	2.9±0.2	3.6±0.4
Annual (41)	20±7	1.17±0.26	0.080±0.026	nd	140±23	5.1±1.6	3.1±0.3
20–30 cm							
Unburnt	35±6	0.93±0.15	0.064±0.005	nd	114±14	1.5±0.01	1.9±0.6
Periodic (9)	30±11	0.80±0.29	0.075±0.023	nd	154±35	1.6±0.4	1.5±0.6
Annual (41)	28±12	0.60±0.23	0.053±0.016	nd	108±19	2.0±0.3	2.0±0.5
Wet sclerophyll site§							
0–10 cm							
Unburnt	22**a**±2	4.30**a**±0.02	0.183**a**±0.021	20.2**a**±1.4	105±12	2.8±1.0	5.2±1.1
Quadrennial (7)	24**a**±3	3.87**ab**±0.03	0.160**ab**±0.024	16.2**ab**±1.6	94±15	3.9±1.0	5.2±1.1
Biennial (10)	18**b**±1	2.37**b**±0.03	0.100**b**±0.025	12.2**b**±1.7	108±19	5.7±1.3	6.0±1.0
10–20 cm							
Unburnt	19±3	2.67±0.30	0.143±0.010	nd	93±7	1.9±0.3	3.4±0.7
Quadrennial (7)	21±5	2.51±0.32	0.123±0.011	nd	90±12	3.4±0.6	3.8±0.7
Biennial (10)	13±1	2.01±0.34	0.103±0.011	nd	109±16	3.9±1.1	4.2±1.1
20–30 cm							
Unburnt	21±2	2.02±0.18	0.100±0.007	nd	83±8	2.0±0.4	2.0±0.3
Quadrennial (7)	25±5	1.68±0.19	0.086±0.008	nd	79±9	2.3±0.5	3.7±0.8
Biennial (10)	17±2	1.29±0.19	0.070±0.008	nd	101±11	2.9±0.5	3.1±0.4

* Values in columns for a given site and soil depth followed by the same letter or no letter are not significantly different at p=0.10.

† Values in parentheses in this column are the total number of burns for each treatment.

‡ nd = not determined

§ Organic carbon and total nitrogen means at this site are ANCOVA-adjusted means.

(1979) has offered four other possible, but not necessarily completely satisfactory, explanations for such an increase. These include: (1) increased growth of fibrous-rooted plants (i.e., grasses) after burns; (2) movement of colloidal-sized charred material from the burnt litter layer in the mineral soil by gravity or water; (3) isoelectric precipitation of alkali humates produced during burning; and (4) accumulation of decomposition-resistant organic residues mixed in the surface mineral soil. Our findings on the effects of repeated fires on total nitrogen concur with those of Hatch (1959) in Western Australian jarrah soils and Humphreys & Craig (1981) in blackbutt soils of northern New South Wales where there were no deleterious impacts of burning on this soil parameter.

At the wet sclerophyll site, burning apparently reduced topsoil organic carbon and total nitrogen levels in similar proportions. Relative to the control, burning every 2 years significantly brought about more than a 40% reduction in organic carbon and total nitrogen. On the other hand, burning every 4 years reduced organic carbon and total nitrogen by 10% and 12%, respectively, but these differences were not statistically significant (Table 1). These losses appear to be quite high and are not in accord with the low-intensity burning practised in this forest and the shorter duration (22 years) of the experiment relative to the dry sclerophyll site. As noted earlier, there were a number of unsuccessful burning attempts. Monleon *et al.* (1997) have also reported significant reductions in topsoil organic carbon and total nitrogen resulting from prescribed fuel reduction burning in ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws) forests of central Oregon, USA.

At the wet scelerophyll site, separate analyses of covariance employing the available pre-treatment surface organic carbon and total nitrogen mentioned earlier as respective covariates were run to provide a baseline comparison of the magnitudes of reduction. The results indicated that surface organic carbon of the biennially burnt treatment (3.69%) was lower than in the unburnt treatment (5.15%) by only 28%, and quadrennial burning (5.07%) had little effect. These reductions were not significant. Surface total nitrogen of the biennially burnt treatment (0.168%) was 25% lower than in the unburnt treatment (0.224%). This reduction was significant ($p = 0.088$). Quadrennial burning had little effect on surface total nitrogen (0.205%). The higher mean values of total nitrogen by fire treatment compared with the mean values reported in Table 1 can be attributed to the higher inherent fertility of the soils in the 12 plots included in this analysis. If we can assume that the computed declines with burning apply also to the plots not included in the analysis, the projected mean total nitrogen values inclusive of all plots would be: unburnt = 0.186%, quadrennial = 0.170%, and biennial = 0.140%. Thus, it seems that, despite adjustment for differences in clay content, this form of analysis may still over-estimate the reductions in organic carbon and total nitrogen. Nevertheless, it is significant to note that reduction in total nitrogen under frequent burning was demonstrated regardless of which technique was used.

