# Magnesium and potassium deficiency induced in glasshouse-grown *Eucalyptus globulus*

A.D. Mitchell[1] and P.J. Smethurst[1,2]*
[1]CRC Forestry Ltd, Private Bag 12, Hobart, Tasmania 7001
[2]CSIRO Sustainable Ecosystems, Private Bag 12, Hobart, Tasmania 7001
*e-mail: Philip.Smethurst@csiro.au (corresponding author)

**Abstract**

*A method of inducing magnesium (Mg) and potassium (K) deficiency in glasshouse-grown* Eucalyptus globulus *seedlings was tested using a field soil from the Florentine Valley and high cumulative rates of nitrogen (N) fertiliser, leaching, and grass growth and biomass removal. Prior to use in the glasshouse experiment, the clay-loam soil had received in the field a total of (kg ha$^{-1}$) 1600 N, 600 phosphorus (P), 450 calcium (Ca), and 1376 sulphur (S).*
E. globulus *seedlings were transplanted into pots of this soil in the glasshouse and treated with factorial combinations of Mg and K (100 kg ha$^{-1}$ per application). All treatments also received a base dressing of N fertiliser as urea (200 kg N ha$^{-1}$ per application). Fertilisers were applied five times during the 13-month experiment.*

*Visual symptoms similar to those reported in the literature for Mg and K deficiency in* E. globulus *were displayed by some seedlings approximately two months after planting, and height growth had responded to combined Mg+K fertilisation by 3 months. By 13 months, Mg and K fertilisers significantly increased foliar concentrations of Mg and K respectively in the relevant Mg, K and Mg+K treatments, and also seedling height and biomass. At this time, deficiency symptoms were more variable and possibly related to zinc and boron deficiency or other nutrient imbalances. An exchange-surface-displaced fertilisation effect seemed to occur for Mg and K, because growth in the Mg and the K treatments was similar and not greater than when both nutrients were applied together. Mg and K deficiencies can thus be artificially induced by accelerating depletion of these nutrients using N fertiliser, leaching and biomass removal. We conservatively speculate that there will be little prospect of serious Mg or K deficiencies in this soil in the field for several rotations if N inputs do not exceed 600 kg N ha$^{-1}$ per rotation. However, less fertile soils are more vulnerable to developing deficiencies of Mg or K.*

*Keywords: Magnesium, potassium, fertiliser, deficiency, growth, foliar analysis*

## Introduction

There are increasing concerns about the availability of magnesium (Mg) and potassium (K) in plantation forest soils in Australia, particularly where nitrogen (N) fertilisers have been applied. Potassium deficiency symptoms have been reported in eucalypt plantations in Victoria and Western Australia (Judd *et al*. 1996; Dell *et al*. 2002). Low concentrations of Mg in *Eucalyptus nitens* foliage in experimental plantations in Victoria suggested a probable response to Mg additions (Bennett *et al*. 1996). Although not yet recorded for eucalypts in Tasmania, Mg and K deficiencies have been reported in Tasmanian *Pinus radiata* plantations (Neilsen and Dredge 1999; Smethurst *et al*. 2001). The incidence of serious base cation deficiencies is likely to increase with an increase in the use of N fertilisers, because fertilisation with N increases tree growth rates and demand for, and export of, Mg

and K, whilst increasing leaching of nitrate and accompanying cations is also likely (Mochoge and Beese 1986; Feger 1992; Stanturf and Stone 1994; Mitchell and Smethurst 2003).

An adequate supply of Mg and K is essential for plant growth. The major function of Mg is as the metal in the centre of the chlorophyll molecule, and no other metal can be substituted for Mg (McLaren and Cameron 1993; Mengel and Kirkby 1987). Potassium is involved in the regulation of stomatal opening, maintaining plant cell turgor, pH stabilisation and the activation of many enzymes. Potassium is also essential for protein synthesis and for the metabolism of carbohydrates and lipids (McLaren and Cameron 1993; Dell *et al*. 2002). Given the important roles of Mg and K in the physiological and biochemical functioning of plants, any deficiencies of these essential plant nutrients will result in reductions in growth.

Neither Mg nor K fertilisers are routinely applied to Australian eucalypt plantations, but N fertiliser use is increasing, which will accelerate the depletion of Mg and K (Smethurst *et al*. 2004). Where Mg or K have been applied in fertiliser experiments, they generally increased foliar concentrations of Mg or K, but did not result in increased growth (Bennett *et al*. 1996; Cromer *et al*. 1981; Judd *et al*. 1996). Research into deficiencies of these nutrients would benefit from reliable methods for inducing these deficiencies in soil-grown plants. We reasoned that a method could be developed by accelerating the removal of Mg and K using N fertilisation, leaching, and grass growth and biomass removal. Therefore, an experiment was conducted to test this hypothesis using glasshouse-grown *E. globulus* seedlings. Deficiency symptoms, based on visual and foliar analysis, were also compared with previous reports.

*Table 1. Characteristics of the Florentine Valley soil.*

| | |
|---|---|
| Field texture | Clay-loam |
| Parent material | Mudstone |
| Australian soil classification[A] | Kurosol |
| Soil pH | 4.5 |
| EC (dS $m^{-1}$) | 0.04 |
| Exch. Ca ($cmol_{(+)}\ kg^{-1}$) | 2.3 |
| Exch. Mg ($cmol_{(+)}\ kg^{-1}$) | 0.4 |
| Exch. K ($cmol_{(+)}\ kg^{-1}$) | 0.2 |
| Exch. Al ($cmol_{(+)}\ kg^{-1}$) | 11.0 |
| ECEC[B] ($cmol_{(+)}\ kg^{-1}$) | 14.0 |

[A] Isbell (1993).
[B] Exchangeable bases plus exchangeable acidity (Blakemore *et al.* 1987).

