MAGNESIUM FERTILISERS AFFECTED GROWTH, UPPER MID-CROWN YELLOWING, AND FOLIAR NUTRIENTS OF *PINUS RADIATA*, AND SOIL MAGNESIUM CONCENTRATION

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(Received for publication 9 February 2000; revision 19 October 2000)

ABSTRACT

A magnesium (Mg) fertiliser trial was established in 1984 in a 5-year-old stand of *Pinus radiata* D. Don with magnesium deficiency in Tauhara Forest in the central North Island of New Zealand. The main trial consisted of rates of dolomite applied at 0, 20, 55, 150, and 400 kg Mg/ha. A range of magnesium fertilisers (kieserite, serpentine, coarse-ground calcined magnesite, fine-ground calcined magnesite, and Epsom salts) was also applied at 55 kg Mg/ha. Since establishment the trial has been regularly measured (height and dbh) and the foliage sampled, and the soil has been sampled periodically. The young trees were subjectively scored for visual symptoms of magnesium deficiency prior to fertiliser application in 1984 and a year later in 1985. In 1993, the trial was used to study the long-term effect of added magnesium on the incidence and severity of Upper Mid-Crown Yellowing (UMCY). Individual trees were scored for UMCY symptoms and needle retention, and measurements of height and dbh were taken. Foliage samples were taken from all plots and analysed for nitrogen, potassium, phosphorus, calcium, magnesium, and boron. Soil samples were collected from selected plots (at depths of 0–10 and 10–20 cm) and analysed for exchangeable cations (magnesium, potassium, calcium) and acid-extractable magnesium.

The incidence and severity of UMCY symptoms were significantly reduced with magnesium additions of 150 and 400 kg/ha. There were no growth responses to magnesium addition in the trial but in an adjacent area of the stand, which had been operationally treated with magnesium (coarse-ground calcined magnesite at 200 kg Mg/ha) in 1984–85, there was a 5% response in dbh to magnesium addition. In the trial, strong positive correlations were found between tree growth measurements and needle retention, indicating that the needle-cast fungus *Cyclaneusma minus* (Butin) DiCosmo *et al*. may have been the most important influence on tree growth.

Where dolomite had been added at 150 and 400 kg Mg/ha, and kieserite at 55 kg Mg/ha, foliar magnesium concentrations were still elevated nearly 10 years after addition. Dolomite added at 400 kg Mg/ha maintained high amounts of soil exchangeable

New Zealand Journal of Forestry Science 31(1): 34–50 (2001)

magnesium in the top 20 cm and acid-extractable magnesium in the 0–10 cm depth while reducing the soil exchangeable potassium/magnesium ratio (both depths) after 10 years. High UMCY values were associated with low foliar and soil exchangeable magnesium and high foliar and soil exchangeable potassium/magnesium ratios. The latter relationships may be developed into useful diagnostics tools for the future identification of resistant genotypes and high-risk sites.

It was concluded that the stand studied in Tauhara Forest was at "medium" risk for UMCY development by age 14 years and a future reassessment of the site may provide stronger relationships between UMCY and soil and foliar chemical characteristics.

Keywords: magnesium; fertiliser; foliar potassium/magnesium ratio; soil exchangeable magnesium; acid-extractable magnesium; soil exchangeable potassium/magnesium ratio; dolomite; calcined magnesite; Epsom salts; kieserite; serpentine.

INTRODUCTION

Since the early 1980s Upper Mid-Crown Yellowing (UMCY) has been increasingly observed in *P. radiata* of mid-rotation age throughout New Zealand (Beets *et al.* 1993). This disorder occurs in the sub-apical zone and is typified by the yellowing of needles followed by premature needle loss leading to crown thinning, twig die-back, and, in its most severe form, the death of branches (Forest Research Institute 1991). Because of the loss of needles as UMCY progresses, it was hypothesised that tree growth would decline as the severity of UMCY increased (Forest Research, unpubl. data). Recent research has confirmed this. Beets & Jokela (1994) found that healthy *P. radiata* clones were larger in mean diameter than clones with severe UMCY. At Puruki, an experimental catchment in the central North Island 50 km from the study site, the loss of dry matter production in UMCY-affected *P. radiata* trees was attributed to a reduction in volume and wood density (P. Beets, unpubl. data)

