SEASONAL FLUCTUATIONS IN FOLIAR NUTRIENT CONCENTRATIONS IN A YOUNG NITROGEN-DEFICIENT STAND OF EUCALYPTUS FASTIGATA WITH AND WITHOUT APPLIED NITROGEN

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ABSTRACT

Foliage samples were collected regularly over a period of 13 months from three treatments of a nitrogen fertiliser trial established in 3-year-old **Eucalyptus fastigata** Deane et Maiden on a yellow-brown pumice soil in Kaingaroa Forest. Treatments sampled were (1) control (no fertiliser), (2) 250 kg urea/ha, and (3) 500 kg urea/ha; (1) and (2) were sampled each month, and (3) every third month. The first collection was made just before treatments were imposed in early November (spring). Samples were analysed for nitrogen, phosphorus, potassium, calcium, magnesium, boron, copper, iron, manganese, and zinc. Both urea treatments gave a positive response in foliar nitrogen concentration. For Treatment (2) this response was shortlived (c. 10 months) and reached a peak about 2 months after treatment (2.34% N compared with 1.15% N for control). Although data for (3) are incomplete, it seems that the response in foliar nitrogen was greater than for (2) but still did not last beyond a year.

Nitrogenous fertiliser significantly increased the N : P ratio in foliage for the 11 months following treatment. A large growth response to applied nitrogen, observed in the season following treatment, indicates that the change in N-P balance was beneficial.

Nutrient concentrations in the foliage of untreated trees varied markedly with season. Fluctuations were relatively small for zinc, iron, nitrogen, and copper; intermediate for magnesium, boron, and potassium; and large for calcium, phosphorus, and manganese.

Keywords: foliar analysis; sampling; seasonal variation; nitrogen fertiliser; **Eucalyptus fastigata**.

INTRODUCTION

Eucalyptus fastigata is one of a small number of eucalypt species shortlisted by the then New Zealand Forest Service in its official policy on special purpose species (New Zealand Forest Service 1981) for wider planting in climatically appropriate localities. The aim of this policy was to produce a sustained yield of high-quality timber for domestic use. *Eucalyptus fastigata* is a fast-growing, moderately frost-tolerant eucalypt, adapted to cool and cold sites with moderate rainfall in the temperate zone

(Turnbull & Pryor 1984). In New Zealand it is usually planted in North Island districts where success of *E. regnans* F. Mueller is doubtful because of the likelihood of frost damage.

Foliar analysis is now widely used to assess nutrient status of forest stands (Mead 1984). This technique has occasionally been used to identify nutritional causes of ill-health in forest stands of eucalypts (Andrews & David 1959; Lamb 1973, 1977; Haag *et al.* 1977; Stewart *et al.* 1981). More recently, it has been used to assess the nutrient status of young, fast-growing, eucalypt stands (Miyasaka *et al.* 1983; Schönau 1981b, 1982a,b; Gonzalez Esparcia *et al.* 1985). Latterly, foliar analysis has been used to develop DRIS (Diagnosis and Recommendation Integrated System) norms for *Eucalyptus saligna* Sm. (Ward *et al.* 1985; Yost *et al.* 1987). There is, however, a dearth of published information on the application of foliar analysis to *E. fastigata* or other ash group* eucalypts.

Before an effective foliage sampling scheme can be developed for any forest species, a knowledge of the patterns of seasonal changes in the foliar concentrations of individual nutrients is necessary (Bates 1971). Although seasonal changes in foliar nutrient concentrations are well documented for many tree species (Leaf 1973), such information for eucalypts is limited to certain tropical or subtropical species, viz *E. deglupta* Bl., *E. grandis* Maiden, *E. saligna,* and *E. wandoo* Blakely.

Leaf age and season were the two factors which most strongly affected the concentration of mineral elements in the crown of *E. deglupta* in Papua New Guinea (Lamb 1976). As occurs with other broadleaved and coniferous trees, nitrogen, phosphorus, and potassium concentrations tended to decrease with leaf age, while the reverse was true for calcium, magnesium, iron, and manganese. With the exception of potassium, foliar concentrations were least variable during the later part of the wet season when the micro-environment was least likely to be affected by soil moisture fluctuations. Seasonal changes in foliar concentrations were most pronounced for micro-elements; concentrations of boron in leaves sampled during the wet season far exceeded those in leaves sampled during the dry season.

Schönau (1981a) studied the seasonal changes in foliar nutrient concentrations of 1- to 2-year-old *E. grandis* trees over two growing seasons at three different sites in the Natal Midlands, South Africa, and found considerable seasonal variation. He observed that the changes in foliar concentrations of macronutrients and zinc conformed closely to the rate of height growth, but that, unlike other nutrients, iron concentration was inversely related to height growth. He also noted that foliar concentrations of nitrogen, calcium, sulphur, copper, and zinc were positively related to rainfall, whereas iron concentration was inversely related. Schönau considered that routine sampling of *E. grandis* leaves should be carried out in the summer of the first year after planting, when growth responses to fertilisers are greatest and differences recorded between sites most pronounced.

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* The vernacular name (originally derived from field classification based on obvious features) for a group of eucalypts having similar timber and botanical characteristics. The species in this group, which include **E. delegatensis** R. T. Baker, **E. fastigata**, **E. fraxinoides** Deane et Maiden, **E. obliqua** L'Herit, and **E. regnans**, have natural affinities and make up the Obliquae series of the Renantheria Section of the subgenus Monocalyptus (Pryor & Johnson 1971).

Bell & Ward (1984) followed seasonal changes in the foliar concentrations of macronutrients (nitrogen, phosphorus, potassium, copper, and magnesium) in sapling trees of *E. saligna* and *E. wandoo* growing in rehabilitated bauxite mined areas in the Darling Range of Western Australia. They reported that the difference in foliar nitrogen concentration between trees growing in good and poor soil conditions respectively was greater during spring. Concentrations of phosphorus in leaves were highest in young developing leaves but, once the leaves reached full size, no seasonal trend in phosphorus was observed. Foliar concentration in potassium was lower during winter and higher during summer. Leaf calcium concentration was highest during early spring. Foliar magnesium concentration tended to decrease with leaf age. These authors tentatively concluded that spring is the most appropriate season for sampling foliage from these two species for the purpose of assessing their nutrient status.