We also analysed pH, total phosphorus, and exchangeable potassium in the same manner and found no significant treatment differences, which is in agreement with covariance analysis using clay as covariate (Tables 1, 2); hence, the adjustments are critical only for organic carbon and total nitrogen. It is unfortunate, however, that the analysis of covariance using pre-treatment soil properties could not be pursued fully because of the lack of pre-treatment data for other plots and depths, and also because not all soil properties measured in the present study were measured before the burning regimes were imposed.

The study by Jones & Richards (1977) on scribbly gum (*E. signata* F. Muell.) forests growing on the sandy lateritic podsolic soils of Beerwah and Beerburrum, a few kilometres away from this site, showed that periodic prescribed burning reduced the total nitrogen and the more labile hydrolysable nitrogen of surface soils by 22% over the control, a reduction very similar in magnitude to that at the wet sclerophyll site. The sandy nature of the soils in these sites may offer little physical protection of the organic matter during burning. Hassink *et al.* (1993) found that, in clayey soils, organic nitrogen was more protected against decomposition than in sandy soils. In clayey soils, organic nitrogen is physically protected by being entrapped in small pores, whereas in sandy soils organic nitrogen is physically

TABLE 2—pH and exchangeable cations (±SE) of soils under long-term prescribed burning in two native eucalypt forests of south-east Queensland*

Soil depth and fire treatment	pH (1:5)	Exchangeable cations (cmol/kg)				
		K	Ca	Mg	Na	Al
Dry sclerophyll site						
0–10 cm						
Unburnt	5.40**b**±0.04	0.29±0.04	0.88**b**±0.17	2.26±0.45	0.28**b**±0.05	0.90±0.45
Periodic (9)†	5.49**ab**±0.35	0.35±0.06	1.65**b**±1.05	4.17±1.81	0.54**a**±0.10	0.22±0.12
Annual (41)	6.06**a**±0.13	0.34±0.09	2.88**a**±1.28	4.28±2.03	0.36**ab**±0.04	0.76±0.25
10–20 cm						
Unburnt	5.59**b**±0.04	0.22±0.03	0.39±0.10	3.06±1.29	0.35**b**±0.14	0.13±0.08
Periodic (9)	5.72**ab**±0.09	0.22±0.06	0.84±0.63	5.07±2.62	0.84**a**±0.30	0.07±0.02
Annual (41)	5.90**a**±0.05	0.21±0.02	1.50±0.80	4.87±2.99	0.62**a**±0.20	0.05±0.01
20–30 cm						
Unburnt	5.44±0.15	0.21±0.03	0.26±0.08	5.92±2.39	0.82±0.43	0.11±0.07
Periodic (9)	5.66±0.18	0.14±0.02	0.35±0.10	7.00±2.89	1.71±0.68	0.07±0.02
Annual (41)	5.80±0.10	0.17±0.02	1.02±0.58	6.65±4.30	1.02±0.60	0.04±0.01
Wet sclerophyll site‡						
0–10 cm						
Unburnt	5.56**b**±0.11	0.22±0.02	1.39±0.30	1.44±0.21	0.16±0.02	0.56±0.14
Quadrennial (7)	5.62**ab**±0.11	0.19±0.02	1.47±0.35	1.33±0.24	0.15±0.03	0.71±0.16
Biennial (10)	5.77**a**±0.12	0.27±0.03	1.80±0.36	1.63±0.26	0.11±0.03	0.35±0.17
10–20 cm						
Unburnt	5.69±0.13	0.17±0.02	0.84±0.23	1.14±0.18	0.12±0.02	0.93±0.13
Quadrennial (7)	5.74±0.11	0.15±0.03	0.66±0.25	0.81±0.20	0.14±0.02	0.98±0.14
Biennial (10)	5.80±0.08	0.23±0.03	0.86±0.26	1.14±0.21	0.10±0.02	0.83±0.15
20–30 cm						
Unburnt	5.68±0.10	0.15±0.02	0.40±0.12	0.92±0.11	0.16±0.06	1.14±0.15
Quadrennial (7)	5.80±0.17	0.14±0.03	0.33±0.09	0.62±0.12	0.12±0.02	0.98±0.16
Biennial (10)	5.70±0.07	0.18±0.03	0.44±0.14	0.94±0.12	0.17±0.06	1.10±0.16

* Values in columns for a given site and soil depth followed by the same letter or no letter are not significantly different at $p = 0.10$.

† Values in parentheses in this column are the total number of burns for each treatment.

‡ Exchangeable potassium, calcium, magnesium, and sodium means at this site are ANCOVA-adjusted means.

protected by its adsorption to clay minerals or by the coating of organic matter with clay particles.