Research has indicated that UMCY is a symptom of magnesium deficiency in older trees as a result of poor magnesium accumulation in the upper crown (Beets & Jokela 1994). Previous research in New Zealand has demonstrated the positive effects of applying magnesium fertiliser to young *P. radiata* with visual symptoms of magnesium deficiency. The addition of magnesium fertiliser elevated foliar magnesium concentrations (Hunter 1996; Payn 1991) and improved tree growth (Forest Research, unpubl. data). To justify the installation of a nationwide series of trials to identify the optimum rate of magnesium fertiliser addition and the effect of applying magnesium fertiliser to prevent or cure UMCY, it was necessary to confirm that the application of magnesium fertiliser to a young stand could prevent UMCY development later and cure UMCY already present in older stands.

In 1993, magnesium trials and areas operationally treated with magnesium in the central North Island, a region of volcanic soils low in available magnesium for *P. radiata* growth (Will 1985; Hunter *et al.* 1991; Payn 1991), were visited to evaluate their usefulness for studying the effect of historical magnesium addition on current UMCY development. The trial described in this paper, located in Tauhara Forest, was selected because it was in a stand of *P. radiata* of mid-rotation age exhibiting a range of UMCY symptoms, and it had received a range of magnesium fertilisers at varying rates when young. Previous studies at this trial had included regular measurement, foliage sampling, visual assessment of magnesium deficiency symptoms when young, and periodic soil sampling to determine exchangeable and acid-extractable magnesium.

The objectives of this study were to test the hypotheses that (1) magnesium fertiliser applied to a young stand of *P. radiata* exhibiting magnesium deficiency symptoms would reduce the incidence and severity of UMCY by mid-rotation, and (2) there was a link between symptoms of magnesium deficiency when the stand was young and UMCY at mid-rotation age. This paper also describes a comparison between two adjacent areas in Tauhara Forest, one of which had been operationally treated with magnesium. This provided a further opportunity to assess the effect that magnesium fertiliser addition to a young stand had on UMCY and tree growth later in the rotation.

METHODS

Tauhara Magnesium Fertiliser Trial

Trial site and design details

Tauhara Forest is located in the central North Island of New Zealand and the trial was located in Stand 2 of Compartment 49 (lat.38°40´S, long.176°13´E). Details of the site history and trial design have been given by Hunter (1996). In brief, *P. radiata* seedlings were planted on this ex-pasture site in 1979. The trial was established in 1984 when magnesium fertiliser treatments were applied to main plots with pruning (i.e., pruned or unpruned) used as a split-plot treatment. The main section of the trial consisted of rates of dolomite ($CaCO_3.MgCO_3$, 11% Mg) added at 0, 20, 55, 150, and 400 kg Mg/ha. These treatments were replicated twice and are referred to as Dol0, Dol20, Dol55, Dol150, and Dol400. An additional two replicates of the 0 and 55 kg rates of dolomite were installed with a total grass control treatment. There was also a series of magnesium fertiliser types added at 55 kg Mg/ha and replicated twice in an area beside the main trial. These included kieserite ($MgSO_4.H_2O$, 17% Mg), serpentine ($Mg_6Si_4O_{10}(OH)_{8,}$ 20% Mg), two grades of calcined magnesite (MgO, 55% Mg) referred to as “causmag” (coarse-ground) and “calmag” (fine-ground), and Epsom salts ($MgSO_4.7H_2O$, 10% Mg).

The stocking rate at establishment was 1500 stems/ha. The area was thinned in 1983 to 500 stems/ha and again in 1989 to give a final stocking of approximately 280 stems/ha.

Historical measurement, assessment, and sampling

The effects of the magnesium fertiliser, pruning, and weed control treatments on tree height and basal area from 1985 to 1989, foliage analysis from 1985 to 1990, and soil sampling in 1984 (prior to fertiliser addition) and 1989 have been described and discussed by Hunter (1996).