Lowry & Avard (1969) have pointed out that, although certain similarities may exist in the pattern of seasonal nutrient element concentration amongst forest tree species, each species seems to differ as to the quantity of the various elements and the length of the stable period. Consequently, they noted, separate investigations are probably required for each species and possibly for different climatic regions.

For routine evaluation of nutrient status, it has been usual in New Zealand to collect foliage samples from plantation trees, irrespective of species, in the late summer. This convention derives from a recommendation given originally for *Pinus radiata* D. Don (Mead & Will 1976). Whereas the recommended sampling time for *P. radiata* (aimed at maximum sensitivity) was based on the results of a study of seasonal changes in foliar nutrient levels in that species, its suitability for other species has not been investigated.

As there is no published information on the effect of season on foliar nutrient concentrations in eucalypts growing under New Zealand conditions, it was thought that data from a preliminary study conducted with *E. fastigata,* as an ancillary to a fertiliser trial, would help to fill the gap. This study was conducted over a single growing season and at one site only, and consequently serves only to give a broad indication of the patterns of seasonal changes in foliar nutrient levels for this species. Further study over a range of sites and growing seasons is needed to give a more broadly based evaluation of such changes.

The main aims of the study were to determine:

(1) The duration of enhanced foliar nitrogen status in young, nitrogen-stressed *E. fastigata* trees following a spring application of nitrogenous fertiliser to a yellow-brown pumice soil.

(2) The effect of applied nitrogen on the foliar concentrations of a range of nine other essential nutrients (phosphorus, potassium, calcium, magnesium, boron, copper, iron, manganese, and zinc) derived from native soil resources.

(3) The magnitude of seasonal fluctuations in the foliar concentrations of 10 essential nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, boron, copper, iron, manganese, and zinc) in young *E. fastigata* trees growing on pumice soil with and without applied nitrogen.

METHODS

Site, Climate, and Soil

The study site was located in Cpt 1207 (38° 27.3′ S; 176° 39.7′ E; 305 m a.s.l.) of Kaingaroa Forest in a 30-ha stand of *E. fastigata* which was planted in 1979. The site, which previously carried *Pinus ponderosa* P. et C. Lawson, was logged and burned prior to planting, but received no further site preparation. The trees were planted at intervals of 2.5 m in lines 3.0 m apart (1333 stems/ha). Soon after planting the eucalypts received fertiliser at 60 g urea/tree. Growth of the trees in the area has since been very variable and generally poor.

The climate is maritime, and rainfall is fairly evenly distributed throughout the year (Fig. 1). The nearest meteorological station, located 4 km to the east of the study area at Murupara, has an average of 141 raindays per year and a mean annual rainfall (1951–80) of 1338 mm (New Zealand Meteorological Service 1984).

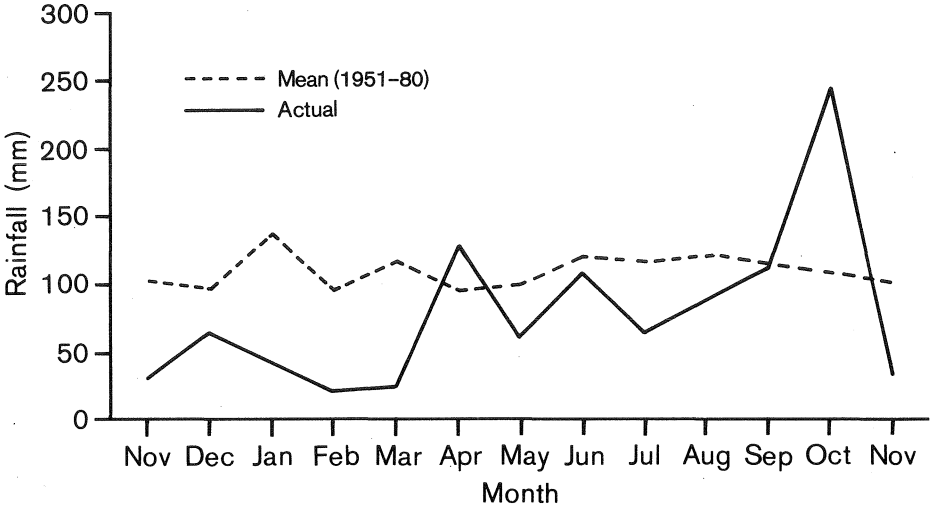

FIG. 1—Monthly rainfall distribution at Murupara. Expectation (based on 1951-80 mean, hatched line) shown against amount (solid line) recorded during the study period.

The soil at the study site is classified as a yellow-brown pumice (New Zealand Soil Bureau 1954). It is formed from pumiceous rhyolitic tephra erupted mainly from two volcanic centres – Okataina and Taupo, which are to the north and to the south of the site respectively. The surface soil, formed on Kaharoa ash (believed to have erupted from Mt Tarawera about 800 years ago), is mapped as Pekepeke sand (W. C. Rijkse unpubl. data). The tephra deposits on the Kaingaroa Plateau have been mapped by Pullar (1980). The tephra within the different ash formations can range from a very fine ash to coarse gravel or lapilli. Also, several paleosols (fossil topsoils buried by later depositions of tephra) can be recognised in the profile.

Experimental Design and Treatments

The study was carried out in a recently established fertiliser trial. The trial had three blocks, each with four randomised treatment plots measuring 18 × 16.8 m. Each plot consisted of six rows of seven trees. Treatments were allocated to plots at random. Only the first three of the following four treatments represented in each block were sampled:

(1) No fertiliser (N_0)
(2) 250 kg urea/ha (N_1) (applied by broadcasting)
(3) 500 kg urea/ha (N_2) (applied by broadcasting)
(4) 250 kg urea/ha (N_1) (applied in a spade slit by each tree (180 g urea/tree).

Fertiliser was applied on 12 November 1982.

Sampling and Chemical Analysis

Trees in the N_0 and N_1 plots were sampled each month for 13 months commencing on 10 November 1982 and ending on 16 November 1983, and those in N_2 plots at 3-monthly intervals only (i.e., on the first, fourth, seventh, tenth, and thirteenth collection dates). To minimise effects of foliar leaching, collection of foliage samples was delayed for at least 1 day after rain had fallen.