It is not yet known if this level of reduction of organic nitrogen at the wet sclerophyll site will have an impact on the nutrition and growth of existing eucalypts and understorey species, or eucalypts in the next rotation, given the well-known adaptations of Australian vegetation for coping with low soil fertility (Bowen 1981). With continued losses, however, it would also be interesting to find out if there is stimulation of understorey N_2 fixation (Guinto *et al.* 2000) to compensate for the lost nitrogen. Acacias are not as predominant in the understorey as they are at the dry sclerophyll site, and the mere presence of legumes in the forest does not necessarily guarantee that appreciable symbiotic N_2 fixation is occurring.

This result implies that, in this ecosystem, less frequent burning would be necessary in order to strike a balance between fuel build-up that could result in catastrophic wildfires, and the concern for nitrogen losses by fire. Also, since the moisture-holding capacity of sandy soils is largely dependent on surface organic matter, any reduction of this organic matter by fire might have a long-term deleterious effect on forest productivity.

Potentially Mineralisable Nitrogen

The loss in soil total nitrogen that occurred at the wet sclerophyll site may, in turn, have led to a decline in the available forms of nitrogen. The anaerobic incubation results show that the clay-adjusted potentially mineralisable nitrogen in the topsoil of the biennially burnt treatment was reduced by about 40% compared with the control (Table 1). Significant declines in potentially mineralisable nitrogen due to prescribed burning have also been reported elsewhere (Monleon *et al.* 1997; Turner *et al.* 1997). Again, this may have an impact on the growth and nutrition of the forest vegetation in the long term.

At the dry sclerophyll site, potentially mineralisable nitrogen in the topsoil tended to be higher in both the periodically burnt and annually burnt treatments than in the unburnt treatment; however, these differences were not statistically significant, probably because of the low number of replications examined, coupled with the high standard errors of the means.

Total and Extractable Inorganic Phosphorus

At the dry sclerophyll site, burnt plots had greater total phosphorus than the unburnt plots but the differences were not significant (Table 1). Total phosphorus of burnt soils had large standard errors, and the trend in the means probably resulted mainly from natural variability of this soil property rather than burning effects alone. No significant treatment differences in total phosphorus were observed at the wet sclerophyll site.

At the dry sclerophyll site, acid-extractable phosphorus increased with increasing burning frequency, regardless of depth (Table 1). In the topsoil, acid-extractable phosphorus was significantly higher in the control than in the annually burnt treatment but not in the periodically burnt treatment. Increases at lower depths were not significant. Similar trends were observed for bicarbonate-extractable phosphorus but none of the differences were significant (Table 1). At the wet sclerophyll site, both acid-extractable phosphorus and bicarbonate-extractable phosphorus tended to be higher with burning frequency at all depths. The tests for "available phosphorus" employed here are apparently sensitive, with the concentrations obtained reflecting well the frequency of burning.

Immediately after burning, appreciable amounts of phosphorus are added to the surface soil in ash but much of this is present as relatively insoluble calcium polyphosphates. However, the solubility of phosphorus increases markedly when the ash is incorporated into the soil and partially neutralised by heavy rainfall (Richards & Charley 1983). The combined effects of soil heating and ash addition almost always lead to increases in extractable inorganic phosphorus, but longevity of the increases varies (Raison *et al.* 1993). Thus, it appears that the major beneficial effect of controlled burning is to increase the available forms of this element in the long term. This may be very significant, given the extreme phosphorus infertility of many Australian forest soils. McKee (1982, 1991) and Waldrop *et al.* (1987) reported similar findings in the coastal-plain pine soils of the south-eastern United States which have been burned for periods ranging from 8 to 65 years. Abbott *et al.* (1984) also found higher available phosphorus in burnt than in unburnt jarrah soils of Western Australia. Waldrop *et al.* (1987) noted that increases in available phosphorus brought about by frequent burning may increase the growth and vigour of crop trees. McKevlin & McKee (1986) even reported that the increased level of available phosphorus through 33 years of annual winter burning had increased the growth and nitrogen and phosphorus uptake of loblolly pine seedlings in a pot experiment. This implies that seedlings of the next stand may benefit nutritionally from the long-term effects of prescribed burning. It has also been suggested that the increased levels of available phosphorus may stimulate the growth of understorey legumes and their nitrogen-fixation ability since phosphorus is a key nutrient in the nitrogen fixation process (Guinto *et al.* 2000; Raison *et al.* 1993; Vitousek & Howarth 1991). In contrast, there are studies (e.g., Binkley *et al.* 1992) which showed that annual burning over 30 years had no significant cumulative effect on soil inorganic phosphorus.

Soil pH and Exchangeable Cations

At both sites, soil pH tended to increase with increasing fire frequency, with the frequently burnt topsoils (0–10 cm) having significantly higher pH values than those of control plots (Table 2). At the dry sclerophyll site, this effect was also observed in the 10–20 cm depth.