Hunter (1996) did not include historical health score data but they were considered very relevant to this current study. The health scores were a subjective assessment of the degree of needle chlorosis which is a symptom of magnesium deficiency (Will 1966). The trial was assessed in 1984 (prior to fertiliser addition) and again in 1985, and was scored as follows: 1 = needles green and healthy, 2 = some yellowing, 3 = severe yellowing, and 4 = dead brown needle tips.

Measurement, assessment, and sampling in 1993 and 1994

In 1993, each tree was measured for diameter (at breast height, dbh) and height. In September 1993, each tree in the trial was visually assessed, and scored for UMCY using the severity classes described by Beets & Jokela (1994). Two people scored the trees from the ground and agreed on a single score for each tree. Binoculars were used to confirm the presence or absence of yellowing in the sub-apical needles.

Of a total of 461 live trees, 416 trees in the trial were scored for UMCY. Trees were not scored if their upper crown was missing (“no top”) or if they exhibited severe symptoms of Cyclaneusma needle-cast (as noted by Beets *et al.* 1997). Data relating to the unscored trees were not included in the data analysis. For statistical analysis, the UMCY score of each individual tree was assigned a numeric value ranging from 1 (for A+ trees) to 5 (for C+ trees) as described by Beets & Jokela (1994).

Needle retention (NR) in the lower half of the crown, a reflection of the effect of Cyclaneusma needle-cast, was assessed from the ground using the following scores: 0 = no needles, 1 = predominantly 1-year-old needles present, 2 = 2-year-old needles present, and 3 = 3-year-old needles present.

Autumn foliage samples were taken in February 1994 from seven trees in each sub-plot of the trial. The samples were dried (65°C), ground (1 mm), and analysed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and boron (B) using the standard methods described by Nicholson (1984).

In February 1994, soil samples were taken from both replicates of the following treatments: 0, 55, and 400 kg Mg/ha added as dolomite, and the serpentine, fine-ground calcined magnesite, and Epsom salts treatments where magnesium had been added at 55 kg/ha. Within each selected fertiliser main plot, a bulk soil sample of 10 randomly sampled cores was taken from two depths, 0 to 10 and 10 to 20 cm. The soil samples were air-dried, sieved (<2 mm), and stored prior to analysis for exchangeable potassium and magnesium (NH_4OAc @ pH 7.0 method) as described by Nicholson (1984). Acid-extractable magnesium was measured using the method described by Payn (1991) which was based on methods described by Adams (1973) and Metson (1968).

Statistics

The individual tree data for UMCY value and the measurements of dbh and height were subject to Generalised Linear Modelling (GLM). The analysis included 12 magnesium treatments, which were combinations of magnesium fertiliser and weed control (control, control+WC, Dol20, Dol55, Dol55+WC, Dol150, Dol400, calmag, serpentine, kieserite, causmag, and Epsom salts), two rates of pruning, and the interaction between magnesium treatments and pruning. The analysis of the UMCY value included the 1984 Health Score as a covariate.

Where the effect of the treatments had been significant, Duncan’s Multiple Range Test was used to compare means at a confidence level of 0.05.

Spearman correlation coefficients (r) were calculated. Relationships between 1984 health score, 1993 UMCY value, 1993 needle retention scores, and the 1993 measurements of dbh and height were investigated for two sets of individual tree data from the control plots only and from all plots.

The foliage data were subject to analysis of variance (ANOVA). A split-plot ANOVA was used to test the differences between the 12 combinations of magnesium fertiliser and weed control previously described. The soils data were subject to a similar statistical analysis based on the six treatments that were sampled. The Duncan's Multiple Range Test was used to compare means at a confidence level of 0.05.

Spearman correlation coefficients (r) were used to identify significant relationships between UMCY value, foliage data, and soil data.