A composite foliage sample was collected in each plot from about 30 marked sample trees which were randomly chosen at the start of the study. Sampling for specific age and physiological stage of foliage is not a simple matter in eucalypts because of the indeterminate pattern of growth. Bud, leaf, and shoot development tend to be continuous and to occur whenever the environment is currently favourable (Cremer *et al.* 1984), and there is no requirement for rest or overwintering. By attempting to collect leaf samples of comparable age and physiological condition it was hoped to avoid any confounding of leaf-age effects with the seasonal changes being studied. Ten, undamaged, mature-size (but not necessarily fully expanded) leaves, of intermediate age (i.e., neither very young nor very old), were taken in the upper third of the crown of each marked tree.

The samples were placed in plastic bags during collection and then transferred to aluminium trays for oven-drying on return to the laboratory. The samples were dried at 70°C for 7 days and were then finely ground in a stainless steel Wiley mill. The samples were analysed by the methods described by Nicholson (1984). A standard FRI reference foliage sample was included with each batch of samples analysed.

RESULTS

Foliar Nutrient Responses to Fertiliser Treatments

The effects of applied nitrogen on concentrations of individual nutrients in the foliage of treated trees over the period of the study can be seen from the time series graphs presented in Fig. 2–5. In the graphs for individual nutrients, the concentrations at a date for the different treatments are shown plotted together.

For most of the nutrients examined, the seasonal trends recorded for the N_0 and N_1 treatments show a reasonably close match in month-to-month fluctuations. Nitrogen (Fig. 2a) was atypical in this respect as the application of fertiliser markedly modified the seasonal pattern as observed in control trees.

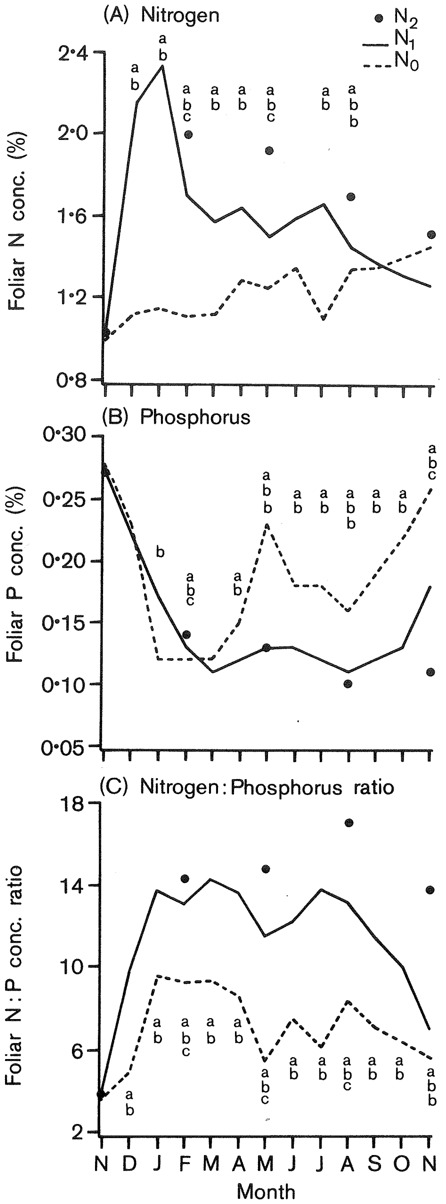

FIG. 2—Seasonal trends in foliar nutrient concentrations in **E. fastigata** subjected to different rates of nitrogen: (A) nitrogen – LSD values for seasonal variation N_1 and N_0 0.18% N; (B) phosphorus – LSD values for seasonal variation N_1 0.02% P, N_0 0.04% P; (C) nitrogen : phosphorus ratio–LSD values for seasonal variation N 1.69, N_0 1.47.

NOTE: In Fig. 2-5, means separation at each date is indicated by lettering. Values represented by the same letter on a particular date do not differ significantly ($LSD_{0.05}$ test). Letters are omitted at dates where no significant differences were recorded.

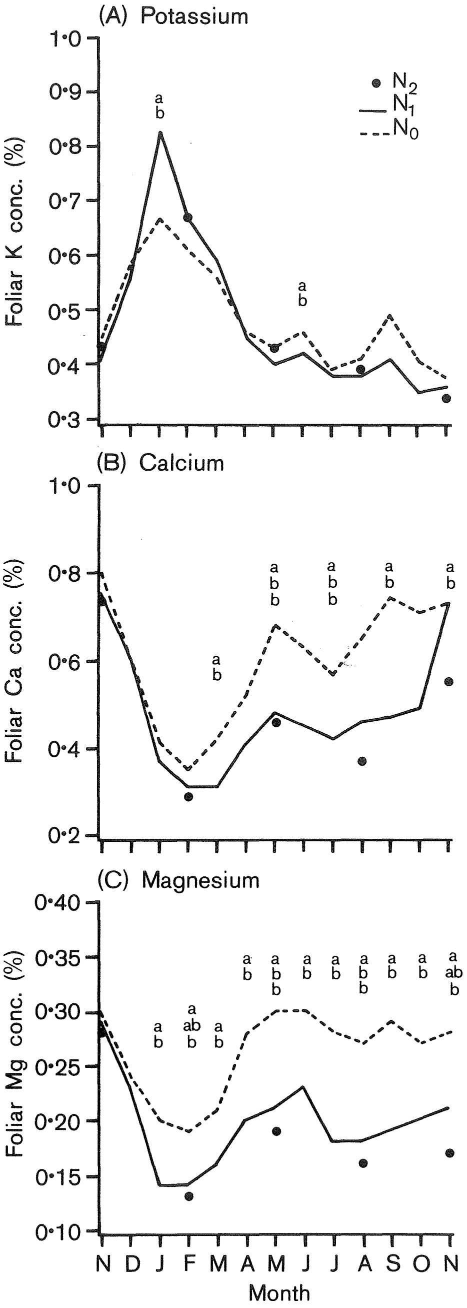

FIG. 3—Seasonal trends in foliar nutrient concentrations in **E. fastigata** subjected to different rates of nitrogen: (A) potassium - LSD values for seasonal variation N_1 0.07% K, N_0 0.05% K; (B) calcium - LSD values for seasonal variation N_1 0.10% Ca, N_0 0.12% Ca; (C) magnesium - LSD values for seasonal variation N_1 0.04% Mg, N_0 0.02% Mg.