The well-known increase in soil pH after burning has been attributed to the release of base cations resulting from combustion of organic matter and the chemical effects of heating on organic matter and minerals (Wells *et al.* 1979). The increase in pH was directly proportional to the amount of material burned and inversely proportional to pre-burn soil pH. The change in soil pH decreased with depth and was short-lived (2 to 3 years), which is similar to the findings of Lynham *et al.* (1998). Recurrent burning, however, may have a long-lasting effect so that burning in successive years would be expected to add pulses of basic cations in the ash with progressive widening of existing differences in pH.

At both sites, topsoil and subsurface exchangeable potassium did not significantly increase with burning, probably because of the high solubility (Khanna *et al.* 1994) and the rapid leaching of this monovalent cation (Pritchett 1979). Calcium and magnesium responses were similar. At the dry sclerophyll site, annual burning apparently increased exchangeable calcium. Exchangeable magnesium was also higher in burnt treatments but the increases were not significant. Topsoil and subsurface exchangeable sodium was highest in the periodically burnt treatment. Caution should be exercised in interpreting increases in exchangeable bases as mainly due to fire effects because, as with total phosphorus, the increases in exchangeable bases at this site could well be due mainly to large natural variation of these soil properties and probably not to treatment effects alone.

The increases in exchangeable calcium, magnesium, and sodium at the wet sclerophyll site were not statistically significant.

No significant reductions in the level of exchangeable aluminium were found, although a linear decrease occurred in the subsurface layers at the dry sclerophyll site with increasing burning frequency (Table 2).

Forest Floor Nutrient Concentrations

Differences in nutrient concentrations in litter may reflect variations in soil nutrient availability, which influence the chemical composition of overstorey components (Hingston *et al.* 1989). Nutrient concentrations of litter at both sites are given in Table 3. At the dry sclerophyll site, there were no significant treatment differences in litter nitrogen and potassium concentrations. Phosphorus concentration was significantly higher under annual burning than in the unburnt treatment ($p = 0.079$); the same applied to calcium ($p = 0.093$) and magnesium concentrations ($p = 0.052$).

TABLE 3–Nutrient concentrations (±SE) in litter under long-term prescribed burning in two native eucalypt forests of south-east Queensland*

Nutrient concentration (%)	Dry sclerophyll site		
	Unburnt	Periodic (9)†	Annual (41)
N	0.548**a** ±0.047	0.559**a** ±0.046	0.627**a** ±0.023
P	0.030**b** ±0.000	0.030**b** ±0.000	0.037**a** ±0.003
K	0.063**a** ±0.003	0.063**a** ±0.003	0.077**a** ±0.009
Ca	0.603**b** ±0.080	0.733**ab** ±0.135	0.980**a** ±0.077
Mg	0.117**b** ±0.017	0.140**b** ±0.021	0.187**a** ±0.007
	Wet sclerophyll site		
	Unburnt	Quadrennial (7)†	Biennial (10)
N	0.632**a** ±0.062	0.498**b** ±0.045	0.491**b** ±0.041
P	0.017**a** ±0.002	0.015**a** ±0.002	0.017**a** ±0.002
K	0.053**a** ±0.003	0.038**b** ±0.003	0.048**a** ±0.007
Ca	0.357**a** ±0.029	0.310**b** ±0.023	0.303**b** ±0.034
Mg	0.125**a** ±0.011	0.108**a** ±0.005	0.115**a** ±0.010

* Within a site, means in rows followed by the same letter are not significantly different at $p = 0.10$

† Values in parentheses in these rows are the total number of burns for each treatment.

At the wet sclerophyll site, litter nitrogen and calcium concentrations were significantly lower in the burnt than the unburnt treatment ($p = 0.097$ and 0.052, respectively). Phosphorus and magnesium concentrations were not affected by burning treatments. Relative to the control, potassium concentration was significantly lower in the quadrennially burnt treatment ($p = 0.018$) but not in the biennially burnt treatment.

Forest Floor Weight and Organic Matter and Nutrient Contents

As expected, both prescribed burning treatments lowered the weight and organic matter contents of the litter layer at both sites (Table 4).

Relative to the control, annual burning at the dry sclerophyll site significantly reduced litter nitrogen content by 53%. The reduction of nitrogen with periodic fires was intermediate between the control and annual fire treatments. At the wet sclerophyll site, quadrennial and biennial burning resulted in 40% and 64% reductions in litter nitrogen content, respectively.