Operational Magnesium Addition at Tauhara

During 1984 and 1985, 77.2 ha of *P. radiata* in Stand 2 of Compartment 49 in Tauhara Forest were operationally treated with coarse-ground calcined magnesite (55% magnesium) at a rate of 200 kg Mg/ha. An area of approximately 15 ha, including the 5 ha occupied by the Tauhara magnesium fertiliser trial and 10 ha located south of the trial, was not treated. Tree establishment and silvicultural treatments in the stand were the same as described for the Tauhara magnesium fertiliser trial. The terrain in Stand 2 was slightly rolling and the undergrowth consisted of rank pasture.

A map, drawn in June 1983, was used to locate the boundary between the operationally treated and untreated areas. In December 1993, 10 pairs of circular plots (0.08 ha each) were installed. The plot size was calculated to contain approximately 20 trees, assuming a stocking rate of 300 stems/ha. One plot of each pair was installed in the untreated area (directly behind the Tauhara magnesium fertiliser trial) with the centre of each plot located on a 50 × 50-m grid. The other plot from each pair was located directly opposite in the treated area in the same way. The distance between the two groups of plots, in each area, was 68 m from plot edge to edge, or 100 m between the plot centres. It was assumed that this distance would be sufficient to ensure that the plots were located in the respective areas (untreated or treated) while maintaining similarities in topography and soil type.

The number of trees per measurement plot ranged from 12 to 25 with a mean of 23, which was equivalent to a stocking rate of 280 stems/ha.

Tree measurements and assessments

In mid-December 1993, the individual trees in each plot were measured for dbh, height, and length of the green crown, and assessed for UMCY and needle retention. Each UMCY score was subsequently converted to an UMCY value for statistical analysis.

Statistics

Data were subjected to ANOVA. The effects of magnesium addition on tree height, dbh, length of the green crown, UMCY value, and needle retention were examined.

Spearman correlation coefficients (r) were calculated for treated and untreated trees separately to identify relationships between UMCY value and tree growth measurements of dbh and height.

RESULTS

Effect of Magnesium Fertiliser Addition in the Tauhara Magnesium Fertiliser Trial

Tree growth

Based on the analysis of the 1993 individual tree data, mean dbh was 38 cm (range of 19 to 54 cm) and mean tree height was 19.6 m (13.3 to 23.3 m). The model of magnesium treatment and pruning explained only a small proportion (approximately 8%) of the variation in the 1993 growth data. While the magnesium fertiliser treatments (rates of dolomite, including the treatments with weed control, and different magnesium fertiliser types) had a weak affect on dbh ($p = 0.045$), the resulting means were not significantly ($p < 0.05$) different from the control.

UMCY

Of the total 416 trees scored for UMCY in the Tauhara magnesium fertiliser trial, 27% had an A+ UMCY score, 49% were A–, 18% were B+, 4% were B–, and 2% had a C+ score.

The application of the magnesium fertiliser treatments had a significant affect ($p < 0.001$) on the UMCY value (Fig. 1). Apart from Dol55, all of the magnesium fertiliser additions reduced the UMCY value compared to the control. The addition of dolomite at 150 or 400 kg Mg/ha resulted in the lowest UMCY values of 1.74 and 1.60, respectively, which were significantly lower ($p < 0.05$) than the value of 2.55 in the control.