## Materials and Methods

*Experimental design and establishment*

A Brown Kurosol soil was collected from an *E. nitens* plantation planted in October 1992 in the Florentine Valley, Tasmania. The previous crop of *P. radiata* at that site had been harvested in 1991. Selected chemical and physical characteristics of the soil are shown in Table 1. In the field, N fertiliser (ammonium sulphate, 20.5% N, at 600 kg N $ha^{-1}$) and P fertiliser (triple superphosphate, 20% P and 15% Ca, at 300 kg P $ha^{-1}$) had been broadcast-applied at 2 and 26 months after re-planting with *E. nitens*. An additional application of N fertiliser at 400 kg N $ha^{-1}$ was broadcast in October 1998 in the form of urea (46% N). This gave a total of 1600 kg N $ha^{-1}$, 600 kg P $ha^{-1}$, 450 kg Ca (calcium) $ha^{-1}$, and 1376 kg S (sulphur) $ha^{-1}$ added by the time of soil collection (Mitchell and Smethurst 2003).

In the glasshouse, *E. globulus* seedlings were raised from a single batch of seed and grown in washed sand. When sufficiently large, they were transferred to root-trainer pots containing a commercial potting mix, and were watered periodically with a complete soluble fertiliser. Seedlings were then transplanted to 18 cm pots, at 3

*Table 2. Schedule of events.*

| Date | Months Since Planting | Fertilisation | Tree harvest | Other Events |
|---|---|---|---|---|
| 08 Nov 2000 | 0.0 | | | Planting |
| 21 Nov 2000 | 0.4 | ✓ | | |
| 13 Dec 2000 | 1.8 | | | Grass cut |
| 22 Jan 2001 | 2.5 | ✓ | | |
| 07 Feb 2001 | 3.0 | | ✓ [A] | |
| 11 Feb 2001 | 3.1 | | | Grass cut |
| 29 Mar 2001 | 4.6 | | | Grass cut |
| 12 Apr 2001 | 5.1 | ✓ | | |
| 25-29 Jun 2001 | 7.6 | | ✓[B] | Grass cut |
| 16 Aug 2001 | 9.3 | ✓ | | |
| 05 Nov 2001 | 11.9 | ✓ | | |
| 03-07 Dec 2001 | 12.9 | | ✓[B] | |

[A] Sampling of foliage and stems from the top third of all seedlings.
[B] Harvesting of entire seedlings plus soils.

seedlings per pot, 8 pots per treatment, on 08 November 2000, considered month 0 of the experiment. Each pot contained 1.6 kg of the field soil that had first been air-dried and passed through a 2 mm sieve, and then combined with perlite at a 60:40 soil:perlite ratio to improve aeration and drainage. A further 12 seedlings were set aside for which baseline (at the time of transplanting) foliar nutrient concentrations could be determined.

Treatments consisted of two fertilisers, $MgSO_4$ (Mg) and $K_2SO_4$ (K), and were applied in factorial combinations, i.e. control, Mg, K, and Mg+K, with eight replicate pots of each treatment. Fertilisers were applied five times at 2 to 3 month intervals (Table 2). At each application, fertilisers were applied at rates of 0.08 g Mg $kg^{-1}$ soil and 0.08 g K $kg^{-1}$ soil (equivalent to 100 kg Mg $ha^{-1}$ and 100 kg K $ha^{-1}$). In addition, at each application, a base dressing of N fertiliser as urea was applied to all treatments at a rate of 0.17 g N $kg^{-1}$ soil (equivalent to 200 kg N $ha^{-1}$). By the first harvest, 0.51 g N $kg^{-1}$ soil, 0.24 g Mg $kg^{-1}$ soil and 0.24 g K $kg^{-1}$ soil (equivalent to 600 kg N $ha^{-1}$, 300 kg Mg $ha^{-1}$ and 300 kg K $ha^{-1}$) had been applied. By the final harvest, 0.85 g N $kg^{-1}$ soil, 0.4 g Mg $kg^{-1}$ soil and 0.4 g K $kg^{-1}$ soil (equivalent to 1000 kg N $ha^{-1}$, 500 kg Mg $ha^{-1}$ and 500 kg K $ha^{-1}$) had been applied.

Although the Mg and K fertiliser applications included S equivalent to a total of 659 and 410 kg $ha^{-1}$, respectively, this was assumed to be not a serious confounding effect because these rates of S application were small compared to the 1376 ka $ha^{-1}$ applied to the soil prior to collection from the field.

Seedlings were watered at regular intervals (daily during summer and every second day during winter) with approximately 150 ml of deionized water per pot, with excess drainage being captured in saucers and re-applied to pot surfaces. Pots were arranged in a randomized fashion in a glasshouse maintained at a temperature range of 18-24ºC.

To increase the rate of cation depletion, each pot was leached with approximately 300 ml of deionized water eight times during the experiment, and ryegrass was grown in each pot and harvested four times. A schedule of events is provided in Table 2.

*Sampling and measurements*

Foliar and stem samples (top third of each seedling) were taken for analysis three months after establishment (n = 8 pots per treatment). Soils and entire seedlings were harvested at eight (n = 3 pots per treatment) and 13 (n = 4 pots per treatment) months after establishment. Abscised foliage from the seedlings was collected as necessary and retained for analysis at each harvest. The 8th pot per treatment was not destructively sampled.

Seedling heights at establishment were measured as the distance from the base of the each seedling (soil level) to the bottom of the apical bud of the main stem. The height for each of the seedlings in a pot was added together to give an overall height for that pot. Heights were measured again at regular intervals, and at each harvest, and the changes in height per pot calculated and recorded.

At each harvest, seedling shoots were oven-dried at 70° C and the dry weights recorded. At the 3-month sampling and 8-month harvest, dry weights for foliage and stems were recorded separately. At the final harvest, dry weights of living foliage, abscised (dead) foliage and stems were recorded separately.

To determine foliar nutrient concentrations, foliage retention was calculated as the ratio of the oven-dry weight of living foliage to the oven-dry weight of the abscised (dead) foliage.

Foliage was finely ground and sub-samples were digested in concentrated $H_2SO_4$/$H_2O_2$ (Lowther 1980). Concentrations of Mg, K and Ca in the resulting solutes were measured by atomic absorption spectrometry, and flow injection analysis was used to measure N and P concentrations.