TABLE 4—Dry weight, organic matter and nutrient contents (± SE) of litter under long-term prescribed burning in two native eucalypt forests of south-east Queensland*

Parameter (kg/ha)	Dry sclerophyll site		
	Unburnt	Periodic (9)†	Annual (41)
Dry weight	19030**a** ±2243	11070**b** ±1612	8056**b** ±556
Organic matter	14270**a** ±1762	8553**b** ±690	6703**b** ±484
N	106.3**a** ±21.0	63.2**b** ±14.5	50.3**b** ±2.1
P	5.7**a** ±0.7	3.3**b** ±0.5	3.0**b** ±0.4
K	12.2**a** ±2.1	7.1**b** ±1.4	6.3**b** ±1.0
Ca	117.7**a** ±29.1	77.2**a** ±7.0	79.7**a** ±11.1
Mg	22.9**a** ±6.0	15.4**a** ±2.6	15.1**a** ±1.4
	Wet sclerophyll site		
	Unburnt	Quadrennial (7)†	Biennial (10)
Dry weight	20680**a** ±1237	14870**b** ±2487	9941**c** ±1088
Organic matter	17520**a** ±1373	12300**b** ±2043	8372**c** ±928
N	131.8**a** ±17.5	78.7**b** ±17.2	47.2**c** ±4.1
P	3.5**a** ±0.5	2.4**b** ±0.6	1.7**c** ±0.3
K	11.1**a** ±1.1	6.0**b** ±1.2	4.7**b** ±0.7
Ca	74.0**a** ±7.6	48.6**b** ±10.0	29.7**c** ±3.9
Mg	26.0**a** ±3.1	16.6**b** ±3.1	11.4**c** ±1.4

* Within a site, means in rows followed by the same letter are not significantly different at p=0.10.

† Values in parentheses in these rows are the total number of burns for each treatment.

At both sites, the burning treatments significantly reduced litter phosphorus content compared with the control. It is important to note that, irrespective of burning treatments, the phosphorus content of litter in the wet sclerophyll forest was considerably less than that in the dry sclerophyll forest.

At the dry sclerophyll site, annual burning reduced the content of potassium in litter by 48% and periodic burning reduced it by 42%. At the wet sclerophyll site, biennial burning reduced potassium content by 58%, and quadrennial burning reduced it by 46%.

At the dry sclerophyll site, both burning treatments tended to have lower litter calcium contents. At the wet sclerophyll site, biennial burning decreased calcium content by 60% and quadrennial burning reduced it by 34%. The difference between the quadrennial and biennial burns was significant.

Magnesium responses to burning were similar to those of calcium. At the dry sclerophyll site, both burning treatments tended to have lower magnesium contents. At the wet sclerophyll site, biennial and quadrennial burning reduced magnesium content by 56% and 36%, respectively. The difference between these two burning treatments was significant.

Evaluating Long-term Impacts of Prescribed Fires on Forest Soils

To understand more fully the long-term effects of fire on forest ecosystems, Raison (1980) and Walker *et al.* (1986) have called for the establishment and maintenance of reference sites with known fire history. As gleaned from the literature, there are only a few such sites within Australia. Examples of other native eucalypt forest sites with known prescribed-fire histories include those in Western Australia (Abbott & Loneragan 1983; Abbott *et al.* 1984), New South Wales (Van Loon 1969; Birk & Bridges 1989), and the Australian Capital Territory (Keith 1991; Keith & Raison 1992). It is hoped that the results reported in these two long-term experiments may contribute to knowledge about the long-term impacts of prescribed fires on forest soils of Australia.

As exemplified in this study, interpretation of prescribed-burning effects on soil chemical properties in long-term ecological experiments was not straightforward owing to design weaknesses and natural soil variation unrelated to burning—confounding factors that could damp, mask, or even exaggerate the actual fire impacts. Given that this problem may be especially serious in forest soils, which are considered more heterogeneous than other soils (Pritchett 1979), the importance of accounting for these inherent differences cannot be over-emphasised.

CONCLUSIONS

At both sites, reductions in forest floor nutrients were directly related to increased burning frequency.

Frequent burning increased soil phosphorus availability at the dry sclerophyll site. This may be very significant given the extreme phosphorus infertility of many Australian forest soils and would be expected to have some nutritional advantage for tree growth. Burning did not result in any significant net loss of soil nitrogen at this site. The reduction of total nitrogen and potentially mineralisable nitrogen in the most frequently burnt treatment (biennial) at the wet sclerophyll site may have an adverse impact on the growth of the existing and future forest vegetation in the long term. Given these nitrogen losses, it is important to establish if there is compensatory stimulation of understorey N_2 fixation by legumes.

The differences in burning responses of individual soil chemical properties at the two sites may be partly explained by inherent differences in site quality and the differences in the number of times the forests have been subjected to various burning regimes.

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REFERENCES

ABBOTT, I.; LONERAGAN, O. 1983: Influence of fire on growth rate, mortality and butt damage in Mediterranean forest of Western Australia. *Forest Ecology and Management 6*: 139–153.