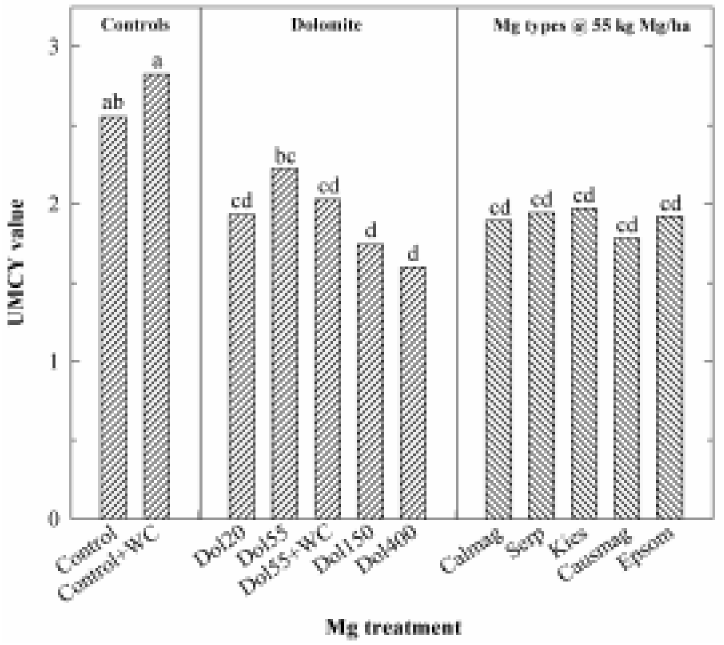

FIG. 1–Magnesium fertiliser reduced the UMCY value, assessed for 14-year-old *Pinus radiata*, 10 years after addition (Tauhara trial).

The effect of applying high rates of magnesium, as dolomite, was further highlighted by the distribution of UMCY scores (Fig. 2). An increase in magnesium rate shifted the peak of the UMCY score distribution to the left. The majority (75%) of trees in the control had an UMCY score of A– to B+ and only 9.7% of the trees exhibited no UMCY symptoms (i.e., were A+ trees). The addition of 150 kg Mg/ha resulted in 55% of the trees having an A– score and 36% with no UMCY. The majority (51%) of trees in the 400 kg Mg/ha treatment had no UMCY. In the 150 and 400 kg Mg/ha, the highest UMCY score was a B+ compared to a C+ in the control.

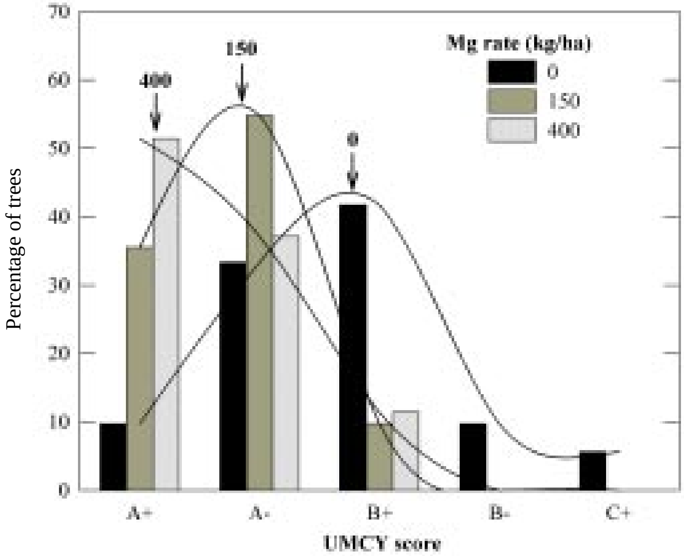

FIG. 2–Dolomitic magnesium addition affected the distribution of UMCY scores, assessed for 14-year-old *P. radiata*, 10 years after addition (Tauhara trial).

In the control plots, the correlation between the 1993 UMCY values and the 1984 health scores was weakly significant (n=71, r = 0.22, p = 0.065). Higher health scores (i.e., more needle chlorosis) were associated with higher UMCY values. Across the trial, the UMCY value was also positively correlated with 1993 tree height (n =409, r = 0.18, p < 0.001) and dbh (n = 409, r = 0.11, p = 0.029). These results suggested that larger trees, particularly taller ones, had higher UMCY values.

The magnesium fertiliser additions in 1984 did not significantly affect the 1985 health scores (mean of 1.8).

Needle retention

Only 7% of the trees had needles that were 3 or more years old (i.e., had a NR score of 3). The majority of trees had 1-year-old needles or younger in the lower half of the crown — 38% had a NR score of 0 and 30% scored 1. The magnesium fertiliser additions in 1984 did not significantly affect needle retention (mean of 1.0).