*Statistical analysis*

Results were analysed for significant treatment differences using the analysis of variance procedure in Statgraphics Plus, version 5. Means were compared using l.s.d. at $p = 0.05$, unless otherwise indicated. Spearman correlation coefficients (r) were calculated for the final harvest data to identify significant relationships between total foliar dry weight, seedling height, stem dry weight, foliar retention and foliar concentrations of N, P, Ca, Mg, and K.

## Results

*Seedling growth*

Seedling height increment was significantly ($p < 0.02$) increased by the application of Mg+K fertiliser by 3 months after establishment of the experiment (Figure 1). By the final harvest, the pot height increments were between 39% and 55% greater in the seedlings fertilised with Mg or K compared to the control, with the combination providing no further significant growth improvement.

Total foliar dry weights (live + abscised) were generally greater at both harvests in the Mg+K fertiliser treatments compared to the control, and the difference was significant ($p < 0.01$) at the final harvest (Figure 2). By the final harvest, foliar dry weights were approximately 56% greater in the Mg+K fertilised seedlings. There was no significant difference in foliar dry weights between seedlings that had been fertilised with Mg, K or Mg+K at any stage, but stem dry weights were significantly ($p < 0.01$) greater in the Mg and K fertiliser treatments compared to the control at the final harvest. By the final harvest stem dry weights were approximately 78% higher in the fertilised seedlings.

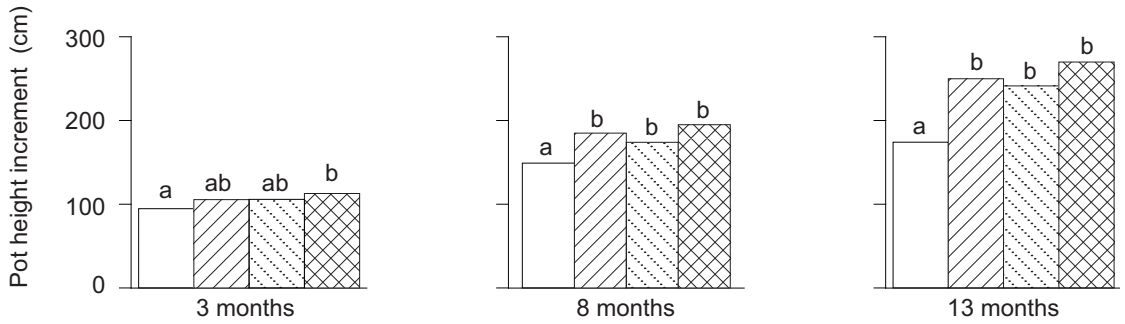


*Figure 1. Mean height increment per pot at 3, 8 and 13 months after establishment. Means with the same letter are not statistically different at p < 0.05.*

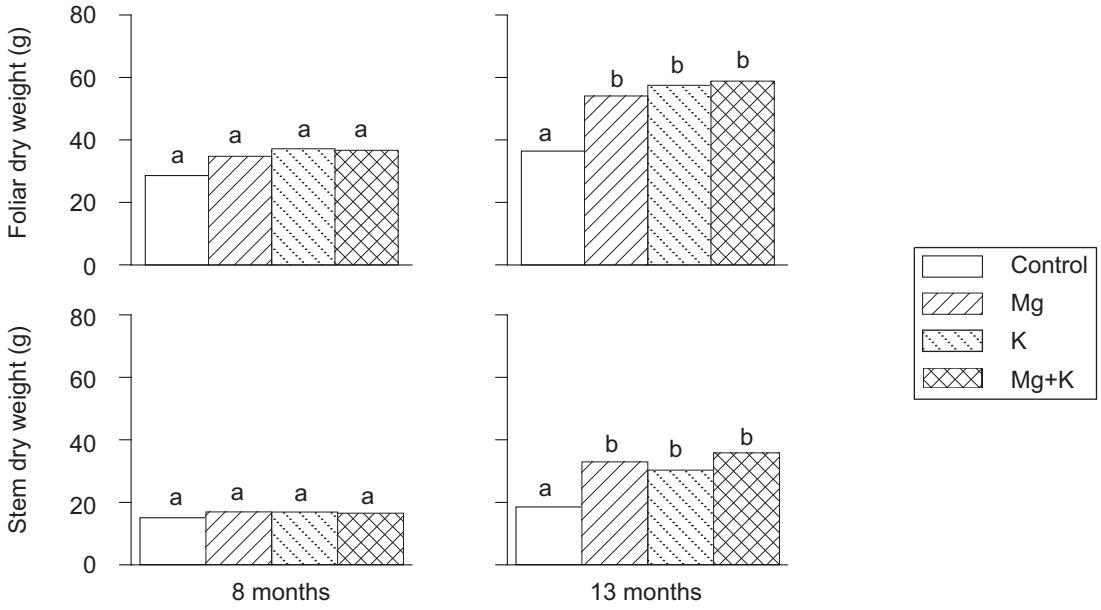


*Figure 2. Mean foliar dry weights per pot and stem dry weights per pot at the harvests 8 and 13 months after establishment. Means with the same letter are not statistically different at p < 0.05.*

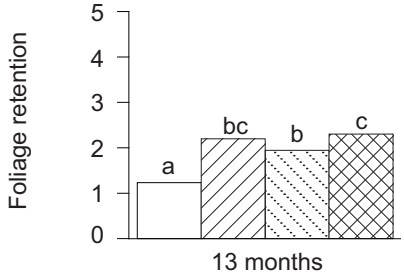


*Figure 3. Mean foliar retention ratio 13 months after establishment. Means with the same letter are not statistically different at p <0.05.*

*Foliage retention*

Foliage retention was significantly ($p < 0.01$) improved in the Mg, K and Mg+K treatments compared to the control (Figure 3). The ratio between living and dead leaves in the control was only slightly better than 1:1, whereas, in the fertilised seedlings, the ratio was 2:1 or better. The highest levels of leaf retention were recorded in the Mg+K treatment and the difference was significant ($p = 0.002$) compared to the control and K treatments.