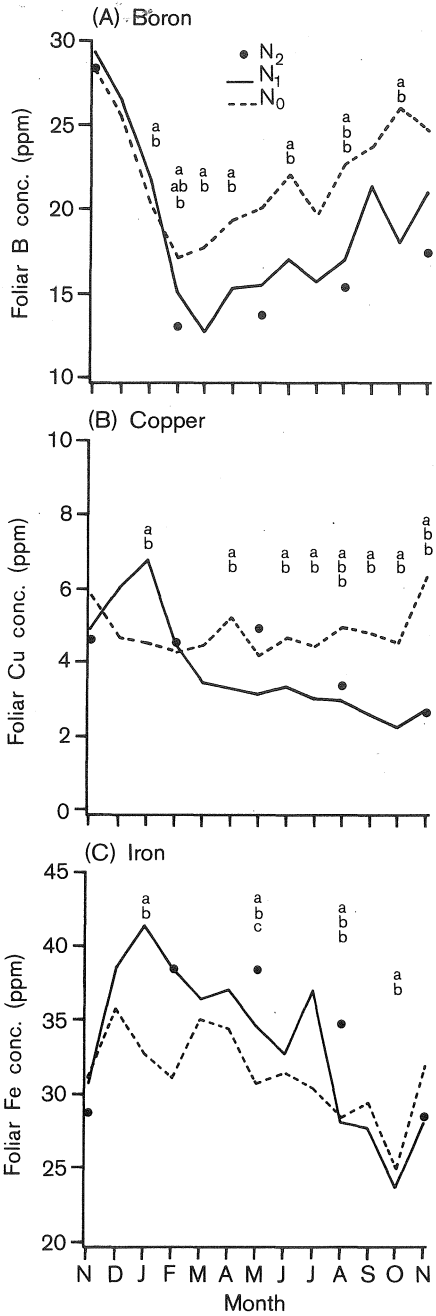

FIG. 4—Seasonal trends in foliar nutrient concentrations in **E. fastigata** subjected to different rates of nitrogen: (A) boron – LSD values for seasonal variation N_1 2.8 ppm B, N_0 2.3 ppm B; (B) copper – LSD values for seasonal variation N_1 1.1 ppm Cu, N_0 1.2 ppm Cu; (C) iron – LSD values for seasonal variation N_1 5.6 ppm Fe, N_0 4.1 ppm Fe.

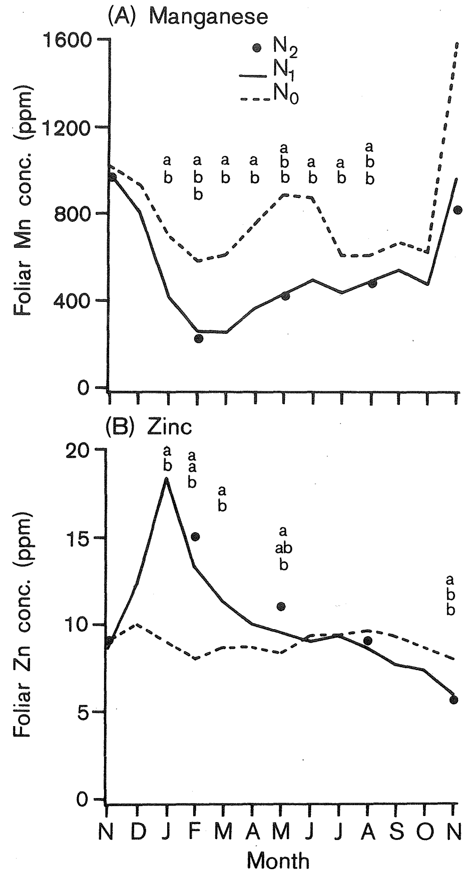

FIG. 5—Seasonal trends for foliar nutrient concentrations in **E. fastigata** subjected to different rates of nitrogen: (A) manganese - LSD values for seasonal variation N_1 137 ppm Mn, N_0 213 ppm Mn; (B) zinc - LSD values for seasonal variation N_1 2.8 ppm Zn, N_0 1.5 ppm Zn.

Spring application of urea at 250 kg/ha resulted in a rapid increase in foliar nitrogen concentration, reaching a peak about 2 months after treatment (2.34% compared with 1.15% for the control, Fig. 2a). The level fell rapidly in the third month of the study and then, with small fluctuations, continued to decline more gradually over the next 10 months of the study. By 9 months from treatment date the level had ceased to differ significantly from the control.

Although foliage samples were collected only at 3-monthly intervals from the N_2 treatment, the limited foliar data suggest a significantly larger response in foliar nitrogen concentration to the heavier rate of urea lasting at least 9 but less than 12 months. This shortlived response in foliar nitrogen concentration supports the view (Miller 1981) that tree recovery of applied nitrogen can generally be explained by increased uptake in the first season after treatment. It is not unusual for nitrogenous fertiliser to have a relatively shortlived effect, as applied nitrogen is either effectively immobilised or lost from the ecosystem within a year of application (Ballard 1984).

Although firm diagnostic foliar criteria have yet to be established for *E. fastigata,* it has been noted that vigorous growth of young trees in the field is usually associated with concentrations of about 2.0% N and 0.15% P in the foliage (Will 1985). These values are comparable to concentrations reported from different parts of the world as consistent with satisfactory growth of various eucalypt species, e.g., *E. grandis* in Brazil (Haag *et al.* 1963; 2.22% N, 0.17% P), *E. deglupta* in Papua New Guinea (Lamb 1977; 2.1% N), *E. grandis* in South Africa (Schönau 1983; 2.0% N, 0.15% P), and *E. globulus* Labill. in Spain (Gonzalez Esparcia *et al.* 1985; 2.0% N, 0.14% P).

Schönau (1981b) has observed that there is strong evidence that the concentrations of foliar nutrients differ little between the many eucalypt species. Thus, in the absence of established criteria for *E. fastigata,* it is interesting to compare the nitrogen and phosphorus values found in the present study with levels reported as "satisfactory" for other species. Over the 12-month period of the study, concentrations in the foliage of untreated trees ranged from 0.99% to 1.45% for nitrogen (average 1.23% N) and 0.12% to 0.28% for phosphorus (average 0.18% P). As the trees showed symptoms characteristic of nitrogen stress and responded well to applied nitrogen, it might be expected that the concentration of nitrogen in the foliage of untreated trees would reflect their low nitrogen status. In fact, throughout the year the concentration of this nutrient remained well below the 2% or so noted by Will and other workers as usual in vigorously growing young eucalypts. Although phosphorus concentration in the foliage of untreated trees was relatively low at times during the year (particularly during the summer months), the possibility that this nutrient was limiting, either before or after application of nitrogen, was not investigated.