There were significant correlations between needle retention and the 1993 measurements of tree height (n = 409, r = 0.17, p < 0.001) and dbh (n = 409, r = 0.41, p < 0.001). High needle retention was associated particularly with the larger diameter trees.

Foliar nutrients

According to the standard values of Will (1985), the foliar nutrient concentrations were generally satisfactory with nitrogen being slightly marginal in some treatments (Table 1). The foliar concentrations of phosphorus (mean of 0.21%), potassium (Table 1), and calcium (0.26%) were all reasonably high, and boron (13 µg/g) was satisfactory.

TABLE 1–Effect of magnesium addition as (a) dolomite (excluding weed control plots) and (b) magnesium fertiliser types on 1994 foliar nutrient concentrations and potassium/magnesium ratio in the Tauhara Forest magnesium fertiliser trial. (For each nutrient, means followed by the same letter were not significantly different at $p<0.05$. Bolded means were significantly greater than the control while shaded means were less.)

a) Nutrient (%)	Mg rate (kg/ha) as dolomite 0	20	55	150	400
N	1.58 a	1.52 ab	1.43 cd	1.47 bcd	1.42 d
Mg	0.108 de	0.121 bcd	0.120 bcde	**0.132 ab**	**0.141 a**
K	1.06 a	1.04 a	0.98 a	1.01 a	0.85 b
K/Mg	9.8 a	8.8 abc	8.2 bc	7.7 c	6.1 d

b) Nutrient (%)	Mg fertiliser type (@ 55 kg Mg/ha) Calmag	Causmag	Epsom	Kieserite	Serp
N	1.45 bcd	1.52 abc	1.50 abcd	1.48 bcd	1.49 bcd
Mg	0.107 e	0.117 cde	0.117 cde	**0.122 bc**	0.110 cde

A number of the magnesium fertiliser treatments affected foliar nutrient concentrations nearly 10 years after addition. The treatments which resulted in significantly higher foliar magnesium concentrations were Dol150, Dol400, and kieserite (Table 1a). The foliar potassium/magnesium ratio decreased with increasing dolomite addition. At 55, 150, and 400 kg Mg/ha rates the ratios were significantly lower than in the control (Table 1a).

Foliar nitrogen concentrations were lower where dolomite had been added at 55, 150, or 400 kg Mg/ha and in the calmag, serpentine, and kieserite treatments. The foliar potassium concentration in the Dol400 treatment was significantly lower than the other dolomite treatments.

An increase in foliar magnesium concentration was associated with a decrease in the UMCY value ($n = 48$, $r = -0.39$, $p = 0.007$). As the foliar potassium/magnesium ratio increased, the UMCY value increased ($n = 48$, $r = 0.33$, $p = 0.023$).

Soil cations

After 10 years, the effect of magnesium fertiliser addition on the soil exchangeable magnesium concentration was still evident and significant ($p < 0.001$). The Dol400 treatment was particularly effective in maintaining high amounts of exchangeable magnesium at both soil depths (Table 2) while Dol55 had higher amounts at 0–10 cm. While magnesium fertiliser treatment was not a significant ($p=0.12$) factor in the analysis of the acid-extractable magnesium data, the amount of acid-extractable magnesium in soils treated with Dol400 and serpentine was significantly higher than the control at a depth of 0–10 cm (Table 2).

Although magnesium fertiliser addition had no significant effect on soil exchangeable potassium, the soil exchangeable potassium/magnesium ratio was affected by the magnesium fertiliser treatments ($p<0.001$). The addition of Dol55, and particularly Dol400, significantly reduced the exchangeable soil potassium/magnesium ratio in both depths of soil (Table 2). At a depth of 10–20 cm, the exchangeable potassium/magnesium ratio for the Epsom salts treatment was significantly lower than in the control (1.8 *vs* 3.2).

TABLE 2–Effect of magnesium addition on exchangeable and acid-extractable magnesium, exchangeable calcium, and the exchangeable potassium/magnesium ratio in soil samples taken from the Tauhara Forest magnesium fertiliser trial in 1994. (For each nutrient, means followed by the same letter were not significantly different at $p<0.05$. Bolded means were significantly greater than the control while shaded means were less.)