*Deficiency symptoms*

The strongest deficiency symptoms were observed in the control seedlings not fertilised with Mg or K, however symptoms were not consistent across all seedlings within the control treatment. Generally, symptoms included cupped or beaked foliage, marginal and interveinal chlorosis, marginal necrosis or scorching of fully expanded juvenile leaves, and stunted new growth. All treatments developed reddish colours in the older leaves and dropped the basal leaves. Some individual seedlings in the Mg+K treatment also developed interveinal chlorosis and marginal necrosis as in the control treatments, but these symptoms were not consistent across all seedlings within a treatment. Towards the end of the experiment some individual seedlings in the Mg and K treatments developed symptoms of stunted and misshapen new leaves, leaf rolling and crowded, dagger-shaped leaves near the apex of the main stems.

*Foliar Ca, Mg and K concentrations*

Concentrations of Ca in the foliage of the seedlings at establishment were 8.6 mg $g^{-1}$ (Table 3) and remained relatively constant in the control treatment up to the final harvest at 13 months (Figure 4). Separate applications of Mg or K fertiliser did not affect foliar Ca concentrations in the sampling at 3 months and harvest at 8 months, but the decrease in foliar Ca

*Table 3. Foliar nutrient concentrations of* E. globulus *seedlings at establishment.*

| Nutrient | Concentration (mg $g^{-1}$) |
|---|---|
| Ca | 8.6 |
| Mg | 2.7 |
| K | 19.9 |
| N | 20.5 |
| P | 2.1 |

at 3 months in the Mg+K treatment was significant ($p = 0.03$) compared to the control and the Mg treatment. Between the harvests at 8 and 13 months, concentrations of Ca in the Mg and K treatments also decreased. At the final harvest, foliar Ca concentrations in the seedlings fertilised with Mg or K were significantly ($p < 0.01$) lower than those in the control. The combined Mg+K treatment resulted in the lowest foliar Ca concentrations, which were significantly ($p < 0.01$) lower than in all other treatments.

At establishment, foliar Mg concentrations were 2.7 mg $g^{-1}$ (Table 3). Mean foliar Mg in the control treatment decreased over time to 1.4 mg $g^{-1}$ at 3 months and to 0.77 mg $g^{-1}$ at 13 months (Figure 4). Magnesium or Mg+K application significantly ($p < 0.003$) increased foliar Mg concentrations compared to the control and the K treatment at all times of sampling, but, like the control treatment, concentrations at final harvest were still lower than at planting. Potassium application had no effect on foliar Mg concentrations.

Potassium concentrations in foliage at establishment were 19.9 mg $g^{-1}$ (Table 3). Mean foliar K concentrations of the control treatment decreased sharply to 5.3 mg $g^{-1}$ at 3 months but remained relatively constant between 3 months and 13 months (Figure 4). Application of K fertiliser in both the K and Mg+K treatments significantly ($p < 0.001$) increased foliar K concentrations compared to the control and the Mg treatment at all sampling times (3, 8 and 13 months). Foliar K concentrations in the Mg treatment were

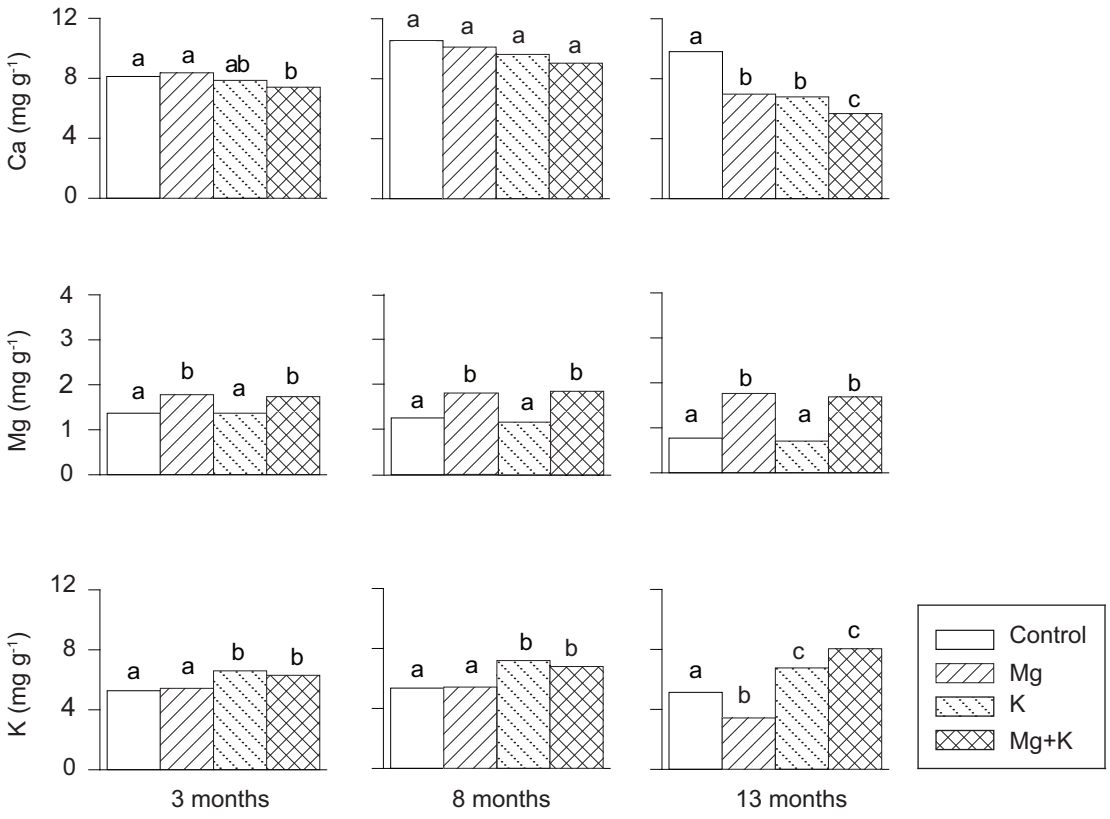


*Figure 4. Mean concentrations of Ca, Mg and K in foliar samples at 3, 8, and 13 months after establishment. Means with the same letter are not statistically different at $p < 0.05$.*