ABBOTT, L.; VAN HEURCK, P.; WONG, L. 1984: Responses to long-term fire exclusion: physical, chemical and faunal features of litter and soil in a Western Australian forest. *Australian Forestry 47*: 237–242.

BARNHISEL, R.; BERTSCH, P.M. 1982: Aluminum. Pp. 275–300 *in* Page, A.L.; Miller, R.H.; Keeney, D.R. (Ed.) "Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties" 2nd ed. ASA-SSSA, Madison.

BEADLE, N.C.W.; COSTIN, A.B. 1952: Ecological classification and nomenclature. *Proceedings of the Linnean Society of New South Wales 77*: 61–82.

BINKLEY, D.; RICHTER, D.; DAVID, M.R.; CALDWELL, B. 1992: Soil chemistry in a loblolly / longleaf pine forest with interval burning. *Ecological Applications 2*: 157–164.

BINKLEY, D.; BECKER-HEIDMANN, P.; CLARK, J. S.; CRUTZEN, P.J.; FROST, P.; GILL, A.M.; GRANSTROM, A.; MACK, F.; MENAUT, J.C.; WEIN, R.W.; VAN WILGEN, B. 1993: Group report: impacts of fire on ecosystems. Pp. 359–372 *in* Crutzen, P.J.; Goldammer, J.G. (Ed.) "Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires". John Wiley and Sons, Chichester.

BIRK, E.M.; BRIDGES, R.G. 1989: Recurrent fires and fuel accumulation in even-aged blackbutt (*Eucalyptus pilularis*) forests. *Forest Ecology and Management 29*: 59–79.

BOWEN, G.D. 1981: Coping with low nutrients. Pp. 33–64 *in* Pate, J.S.; McComb, A.J. (Ed.) "The Biology of Australian Plants". University of Western Australia Press, Nedlands, Western Australia.

BREMNER, J.M.; MULVANEY, C.S. 1982: Nitrogen-total. Pp. 595–624 *in* Page, A.L.; Miller, R.H.; Keeney, D.R. (Ed.) "Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties" 2nd ed. ASA-SSSA, Madison.

BUBB, K.A.; XU, Z.H.; SIMPSON, J.A.; SAFFIGNA, P.G. 1998a: *In situ* measurements of soil mineral nitrogen fluxes in hoop pine plantations of subtropical Australia. *New Zealand Journal of Forestry Science 28*: 152–164.

——— 1998b: Some nutrient dynamics associated with litterfall and litter decomposition in hoop pine plantations of southeast Queensland, Australia. *Forest Ecology and Management 110*: 343–352.

——— 1999: Growth response to fertilization and recovery of ^{15}N-labelled fertilizer by young hoop pine plantations of subtropical Australia. *Nutrient Cycling in Agroecosystems 54*: 81–92.

CHAPMAN, H.D. 1965: Cation-exchange capacity. Pp. 891–901 *in* Black, C.A. (Ed.) "Methods of Soil Analysis. Part 2 Chemical and Microbiological Properties". ASA, Madison, Wisconsin.

CHRISTENSEN, N.L. 1987: The biogeochemical consequences of fire and their effects on the vegetation of the coastal plain of the southeastern United States. Pp. 1–21 *in* Trabaud, L. (Ed.) "The Role of Fire in Ecological Systems". SPB Academic Publishing, The Hague.

COLWELL, J.D. 1963: The estimation of phosphorus fertilizer requirements of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry 3*: 190–197.

DAY, P.R. 1965: Particle fractionation and particle-size analysis. Pp. 545–567 *in* Black, C.A. (Ed.) "Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties". ASA, Madison, Wisconsin.

FLORENCE, R.G. 1994: The ecological basis of forest fire management in New South Wales. Pp. 15–33 *in* Attiwill, P.M.; Florence, R.; Hurditch, W.E.; Hurditch, W.J. (Ed.) "The Burning Continent: Forest Ecosystems and Fire Management in Australia". Institute of Public Affairs, Jolimont, Australia.

GUINTO, D.F.; XU, Z.H.; HOUSE, A.P.N.; SAFFIGNA, P.G. 2000: Assessment of N_2 fixation by understorey acacias in recurrently burnt eucalypt forests in subtropical Australia using ^{15}N isotope dilution techniques. *Canadian Journal of Forest Research 30*: 112–121.

GUINTO, D.F.; SAFFIGNA, P.G.; XU, Z.H.; HOUSE, A.P.N.; PERERA, M.C.S. 1999: Soil nitrogen mineralisation and organic matter composition revealed by ^{13}C NMR spectroscopy under repeated prescribed burning in eucalypt forests of south-east Queensland. *Australian Journal of Soil Research 37*: 123–135.

GIOVANNINI, G.; LUCCHESI, S. 1997: Modifications induced in soil physico-chemical parameters by experimental fires at different intensities. *Soil Science 162*: 470–486.