Variable	Depth (cm)	Control	Dolomite (kg Mg/ha)		Serp	Causmag	Epsom
					----------	(kg Mg/ha)	------------
		0	55	400	55	55	55
Exch Mg	0–10	0.19 de	**0.70 b**	**2.50 a**	0.29 de	0.28 de	0.33 cd
($\text{cmol}_{(+)}$/kg)	10–20	0.05 e	0.10 de	**0.58 bc**	0.08 de	0.08 de	0.10 de
Acid-ex Mg	0–10	1.54 cde	2.66 bc	**4.13 a**	**3.08 ab**	2.29 bcde	2.50 bcd
($\text{cmol}_{(+)}$/kg)	10–20	1.76 bcde	2.25 bcde	1.67 cde	1.17 de	1.72 bcde	1.03 e
Exch K/Mg	0–10	1.77 cd	0.52 ef	0.13 f	1.3 de	1.09 def	1.08 def
	10–20	3.2 a	2.08 bcd	0.29 ef	2.80 abc	3.01 ab	1.84 cd

A decrease in the UMCY value was associated with an increase in exchangeable magnesium at a depth of 0 to 10 cm (Fig. 3). The significance of this relationship depended on the Dol400 data points which represented high exchangeable soil magnesium and low UMCY values. The remaining data points were scattered. An increase in the soil exchangeable potassium/magnesium ratio (0 to 10 cm) was associated with an increase in the UMCY value (Fig. 3). In this relationship there was a better spread of data points along the X axis. However, the relationship between UMCY value and acid-extractable magnesium was not significant.

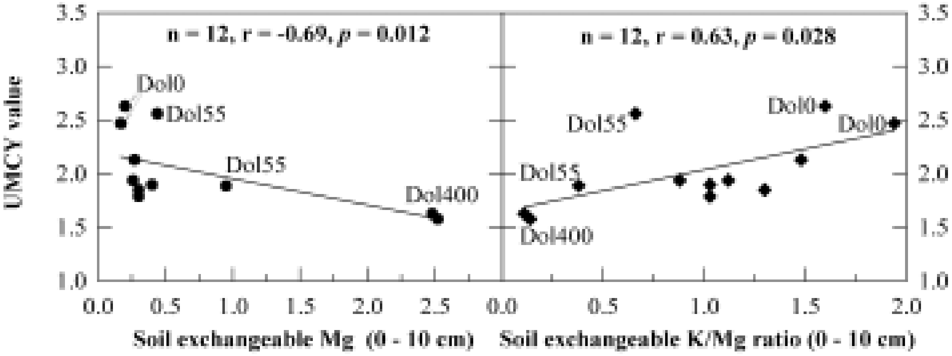

FIG. 3–Relationships between UMCY value and soil exchangeable potassium/magnesium and exchangeable potassium/magnesium ratio (Tauhara trial).

The foliar magnesium concentration was positively correlated with the amount of soil exchangeable magnesium from both soil depths, and acid-extractable magnesium in the 0 to 10 cm depth (Fig. 4a). There were some strong negative relationships between foliar magnesium concentrations and the soil exchangeable potassium/magnesium ratio (Fig. 4b).

The foliar potassium/magnesium ratio was highly correlated with the soil exchangeable potassium/magnesium ratio from both depths of soil (Fig. 5). The soil exchangeable