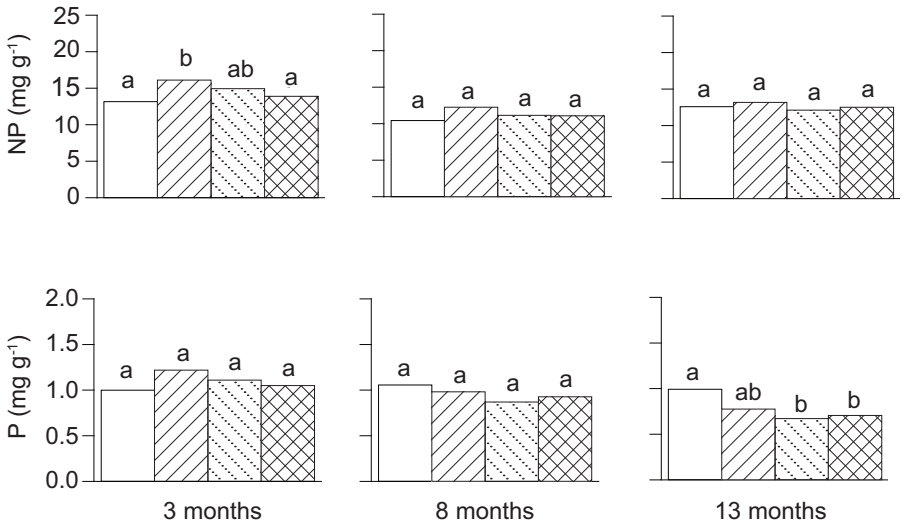


*Figure 5. Mean concentrations of N and P in foliar samples at 3, 8 and 13 months after establishment. Means with the same letter are not statistically different at $p < 0.05$.*

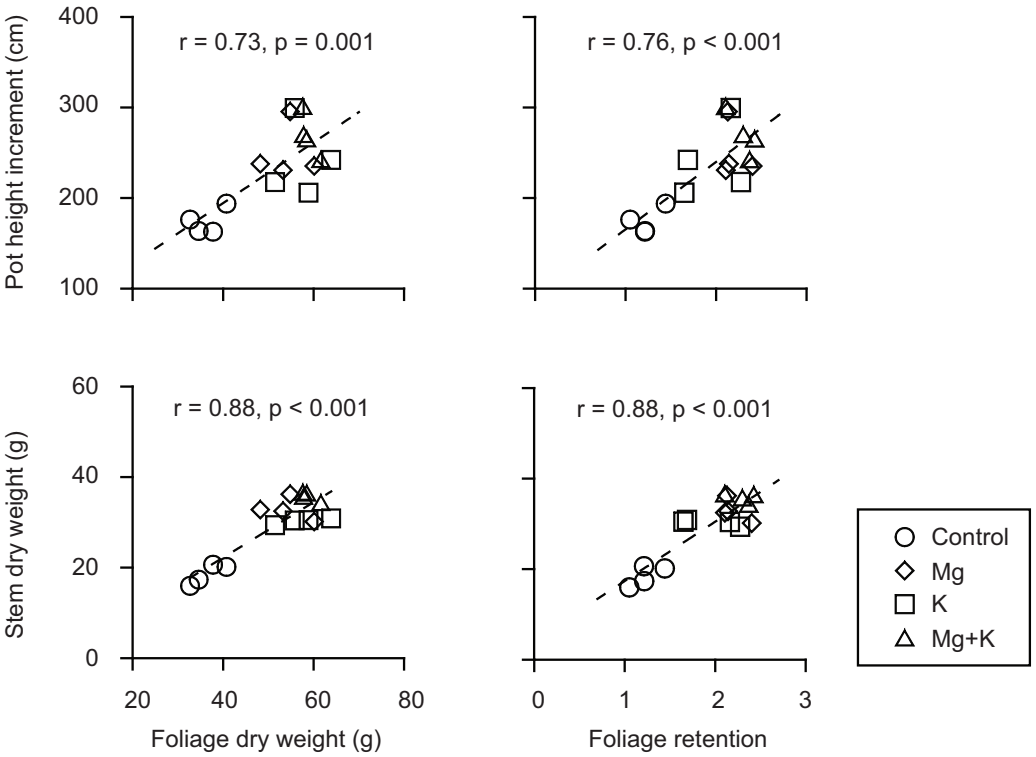


*Figure 6. Relationships between foliage dry weight and foliage retention ratio, and seedling increments per pot and stem dry weights per pot at 13 months after establishment.*

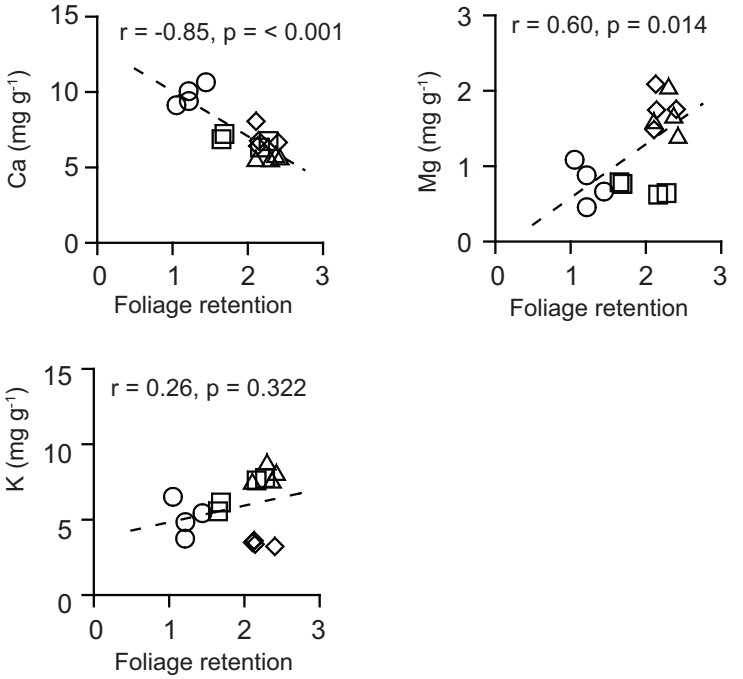


*Figure 7. Relationships between foliage retention ratio and foliar Ca, Mg and K concentrations at 13 months after establishment.*