HALL, S.J.; MATSON, P.A. 1999: Nitrogen oxide emissions after nitrogen additions in tropical forests. *Nature 400*: 152–155.

HASSINK, J.; BOUWMAN, L.A.; ZWART, K.B.; BLOEM, J.; BRUSSAARD, L. 1993: Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils. *Geoderma 57*: 105–128.

HATCH, A.B. 1959: The effect of frequent burning on the jarrah (*Eucalyptus marginata*) forest soils of Western Australia. *Journal of the Royal Society of Western Australia 42*: 97–100.

HENRY, N.B. 1961: Complete protection versus prescribed burning in the Maryborough hardwoods. *Queensland Forest Service Research Note No. 13.*

HINGSTON, F.J.; O'CONNELL, A.M.; GROVE, T.S. 1989: Nutrient cycling in jarrah forest. Pp. 155–177 *in* Dell, B.; Havel, J.J.; Malajczuk, N. (Ed.) "The Jarrah Forest: A Complex Mediterranean Ecosystem". Kluwer Academic Publishers, Dordrecht.

HOUSE, A.P.N. 1995: Fire ecology research in Queensland native forests — current status and new directions. Pp. 86–97 *in* Roberts, B.R. (Ed.) "Sixth Queensland Fire Research Workshop Working Papers, 8–10 March, Bargara". Land Use Study Centre of University of Southern Queensland, Toowoomba, and Queensland Emergency Services, Brisbane.

HUMPHREYS, F.R.; CRAIG, F.G. 1981: Effects of fire on soil chemical, structural and hydrological properties. Pp. 177–200 *in* Gill, A.M.; Groves, R.H.; Noble, I.R. (Ed.) "Fire and the Australian Biota". Australian Academy of Science, Canberra.

HURLBERT, S.H. 1984: Pseudoreplication and the design of ecological field experiments. *Ecological Monographs 54*: 187–211.

ISBELL, R.F. 1996: "The Australian Soil Classification". CSIRO Publishing, Collingwood.

JACKSON, M.L. 1958: "Soil Chemical Analysis". Prentice-Hall, New Jersey.

JONES, J.B. Jr; CASE, V.W. 1990: Sampling, handling and analyzing plant tissue samples. Pp. 389–427 *in* Westerman, R.L. (Ed.) "Soil Testing and Plant Analysis". 3rd ed. SSSA, Madison, Wisconsin.

JONES, J.M.; RICHARDS, B.N. 1977: Effect of reforestation on turnover of ^{15}N-labelled nitrate and ammonium in relation to changes in soil microflora. *Soil Biology and Biochemistry 9*: 383–392.

KEITH, H. 1991: Effects of fire and fertilization on nitrogen cycling and tree growth in a subalpine eucalypt forest. Ph.D. thesis, Australian National University, Canberra.

KEITH, H.; RAISON, R.J. 1992: Effects of prescribed fire on nitrogen cycling and tree growth in an Australian eucalypt forest. Pp. 889–891 *in* Teller, A.; Mathy, P.; Jeffers, J.N.R. (Ed.) "Responses of Forest Ecosystems to Environmental Changes". Elsevier Applied Science, London.

KHANNA, P.K., RAISON, R.J.; FALKINER, R.A. 1994: Chemical properties of ash derived from *Eucalyptus* litter and its effects on forest soils. *Forest Ecology and Management 66*: 107–125.

KIMMINS, J.P. 1987: "Forest Ecology". MacMillan Publishing, New York.

LYNHAM, T.J.; WICKWARE, G.M.; MASON, J.A. 1998: Soil chemical changes and plant succession following experimental burning in immature jack pine. *Canadian Journal of Soil Science 78*: 93–104.

MacLEOD, S.; CLARKE, A.R.P. 1975: "Notes on Soil Techniques 1973". CSIRO Division of Soils, Melbourne.

McKEE, W.H. Jr 1982: Changes in soil fertility following prescribed burning on Coastal Plain pine sites. *USDA Forest Service, Southeastern Forest Experiment Station Research Paper SE-234.*

———1991: Long-term impacts of fire on Coastal Plain pine soils. Pp. 405–413 *in* Nodvin, S.C.; Waldrop, T.A. (Ed.) "Fire in the Environment: Ecological and Cultural Perspectives". *USDA Forest Service General Technical Report SE-69.*

McKEVLIN, M.R.; McKEE, W.H. Jr 1986: Long-term prescribed burning increases nutrient uptake and growth of loblolly pine seedlings. *Forest Ecology and Management 17*: 245–252.

MONLEON, V.J.; CROMACK, K.; LANDSBERG, J.D. 1997: Short- and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. *Canadian Journal of Forest Research 27*: 369–378.