Several authors have suggested that certain foliar ratios may provide a useful indication of nutrient balance for eucalypts. For example, Lamb (1977) reported that maximum height growth of the tropical eucalypt *E. deglupta* was associated with an N : P ratio of 10.4. Cromer *et al.* (1981) reported a relationship between fertiliser (N, P, or NP) response and N : P ratio in the foliage of *E. globulus* and *E. sieberi* L. Johnson, and postulated a tentative optimum value of about 15 for maximum growth of both species. They noted that, whereas the effects of the various fertiliser treatments of foliar nitrogen or phosphorus concentration were generally small, the effect on foliar N : P ratio was often much greater; young eucalypt trees with lower N : P ratios responded to nitrogen, whereas those with higher ratios generally responded to phosphorus. For young *E. grandis* growing under South African conditions, optimum ratios of N : P, N : K, P : K, and Ca : Mg in the foliage have been reported at 13, 3.0, <0.23, and >3.3 respectively (Schönau & Herbert 1983; Schönau 1983).

In the present study, the fertiliser treatments resulted in an appreciable variation in N : P ratio (Fig. 2c). For the 250 kg urea/ha treatment, the ratio increased rapidly over the first 2 months after treatment. Over the next 7 months it remained stable, averaging 13.3 (s.e. ± 0.32) compared with 8.0 (s.e. ± 0.54) for the control over the same period. As applied nitrogen markedly stimulated tree growth (Table 1), it may be supposed that the increase in the N : P ratio in the foliage of treated trees reflected a more favourable N-P balance. If this hypothesis is correct, an N : P ratio of 12–14 (corresponding to the range encountered in the foliage of treated trees in mid to late summer) might be indicative of a favourable N-P balance in young *E. fastigata* sampled at that time. This range is close to the optima proposed for other eucalypt species (Cromer *et al.* 1981; Schönau & Herbert 1983).

TABLE 1—Height and diameter increments for the 9.5-month period after treatment

Treatment	dbh increment	Height increment
N_0	0.675 b	0.378 c
N_1	1.659 a	0.744 b
N_2	1.742 a	1.184 a

Means in the same column followed by the same letter do not differ significantly at the 5% level (LSD test)

The urea treatments tended to have a predominantly depressive effect on foliar concentrations of most nutrients other than nitrogen. Exceptions were potassium and iron. Applied nitrogen at either rate had very little significant effect on foliar potassium concentration beyond giving a shortlived positive response in the summer after treatment (Fig. 3a). Foliar potassium concentration for both N_1 and control rose to a peak in mid-January (0.93% and 0.77% respectively) and then, with minor fluctuations, declined for the remainder of the study period. From about April on, the values of N_1 remained slightly lower than for the control, although the difference at any one date was not usually statistically significant. The 3-monthly foliar potassium values for N_2 match the corresponding values for N_1 very closely.

The trends for iron (Fig. 4c) suggest a mainly positive effect of applied nitrogen on foliar iron concentration lasting about as long as the foliar nitrogen response (Fig. 2a), i.e., c. 8 months for N_1 and 9–11 months for N_2.

Whereas for calcium, magnesium, and manganese, fertiliser nitrogen exerted a consistently negative effect on the concentration in foliage soon after treatment (Fig. 3b, 3c, 5a), for copper and zinc (Fig. 4b, 5b) it appeared to have an initially positive effect but later depressed levels relative to control.

Although the trends for certain elements, notably phosphorus, calcium, magnesium, and boron (Fig. 2b, 3b, 3c, 4a), suggest that the heavier fertiliser rate had a more depressive action than the lighter rate in terms of its effect on foliar concentration, the differences between the means for N_1 and N_2 at any one date were not statistically significant.

Negative effects of fertiliser nitrogen addition on leaf concentrations of other nutrients have been reported from other studies (e.g., Miller & Cooper 1973; Timmer & Stone 1978). Nitrogen fertiliser application is well known to increase foliage mass in trees (Linder & Rook 1984). In the fertiliser trial to which this study relates, applied nitrogen resulted in large responses in height and diameter growth in the season after treatment (Table 1). It therefore seems reasonable to suppose that the response in stem growth was associated with an increase in canopy and hence photosynthetic activity. If, as seems likely, there was a large increase in foliage mass after treatment, the concentrations of nutrients other than nitrogen in the foliage could be expected to decline as a result of growth dilution. In the absence of any biomass data, this explanation must remain tentative.

Seasonal Fluctuations in Foliar Nutrient Concentrations in Untreated Trees

Magnitude of fluctuations

The fluctuations in foliar nutrient concentrations recorded in the control trees afford some indication of the broad seasonal trends in this eucalypt species. Over the 13-month period of this study, the coefficients of variation for individual nutrients (based on the monthly means recorded for control trees, Table 2) ranged from about 7% to 34%; nitrogen, iron, and zinc were at the lower end of the range (<12%), copper, magnesium, boron, and potassium intermediate (13–16%), and calcium, phosphorus, and manganese at the upper end (23–34%). Thus, sampling date seems particularly important for phosphorus, calcium, and manganese, and less so for nitrogen, iron, and zinc.

TABLE 2—Foliar nutrient concentrations in untreated (control) trees: period mean, coefficient of variation (CV%), and range over 13 sampling dates

Nutrient	Period mean	CV (%)	Range
N (%)	1.232	11.6	0.99–1.45
P (%)	0.192	25.6	0.12–0.28
K (%)	0.585	15.6	0.48–0.77
Ca (%)	0.602	23.4	0.35–0.80
Mg (%)	0.261	15.3	0.18–0.30
B (μg/g)	22.0	15.5	18–28
Cu (μg/g)	4.8	13.1	4.2–6.3
Fe (μg/g)	31.2	9.2	25–36
Mn (μg/g)	798.1	34.4	578–1573
Zn (μg/g)	8.9	6.8	8–10
N:P ratio	7.1	26.7	3.5–9.6

As the trees in the study area were evidently under stress for nitrogen, the seasonal pattern for nitrogen which was observed in control trees could well differ from that in trees adequately supplied with this nutrient. Certainly, the trends (Fig. 2a) indicate that the seasonal pattern for nitrogen in untreated trees is quite different from that in trees supplied with fertiliser nitrogen.