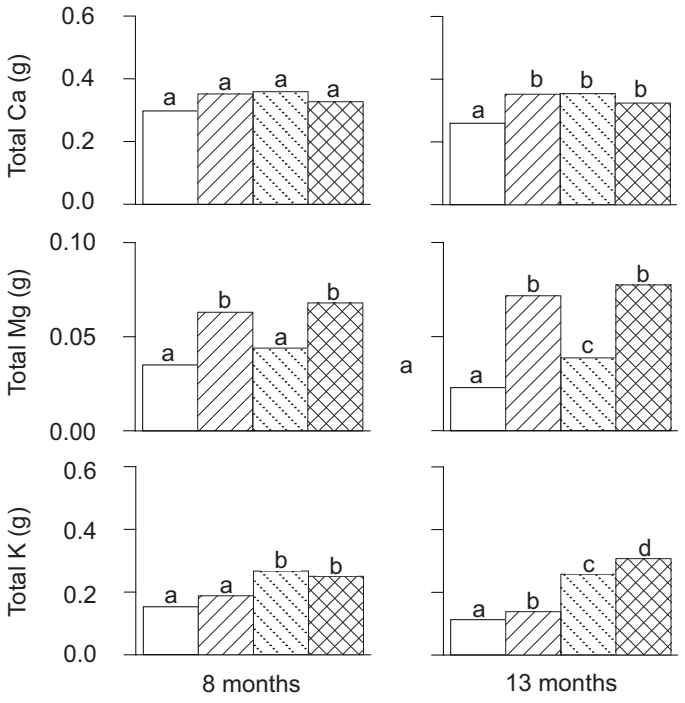


*Figure 8. Mean totals of Ca, Mg and K per pot in foliar samples at 8 and 13 months after establishment. Means with the same letter are not statistically different at p < 0.05.*

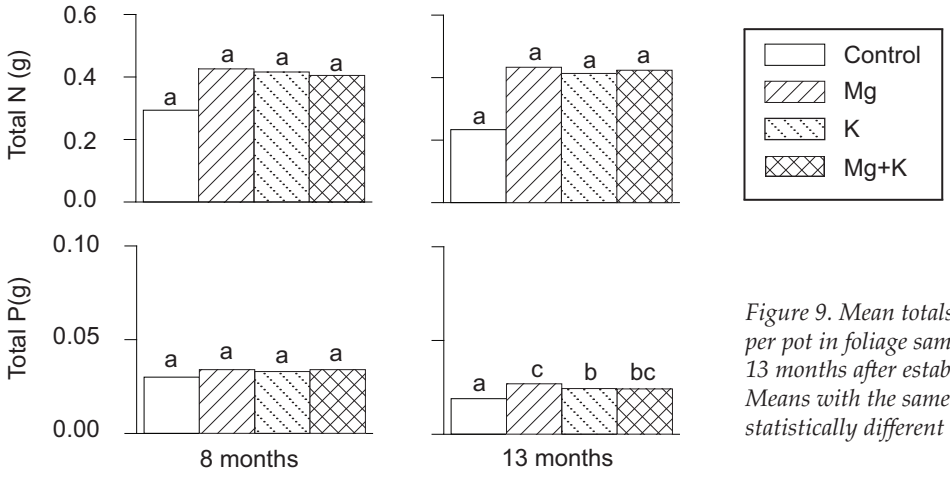


*Figure 9. Mean totals of N and P per pot in foliage samples at 8 and 13 months after establishment. Means with the same letter are not statistically different at p < 0.05.*

similar to those in the control at 3 and 8 months but by 13 months had decreased to be significantly (p = 0.03) lower than the control.

*N and P concentrations*

Concentrations of foliar N were 20.5 mg $g^{-1}$ at establishment (Table 2). Despite N application, mean concentrations in the control treatment decreased to 13.2 mg $g^{-1}$ at 3 months and were maintained at similar levels in the subsequent two harvests (Figure 5). Magnesium and K application generally had no effect on foliar N concentrations, except at 3 months when foliar N concentrations were significantly (p = 0.02) greater in the Mg treatment compared to the control and Mg+K treatments.

Foliar P concentrations at establishment were 2.1 mg $g^{-1}$ (Table 3). At 3 months, foliar P concentrations in the control treatment had decreased by half and remained relatively constant in the subsequent two harvests (Figure 5). Both Mg and K treatments had no effect on foliar P concentrations at 3 and 8 months and concentrations were similar to those in the control treatment. However, by 13 months concentrations of foliar P were significantly ($p = 0.05$) lower in the K and Mg+K treatments compared to the control.

*Growth in relation to foliar dry weights, retention and nutrient concentrations*

At 13 months, significant ($p < 0.001$) positive correlations were found between total foliar dry weight or foliage retention, and pot height increment or stem dry weight (Figure 6). High foliar weight and a high pot level of foliage retention were associated with tall, heavy seedlings.

Significant ($p < 0.014$) correlations were found between foliage retention and foliar Ca and Mg concentrations, but not foliar K concentrations (Figure 7). High foliage retention was associated with a high concentration of foliar Mg and a low concentration of foliar Ca. Significant correlations were also recorded between foliage retention and foliar P concentration ($r = -0.59$, $p = 0.016$) (data not shown). Significant correlations recorded for seedlings at 8 months were generally those also recorded at 3 months.

*Foliar nutrient contents*

At both harvests, Ca and N were the dominant nutrients in foliage of the control treatment, followed by K, and approximately equal amounts of Mg and P (Figures 8 and 9). Total foliar K was approximately half that of Ca and N, whereas total Mg and P were approximately one tenth that of Ca and N. The total of each nutrient at the second harvest was similar to or less than that in the first harvest. Both Mg and K application generally increased the total amount of these nutrients in foliage compared to the control, but not all the increases were significant ($p < 0.05$). These increases, generally, reflected increases in foliar dry weights in the seedlings treated with Mg and K (Figure 2), but also the increased Mg and K concentrations of the fertilised seedlings (Figure 4).