NOBLE, I. 1986: Fire. Pp. 224–232 *in* Wallace, H.R. (Ed.) "Ecology of the Forests and Woodlands of South Australia". Waite Agricultural Research Institute, South Australia.

PRITCHETT, W.L. 1979: "Properties and Management of Forest Soils". Wiley, New York.

QUEENSLAND DEPARTMENT OF FORESTRY 1984: Fire School Notes (mimeo.). 99 p.

RAISON, R.J. 1980: A review of the role of fire in nutrient cycling in Australian native forests and of methodology for studying the fire-nutrient interaction. *Australian Journal of Ecology 5*: 15–21.

RAISON, R.J.; KHANNA, P.K.; WOODS, P.V. 1985: Transfer of elements to the atmosphere during low-intensity prescribed fires in three Australian sub-alpine eucalypt forests. *Canadian Journal of Forest Research 15*: 657–664.

RAISON, R.J.; O'CONNELL, A.M.; KHANNA, P.K.; KEITH, H. 1993: Effects of repeated fires on nitrogen and phosphorus budgets and cycling processes in forest ecosystems. Pp. 347–363 *in* Trabaud, L.; Prodon, R. (Ed.) "Fire in Mediterranean Ecosystems". CEC, Brussels-Luxembourg.

RICHARDS, B.N.; CHARLEY, J.L. 1983: Mineral cycling processes and system stability in the eucalypt forest. *Forest Ecology and Management 7*: 31–47.

SAS INSTITUTE INC. 1987: "SAS/STAT Guide for Personal Computers". 6th ed. SAS Institute Inc., Cary, North Carolina.

SPECHT, R.L. 1970: Vegetation. Pp. 44–67 *in* Leeper, G.W. (Ed.) "The Australian Environment". 4th ed. CSIRO and Melbourne University Press, Melbourne.

STEEL, R.G.D.; TORRIE, J.H.; DICKEY, D.A. 1997: "Principles and Procedures of Statistics: A Biometrical Approach". 3rd ed. McGraw-Hill, New York.

STEVENSON, F.J. 1982: "Humus Chemistry: Genesis, Composition, Reactions". Wiley, New York.

TAYLOR, M. 1989: Fire in subtropical forest management. Pp. 56–68 *in* Roberts, B.R.; Unwin, G.L. (Ed.) "Fourth Queensland Fire Research Workshop Working Papers, 27–29 June, Atherton". School of Applied Science of Darling Downs Institute, Toowoomba, and CSIRO Tropical Forest Research Centre, Atherton.

TAYLOR, P. 1994: "Growing Up: Forestry in Queensland". Allen and Unwin, St. Leonards, NSW.

TURNER, C.L.; BLAIR, J.M.; SCHARTZ, R.J.; NEEL, J.C. 1997: Soil N and plant responses to fire, topography, and supplemental N in tallgrass prairie. *Ecology 78*: 1832–1843.

VAN LOON, A.P. 1969: Investigations into the effects of prescribed burning on young even-aged blackbutt. *Forestry Commission of NW Research Note No. 23.*

VITOUSEK, P.M.; HOWARTH, R.W. 1991: Nitrogen limitation on land and in the sea: How can it occur? *Biogeochemistry 13*: 87–115.

WALDROP, T.A.; VAN LEAR, D.H.; LLOYD, T.F.; HARMS, W.R. 1987: Long-term studies of prescribed burning in loblolly pine forests of the Southeastern Coastal Plain. *USDA Forest Service Southeastern Forest Experiment Station General Technical Report SE-45.*

WALKER, J.; RAISON, R.J.; KHANNA, P.K. 1986: Fire. Pp. 185–216 *in* Russell, J.S.; Isbell, R.F. (Ed.) "Australian Soils: The Human Impact". University of Queensland Press, St Lucia, Queensland.

WARING, S.A.; BREMNER, J.M. 1964: Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. *Nature 201*: 951–952.

WELLS, C.G. 1971: Effects of prescribed burning on soil chemical properties and nutrient availability. Pp. 86–99 *in* "Prescribed Burning Symposium Proceedings". USDA Forest Service, Asheville, NC.

WELLS, C.G.; CAMPBELL, R.E.; DEBANO, L.F.; LEWIS, C.E.; FREDRIKSEN, R.L.; FRANKLIN, E.C.; FROELICH, R.C.; DUNN, P.H. 1979: Effects of fire on soil: a state-of-knowledge review. *USDA Forest Service General Technical Report WO-7.*

XU, Z.H.; SIMPSON, J.A.; OSBORNE, D.O. 1995a: Mineral nutrition of slash pine in subtropical Australia. I. Stand growth response to fertilization. *Fertilizer Research 41*: 93–100.

———1995b: Mineral nutrition of slash pine in subtropical Australia. II. Foliar nutrient response to fertilization. *Fertilizer Research 41*: 101–107.