The more stable periods for individual nutrient elements can be judged from trends shown in Fig. 2–5. For certain elements, e.g., boron, there does not appear to be a stable period whereas for others, e.g., magnesium, copper, and zinc, concentrations appear reasonably stable over several months. The period of maximum stress for phosphorus, calcium, magnesium, and boron appears to be mid to late summer (Feb.–March). At this stage of the growing season, most resources of these four nutrients, at least, have probably been mobilised for growth. It could be argued then that, for this species, late summer should afford greatest sensitivity for detecting shortages of these nutrients by foliar analysis.

Similarities in trends for different nutrients

Similarities in seasonal patterns between certain of the nutrient elements are evident from the matrices of simple correlations given in Table 3. For both the N_0 and the N_1 treatments, foliar phosphorus concentration over 13 dates was significantly and positively correlated with foliar calcium, magnesium, boron, copper, and manganese. For the N_0 treatment, foliar potassium concentration was significantly and negatively correlated with foliar calcium and magnesium concentrations. As potassium uptake and retention in plant cells are known to be competitively affected by other cations, including Ca^{2+} and Mg^{2+} (Mengel & Kirby 1982), the latter inverse relationships may reflect this so-called "cation antagonism".

For the control treatment, correlations between foliar nitrogen concentration and foliar concentrations of the other nutrients determined over 13 dates were consistently weak and non-significant. By contrast, for the urea treatment (N_1) highly significant, positive correlations were recorded between foliar nitrogen concentration and foliar potassium, copper, iron, and zinc concentrations.

TABLE 3—Simple correlation matrices for the concentrations of 10 foliar nutrient elements over 13 dates

	N	P	K	Ca	Mg	B	Cu	Fe	Mn
(a) Control trees (N_0)									
P	0.1009								
K	−0.4914	−0.5460							
Ca	0.3817	0.8690**	−0.7046**						
Mg	0.3907	0.6803*	−0.8430**	0.8628**					
B	0.1644	0.8275**	−0.3454	0.8311**	0.5264				
Cu	0.2300	0.5807*	−0.4011	0.5292	0.3894	0.5775*			
Fe	−0.4429	−0.2266	0.5210	−0.4584	−0.3644	−0.3255	0.0631		
Mn	0.2671	0.6969**	−0.3045	0.4900	0.3571	0.4706	0.7815**	0.2093	
Zn	−0.1433	0.0255	0.0611	0.1914	0.1877	0.3297	−0.1450	0.0760	−0.2814
(b) Urea-treated trees (N_1)									
P	−0.0460								
K	0.7763**	0.0985							
Ca	−0.4515	0.7582**	−0.4884						
Mg	−0.5399	0.6594*	−0.5754*	0.8257**					
B	−0.0342	0.9036**	0.0077	0.7724**	0.6391*				
Cu	0.7091**	0.5969*	0.7984**	0.0186	−0.0638	0.5104			
Fe	0.7905**	0.0572	0.7531**	−0.4461	−0.3921	−0.1227	0.7001**		
Mn	−0.3384	0.8063**	−0.3712	0.9807**	0.7732**	0.8402**	0.1404	−0.3586	
Zn	0.8554**	0.0934	0.9593**	−0.5006	−0.5438	0.0096	0.8385**	0.8230**	0.3957

* Significant at the 5% level
** Significant at the 1% level

Impact of climatic factors on trends

The effect of rainfall on the seasonal patterns for individual nutrients was not investigated and must therefore remain a matter for conjecture in this preliminary study. However, it should be noted that the study period was unusually dry with appreciably less than the monthly expectation in each month except April, September, and October (Fig. 1). Climatic factors, particularly temperature and rainfall, have been shown to influence nutrient concentrations in the foliage of pines (Miller 1966; Bickelhaupt *et al.* 1979; Lambert 1984). The abrupt, seemingly anomalous dip in foliar concentration of nitrogen (for N_0) and boron (for N_0 and N_1) recorded in July could possibly be associated with an unidentified climatic event.

Trends for individual nutrients

The causes of variation in nutrient levels in forest tree foliage have been reviewed by Turner *et al.* (1978). Variation during the year may be caused by the environment, leaf and tree growth, nutrient accumulation or redistribution within the tree, and foliage leaching.

At this nitrogen-deficient site, the seasonal fluctuations in foliar nitrogen were not very pronounced (Fig. 2a). The trend suggests a progressive, gradual improvement in nitrogen status with time, with foliar nitrogen concentration rising from 0.99% to 1.45% over the period of the trial. For phosphorus (Fig. 2b), the trend suggests a plateau low level of about 0.12% over the summer months (January–March) with an increase in the autumn reaching a peak value of 0.23% in May, and then another more pronounced increase in spring reaching a peak value of 0.28% in November. For potassium (Fig. 3a), the trend indicates a moderate increase in concentration in early summer reaching a peak value of 0.77% in January, and then a decline to a level which remains fairly stable over the winter period (May to August, 0.49–0.56%); this is followed by a small shortlived increase in the spring with a peak value of 0.59% about September. For calcium (Fig. 3b), the trend shows a steep decline in concentration from late spring until mid summer (February, 0.35%), followed by an increase in late autumn (May) then another small decline to mid winter (July). Magnesium concentration (Fig. 3c) seems to decline over the late spring–early summer period reaching a low in February (0.18%) and then climbs again becoming fairly stable at 0.27% to 0.30% from May to November.

Trends for individual micronutrients (boron, copper, iron, manganese, and zinc) are shown in Fig. 4–5. The trends for boron, copper, and manganese (Fig. 4a, 4b, 5a) are similar to that for phosphorus (q.v.). Iron concentration in the foliage increases to a summer maximum (January) and then tends, with some fluctuations, to decline until the following spring (Fig. 4c). The trend for zinc (Fig. 5b) shows comparatively little seasonal change.

Foliar concentrations of manganese rose steeply to a maximum in late spring (November) in both treated and control trees. The elevated manganese values which were recorded at this time seem high compared with levels reported as average for *Pinus radiata* in Kaingaroa Forest (c. 260 ppm, Hunter *et al.* 1985). There is a possibility of a difference in nutrient concentrations between the two genera as other studies (Frederick *et al.* 1985; Knight unpubl. data) have shown that foliar concentrations of several elements, notably manganese but also calcium and magnesium, are appreciably higher for *E. fastigata* and *E. regnans* than for *P. radiata* of the same age on the same pumice soil type; conversely, concentrations of certain nutrients (phosphorus, potassium, zinc) are lower. The manganese values recorded in the present study do not seem excessive when considered in relation to ranges reported for many other forest species (Stone 1968; Burg 1985). In the review (Stone 1968), it is suggested that a high concentration of manganese in foliage of healthy trees is a better testimony for physiological accommodation than for toxicity. There is some evidence that eucalypt species differ in their sensitivity to high levels of available manganese in the soil (Winterhalder 1963). However, as the trees in the study area responded well to applied nitrogen and symptoms associated with manganese toxicity were lacking, the consistently higher concentrations of manganese in control trees are more likely to reflect accumulation under conditions of slow growth than toxicity.