**Discussion**

Treatment of glasshouse-grown *E. globulus* seedlings with N fertiliser, leaching, and growth and removal of grass resulted in Mg and K deficiency. This conclusion was supported by analysis of leaf Mg and K concentrations, by increased growth rates after fertilisation with Mg, K or Mg+K, and partly by observed symptoms of deficiency.

Applications of Mg and K fertiliser improved seedling height increment and biomass. Foliage retention, and therefore leaf area, was improved in the seedlings fertilised with Mg or K over the control, which would have been partially responsible for the increases in seedling height and stem dry weight in the fertilised seedlings. Foliar dry weights and foliage retention were highly correlated with seedling height increments and stem dry weights (Figure 6), which is not surprising because field studies have also identified a relationship in eucalypts between leaf area and stem volume (e.g. Smethurst *et al*. 2003).

Growth responses of eucalypts to N fertilisation have been widely reported (Cromer *et al*. 1981; Cromer and Williams 1982; Bennett *et al*. 1996; Judd *et al*. 1996; Smethurst *et al*. 2004), but apart from a K response in *E. globulus* in Victoria (Smethurst and Appleton, pers. comm.) we know of no examples where growth responses to Mg and K fertiliser in field-grown *E. globulus* or other eucalypts within the sub-genus Symphyomyrtus have been reported in Australia. Bennett *et al*. (1996) reported that, although there was no direct growth

response to K fertiliser, K concentrations in the foliage of *E. regnans* seedlings at age 1 year were increased and this was correlated with growth at 26 months. They also identified Mg fertilisation as potentially beneficial to the growth of *E. nitens.*

In this experiment, we successfully accelerated the depletion of soil Mg and K, as evidenced by differences in seedling growth, leaf nutrient content and the occurrence of deficiency symptoms. However nutrient uptake by the seedlings was from only a small soil volume. Therefore, these conditions contrasted markedly with, and were more extreme than, those experienced by field-grown trees. Whether the positive response to Mg and K fertilisation reported in this glasshouse study would be observed in this soil under field conditions is unknown. Care should be exercised when using results from this glasshouse study to predict field behaviour.

Based on visual symptoms in the foliage of *E. globulus* seedlings in this study, it was difficult to diagnose specific nutrient deficiencies. A range of symptoms was displayed by all treatments, but not by all seedlings within one pot. Some symptoms observed match those observed by Dell (1996) and Dell *et al*. (2002) for seedlings fertilised with Mg or K. Symptoms in the control seedlings, although possibly related to Mg and K deficiency, could also have been the result of deficiencies in zinc and boron or a combination of nutrient deficiencies (Dell *et al*. 2002). There were no visual symptoms of S deficiency, i.e. red new growth. Some leaf blistering was also observed that probably resulted from warm and humid glass-house conditions.

Foliar analysis provided additional insights into the nutritional status of the seedlings, but did not assist in diagnosing specific nutrient deficiencies or help to explain growth responses. Observations of foliar symptoms suggested Mg and K deficiency was induced in the control treatment, and that foliar concentrations of 0.8-1.4 mg Mg $g^{-1}$ and 5.1-5.4 mg K $g^{-1}$ were not adequate to maintain healthy growth. However, foliar concentrations of Mg in the K treatment and of K in the Mg treatment were similar to those in the control. The two elements have a different function within the plant and they are not interchangeable, and application of one might decrease uptake and foliar nutrient concentrations of the other. Therefore, Mg deficiency symptoms might have been expected to have been widely displayed by the K-treated seedlings and K deficiency by the Mg-treated seedlings. This effect was not observed, so growth responses were probably partly due to a secondary effect of the addition of Mg and K, e.g. via the soil base cation balance, pH or availability of aluminium (Al). For example, as well as increased concentrations of the applied nutrients in soil solution, we measured a 30% increase in soil solution K concentration in the Mg treatment and a 550% increase in soil solution Mg concentration in the K treatment (data not shown). Such exchange-surface-displaced fertilisation effects, which were accompanied by growth responses in both the Mg and K treatments, were apparently enough to obviate a further increase in growth due to the combined application of these nutrients in the Mg+K treatment.

Although seedlings in this experiment had height growth rates similar to healthy field-grown seedlings (e.g. Adams *et al*. 2003), we suspect some Al toxicity may have developed by the end of the experiment because the soil had a low initial pH (pH 4.5) that decreased to pH 4.3 in the control treatment during the experiment, and even further in the Mg (pH 3.7), K (pH 3.9) and Mg+K (pH 3.6) treatments (data not shown). Also, concentrations of exchangeable Al after 13 months were significantly higher in the Mg+K treatment (12.3 $cmol_{(+)}$ $kg^{-1}$) than in the control treatment (11.5 $cmol_{(+)}$ $kg^{-1}$).

Concentrations of Mg, K, Ca, N and P in foliage of the control treatment at the 3, 8 and 13 months were within typical ranges

reported for plantation-grown *E. globulus* and for eucalypts within the sub-genus Symphyomyrtus, although Mg was at the low end of the reported range (Bennett *et al*. 1996; Judd 1996; Judd *et al*. 1996). The usefulness of foliar analysis might be improved by understanding the importance of seedling age and leaf position on the critical concentration for each nutrient.

The data for total foliar Mg and K content and growth indicated that seedling uptake of Mg and K did not meet the demands of growth where these nutrients were not added. Total foliar Mg and K in the control treatment decreased between 8 and 13 months, probably because redistribution of nutrients from older foliage to new shoots did not match the rate of leaf senescence. The application of Mg and K improved foliar nutrient status of the fertilised seedlings, and by 13 months foliar Mg concentrations in the Mg-fertilised seedlings were close to double the critical concentrations reported by Dell *et al*. (2002). However, foliar K concentrations remained close to or below reported critical concentrations. Some care needs to be taken when comparing the results reported in this paper with those of Dell *et al*. (2002), because the concentrations of Mg and K reported here are a mean across all leaves of seedlings within a treatment whereas the critical concentrations of Dell *et al*. (2002) are for the youngest fully expanded leaves of plantation-grown one-to two-year-old *E. globulus.* Foliar K concentrations provided some evidence that the uptake of K was suppressed by the application of Mg fertiliser but, after increases in foliar dry weights due to Mg fertilisation were considered, total K content was greater than in the control treatment.