The limited data from this trial show that foliar concentrations of both macronutrients and micronutrients in this species are strongly influenced by season. Clearly, time of sampling is an important factor and needs to be considered in any attempt to use foliar data for diagnostic purposes. The seasonal fluctuations recorded in this study apply to only one site and to a single growing season; the relevance of these results to other sites and seasons needs to be examined before firm recommendations can be made on the most appropriate time or times of year for sampling eucalypt foliage anywhere in the country.

CONCLUSIONS

Marked seasonal changes in concentrations of foliar nutrients found in this preliminary study highlight the importance of standardising time of sampling when collecting foliage samples from young *E. fastigata* trees. Seasonal fluctuations in untreated (control) trees were greatest for manganese, phosphorus, and calcium; intermediate for potassium, boron, and magnesium; and smallest for copper, nitrogen, iron, and zinc. Further study across a range of sites and growing seasons is needed to identify the best time to sample eucalypt foliage for the purpose of evaluating tree nutrient status.

In young *E. fastigata* trees growing on a yellow-brown pumice soil, the response in foliar nitrogen concentration to urea fertiliser broadcast in late spring at either 250 or 550 kg urea/ha is shortlived, apparently lasting less than a year.

At this site, urea fertiliser at either rate effectively increases the foliar N : P ratio over the growing season following application. The duration of the increased ratio (and by inference improved N-P balance) is apparently limited to a single growing season at the lower rate, but persists into the following season for the higher rate. Tentatively, an N : P ratio of 12–14 appears consistent with satisfactory N-P balance.

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REFERENCES

ANDREW, C. S.; DAVID, D. J. 1959: Iron deficiency in **Eucalyptus dives** Schauer. **Proceedings of the Linnean Society, New South Wales, Part 2, 84:** 256–7.

BALLARD, R. 1984: Fertilization of plantations. Pp. 327–60 **in** Brown, G. D.; Nambiar, E. K. S. (Ed.) "Nutrition of Plantation Forests". Academic Press. 516 p.

BATES, T. E. 1971: Factors affecting critical nutrient concentrations in plants and their evaluation: A review. **Soil Science 112:** 116–30.

BELL, D. T.; WARD, S. C. 1984: Seasonal changes in foliar macronutrients (N, P, K, Ca, and Mg) in **Eucalyptus saligna** Sm. and **E. wandoo** Blakely growing in rehabilitated bauxite mine soils of the Darling Range, Western Australia. **Plant and Soil 81:** 377–88.

BICKELHAUPT, D. J.; LEA, R.; TARBET, D. D.; LEAF, A. L. 1979: Seasonal weather regimes influence interpretation of **Pinus resinosa** foliar analysis. **Soil Science Society of America Journal 43:** 417–20.

BURG, J. van den 1985: Foliar analysis for determination of tree nutrient status – A compilation of literature data. **Rijksinstitut voor onderzoek in de bos- en landscapsbouw "De Dorschkamp" Wageningen. Rapport Nr. 414.**

CREMER, K. W.; CROMER, R. N.; FLORENCE, R. G. 1984: Stand establishment. Pp. 81–135 **in** Hillis, W. E.; Brown, A. G. (Ed.) "Eucalypts for Wood Production". CSIRO/ Academic Press, Sydney. 434 p.

CROMER, R. N.; CAMERON, D.; CAMERON, J. N.; FLINN, D. W.; NIELSEN, W. A.; RAUPACH, M.; SCHÖNAU, P.; WARING, H. D. 1981: Response of eucalypt species to fertiliser applied soon after planting at several sites. **Australian Forestry 44(1):** 3–13.

FREDERICK, D. J.; MADGWICK, H. A. I.; JURGENSEN, M. F.; OLIVER, G. R. 1985: Dry matter, energy, and nutrient contents of 8-year-old stands of **Eucalyptus regnans, Acacia dealbata**, and **Pinus radiata** in New Zealand. **New Zealand Journal of Forestry Science 15:** 142–57.

GONZALES ESPARCIA, E.; PENALVA RODRIGUEZ, F.; RODRIGUEZ FERNANDEZ, V.; GOMEZ ALTAMIRANO, C. 1985: Concentracion foliar de nutrientes en **Eucalyptus globulus** segun el tratamiento fertilizante y epoca de su applicacion. **Anales del Instituto Nacional de Investigaciones, Agrarias (Madrid); Serie: Forestal 9:** 47–56.

HAAG, H. P.; MELLO, F. A. F.; MELLO, H. A.; BRASIL SOBRINHO, M. O. C.; VEIGA, A. A. 1963: Chemical composition of **Eucalyptus alba** Reinw. and **Eucalyptus grandis** Maiden. Preliminary results, **Fertilité 18:** 9–14.

HUNTER, I. R.; NICHOLSON, G.; THORN, A. J. 1985: Chemical analysis of pine litter – An alternative to foliage analysis? **New Zealand Journal of Forestry Science 15:** 101–10.

LAMB, D. 1973: A suspected phosphorus and potassium deficiency in the tropical eucalypt **E. deglupta**. FAO/IUFRO Symposium on Forest Fertilisation, Paris FOR : FAO/ IUFRO/F/73/4.

——— 1976: Variations in the foliar concentrations of macro- and microelements in a fast growing tropical eucalypt (**E. deglupta**). **Plant and Soil 45:** 477–92.

——— 1977: Relationship between growth and foliar nutrient concentrations in **Eucalyptus deglupta. Plant and Soil 47:** 495–508.

LAMBERT, M. J. 1984: The use of foliar analysis in fertiliser research. Pp. 269–91 **in** Proceedings of IUFRO Symposium on Site and Productivity of Fast Growing Plantations, Vol. 1. Pretoria and Pietermaritzburg.

LEAF, A. L. 1973: Plant analysis as an aid in fertilising forests. Pp. 427–54 **in** Walsh, L. L.; Beaton, J. D. (Ed.) "Soil Testing and Plant Analysis". Soil Science Society of America Inc., Madison, Wisconsin.

LINDER, S.; ROOK, D. A. 1984: Effects of mineral nutrition on carbon dioxide exchange and partitioning of carbon in trees. Pp. 211–53 **in** Bowen, G. D.; Nambiar, E. K. S. (Ed.) "Nutrition of Plantation Trees". Academic Press. 516 p.

LOWRY, G. L.; AVARD, P. M. 1969: Nutrient content of black spruce and jack pine needles. III. Seasonal variation and recommended sampling procedures. **Pulp and Paper Research Institute of Canada Woodlands Paper No. 10.**

MEAD, D. J. 1984: Diagnosis of nutrient deficiencies. Pp. 259–91 **in** Bowen, G. D.; Nambiar, E. K. S. (Ed.) "Nutrition of Plantation Forests". Academic Press. 516 p.

MEAD, D. J.; WILL, G. M. 1976: Seasonal and between-tree variation in the nutrient levels in **Pinus radiata** foliage. **New Zealand Journal of Forestry Science 6:** 3–13.

MENGEL, K.; KIRKBY, E. A. 1982: "Principles of Plant Nutrition" (third ed.). International Potash Institute, Berne, Switzerland. 655 p.

MILLER, H. G. 1981: Forest fertilization: some guiding concepts. **Forestry 54(2):** 158–67.

MILLER, H. G.; COOPER, J. M. 1973: Changes in amount and distribution of stem growth in polestage Corsican pine following application of nitrogen fertiliser. **Forestry 46(2):** 157–90.

MILLER, W. F. 1966: Annual changes in foliar nitrogen, phosphorus and potassium levels of loblolly pine (**Pinus taeda** L.) with site and weather factors. **Plant and Soil 24(3):** 369–78.

MIYASAKA, S. C.; YEH, A. W.; WHITESELL, C. D. 1983: Use of soil and tissue testing in forest crops. Pp. 139–41 **in** Proceedings of First Fertiliser and Ornamentals Workshop; Kailua-Kona, Hawaii. **College of Tropical Agriculture and Human Resources, University of Hawaii, Research Extension Series 037.**

NEW ZEALAND FOREST SERVICE 1981: "New Zealand Forest Service Policy on Exotic Special Purpose Species". Government Printer, Wellington.

NEW ZEALAND METEOROLOGICAL SERVICE 1984. Rainfall normals for New Zealand 1951 to 1980. **New Zealand Meteorological Service Miscellaneous Publication 185.**

NEW ZEALAND SOIL BUREAU 1954: General survey of the soils of North Island, New Zealand. **New Zealand Soil Bureau Bulletin 5.**

NICHOLSON, G. 1984: Methods of soil, plant, and water analysis. **New Zealand Forest Service, FRI Bulletin No. 70.**

PRYOR, L. P.; JOHNSON, L. A. S. 1971: "A Classification of the Eucalypts". Australian National University, Canberra.

PULLAR, W. A. 1980: Tephra and loess cover deposits on Kaingaroa Plateau including detailed lithology of Upper Taupo Pumice. **New Zealand Soil Bureau Scientific Report No. 44.**

SCHÖNAU, A. P. G. 1981a: Seasonal changes in foliar nutrient content of **E. grandis. South African Forestry Journal 119:** 1–4.

——— 1981b: The effects of fertilising on the foliar nutrient concentrations in **Eucalyptus grandis. Fertilizer Research 2:** 73–87.

——— 1982a: Additional effects of fertilizing on several foliar nutrient concentrations and ratios in **Eucalyptus grandis. Fertilizer Research 3:** 385–97.

——— 1982b: Relationship between growth rate and foliar concentrations of nitrogen, phosphorus and potassium in **Eucalyptus grandis. South African Forestry Journal 120:** 19–23.

——— 1983: Fertilisation in South African forestry. **South African Forestry Journal 125:** 1–19.

SCHÖNAU, A. P .G.; HERBERT, M. A. 1983: Relationship between growth rate, fertiliser and foliar nutrient concentrations for **Eucalyptus grandis**; preliminary investigations. **Fertilizer Research 4:** 369–80.

STEWART, H. T. L.; FLINN, D. W.; BALDWIN, P. J.; JAMES, J. M. 1981: Diagnosis and correction of iron deficiency in planted eucalypts in Northwest Victoria. **Australian Forestry Research 11:** 185–90.

STONE, E. L. 1968: Microelement nutrition of forest trees: a review. Pp 132–75 **in** "Forest Fertilization Theory and Practice". Tennessee Valley Authority, Muscle Schoals, Alabama. 306 p.

TIMMER, V. R.; STONE, E. L. 1978: Comparative foliar analysis of young balsam fir fertilised with nitrogen, phosphorus, potassium and lime. **Soil Science Society of America Journal 42:** 125–33.

TURNBULL, J. W.; PRYOR, L. D. 1984: Choice of species and seed sources. Pp. 6–65 **in** Hillis, W. E.; Brown, A. G. (Ed.) "Eucalypts for Wood Production". CSIRO/Academic Press, Sydney. 434 p.

TURNER, J.; DICE, S. F.; COLE, D. W.; GESSEL, S. P. 1978: Variation of nutrients in forest tree foliage: A review. **College of Forest Resources, University of Washington, Institute of Forest Products, Contribution No. 35.** 32 p.

WARD, S. C.; PICKERSGILL, G. E.; MICHAELSEN, D. V.; BELL, D. T. 1985: Responses to factorial combinations of nitrogen, phosphorus and potassium fertilizers by saplings of **Eucalyptus saligna** Sm., and the prediction of the responses by DRIS indices. **Australian Forest Research 15:** 27–32.

WILL, G. M. 1985: Nutrient deficiencies and fertiliser use in New Zealand exotic forests. **New Zealand Forest Service, FRI Bulletin No. 97.**

WINTERHALDER, E. K. 1963: Differential resistance of two species of **Eucalyptus** to toxic soil manganese levels. **Australian Journal of Science 23(8):** 363–4.

YOST, R. S.; DeBELL, D. S.; WHITESELL, C. D.; MIYASAKA, S. C. 1987: Early growth and nutrient status of **Eucalyptus saligna** as affected by nitrogen and phosphorus fertilisation. **Australian Forest Research 17:** 203–14.