The soil used in this experiment had intermediate reserve levels of Mg and K compared to other soils used for plantation forestry (Mitchell and Smethurst 2003), and a conservative prediction for this soil is that there will be little prospect of serious Mg or K deficiencies for several rotations if N inputs do not exceed about 600 kg N $ha^{-1}$ per rotation. Less fertile soils would be more vulnerable to Mg or K depletion.

In this experiment, there was a positive relationship between foliar Mg and foliage retention, suggesting that high foliar Mg concentrations may be important for maintaining high leaf areas and therefore seedling growth. A positive although not significant relationship was also found between foliar K and foliage retention. Therefore, high foliar K concentrations may also be important in maintaining high leaf areas.

## Conclusions

Magnesium and K deficiencies in *E. globulus* were induced by high rates of N fertilisation, leaching, and grass growth and biomass removal. Visual deficiency symptoms were difficult to use as a diagnostic tool, but deficiencies of Mg and K were reflected in foliar analysis. The methodology described could be used to induce deficiencies of Mg or K in young trees and characterise the associated soil and plant characteristics, but micronutrient applications should be included.

## Acknowledgements

We thank Mr Craig Baillie for his assistance in collecting the soils used in the experiment, Mr Keith Churchill and Ms Liz Vinall for their assistance in establishing and harvesting the experiment, and Ms Ann Wilkinson for her assistance in analysing plant material from the experiment. We also appreciated helpful comments from two anonymous reviewers.

## References


Adams, P.R., Beadle, C.L., Mendham, N.J. and Smethurst, P.J. (2003). The impact of timing and duration of grass control on growth of a young *Eucalyptus globulus* Labill. plantation. *New Forests* 26: 147-65.

Bennett, L.T., Weston, C.J., Judd, T.S., Attiwill, P.M. and Whiteman, P.H. (1996). The effects of fertilisers on early growth and foliar nutrient concentrations of three plantation eucalypts on high quality sites in Gippsland, southeastern Australia. *Forest Ecology and Management* 89: 213-226.

Blakemore, L.C., Searle, P.L. and Daly, B.K. (1987). *Methods for chemical analysis of soils*. New Zealand Soil Bureau, Scientific Report 80, Lower Hutt, New Zealand.

Cromer, R.N. and Williams, E.R. (1982). Biomass and nutrient accumulation in a planted *E. globulus* (Labill.) fertiliser trial. *Australian Journal of Botany* 30: 265-278.

Cromer, R.N., Cameron, D., Cameron, J.N., Flinn, D.W., Neilsen, W.A., Raupach, M., Snowdon, P. and Waring, H.D. (1981). Response of eucalypt species to fertiliser applied soon after planting at several sites. *Australian Forestry* 44: 3-13.

Dell, B. (1996). Diagnosis of nutrient deficiencies in eucalypts. In: *Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Melbourne.*

Dell, B., Malajczuk, N., Xu, D. and Grove, T.S. (2002). *Nutrient Disorders in Plantation Eucalypts.* ACIAR Monograph No. 74, Canberra, 188 pp.

Feger, K.H. (1992). Nitrogen cycling in two Norway spruce (*Picea abies*) ecosystems and effects of a $(NH_4)_2SO_4$ addition. *Water, Air and Soil Pollution* 61: 295-307.

Isbell, R.F. (1996). *The Australian Soil Classification*. CSIRO, Australia.

Judd, T.S. (1996). Nutrient concentrations in Eucalyptus: A synthesis in relation to differences between taxa, sites and components. In: *Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Melbourne.*

Judd, T.S., Bennett, L.T., Weston, C.J., Attiwill, P.M. and Whiteman, P.H. (1996). The response of growth and foliar nutrients to fertilisers in young *Eucalyptus globulus* (Labill.) plantations in Gippsland, southeastern Australia. *Forest Ecology and Management* 82: 87-101.

Lowther, J. R. (1980). Use of a single acid – hydrogen peroxide digest for the analysis of *Pinus radiata* needles. *Communications in Soil Science and Plant Analysis* 11: 175-88.

McLaren, R.G. and Cameron, K.C. (1993). *Soil Science: An Introduction to the Properties and Management of New Zealand Soils.* Oxford University Press, Auckland, New Zealand.

Mengel, K. and Kirkby, E.A. (1987). *Principles of Plant Nutrition*. 4th edition. International Potash Institute, Bern, Switzerland.

Mitchell, A.D. and Smethurst, P.J. (2003). Surface soil changes in base cation concentrations in fertilised hardwood and softwood plantations in Australia. *Forest Ecology and Management* 191: 253-265.

Mochoge, B.O. and Beese, F. (1986). Leaching of plant nutrients from an acid forest soil after nitrogen fertiliser application. *Plant and Soil* 91: 17-29.

Neilsen, W.A. and Dredge, P.D. (1999). *Magnesium deficiency in Forestry Tasmania plantations*. Paper presented to RWG 3, Rotorua, New Zealand.

Smethurst, P.J., Baillie, C., Cherry, M. and Holz, G. (2003). Fertiliser effects on LAI and growth of four *Eucalyptus nitens* plantation. *Forest Ecology and Management* 176: 531-542.

Smethurst, P., Holz, G., Moroni, M. and Baillie, C. (2004). Nitrogen management in *Eucalyptus nitens* plantations. *Forest Ecology and Management* 193: 63-80.

Smethurst, P.J., Lyons, A. and Churchill, K. (2001). Yellow pines signal potassium deficiency in reforested old pasture land in Tasmania. *Better Crops International* 15: 11-13.

Stanturf, J.A. and Stone, E.L. (1994). Loss of nitrogen and bases after fertilisation of second-growth hardwood forest soils. *Forest Ecology and Management* 65: 265-277.