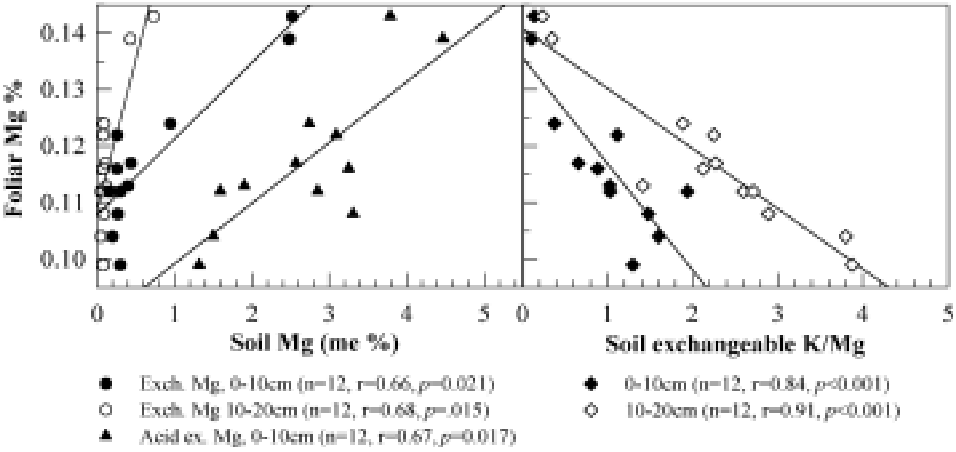

FIG. 4–Relationships between foliar magnesium concentrations and soil magnesium and soil exchangeable potassium/magnesium ratio (Tauhara trial).

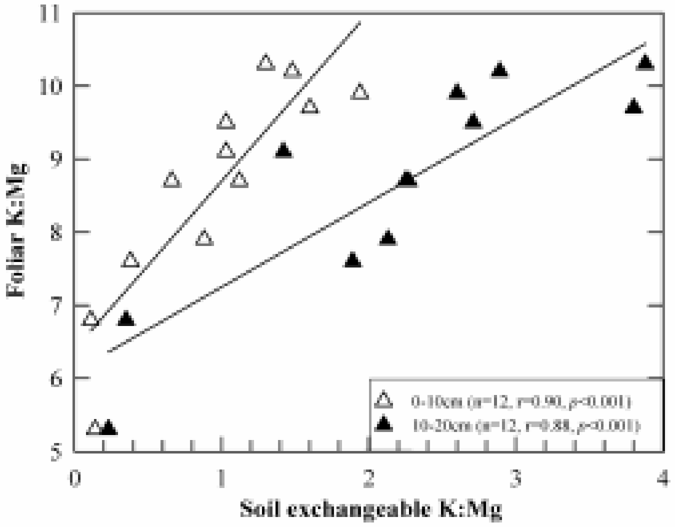

FIG. 5–Relationship between foliar potassium/magnesium ratio and soil exchangeable potassium/magnesium ratio (Tauhara trial).

potassium/magnesium ratios were higher in the 10 to 20 cm depth of soil because exchangeable magnesium was about $^1/_4$ of the amount in the 0 to 10 cm depth (0.17 *vs* 0.71 cmol(+)/kg) while exchangeable potassium was approximately $^2/_3$ the amount (0.20 *vs* 0.3 cmol(+)/kg).

Operational Magnesium Fertiliser Treatment at Tauhara

Tree growth

The addition of magnesium did not affect tree height (mean of 19.4 m), or the length of the green crown (mean of 12.7 m), but significantly (p = 0.003) affected the 1994 dbh measurement. Treated trees had a mean dbh of 39 cm compared to 37 cm for the untreated trees. This difference represented a 5% increase in dbh for the magnesium-treated trees.

UMCY

Of the total 403 trees within the measurement plots (208 in the untreated plots and 195 in the treated plots), 334 were scored for UMCY, 46 had severe Cyclaneusma needle-cast, 14 had leader damage, and nine trees could not be scored for other reasons (e.g., significant stem loss or severe lean).

The operational addition of magnesium significantly ($p < 0.001$) affected the UMCY value which decreased from a mean of 3.5 in the untreated area, to 2.3 where magnesium fertiliser had been applied. The distribution of UMCY scores indicated that most (53%) of the magnesium-treated trees had an UMCY score of A– while most of the scores for the untreated trees were spread across the A– to C+ categories (Fig. 6). Of the trees scored for UMCY, 19% of the magnesium-treated trees had no UMCY symptoms compared to 4% for the untreated trees. The highest UMCY scores were a C– in the treated trees and a D+ in the untreated trees.

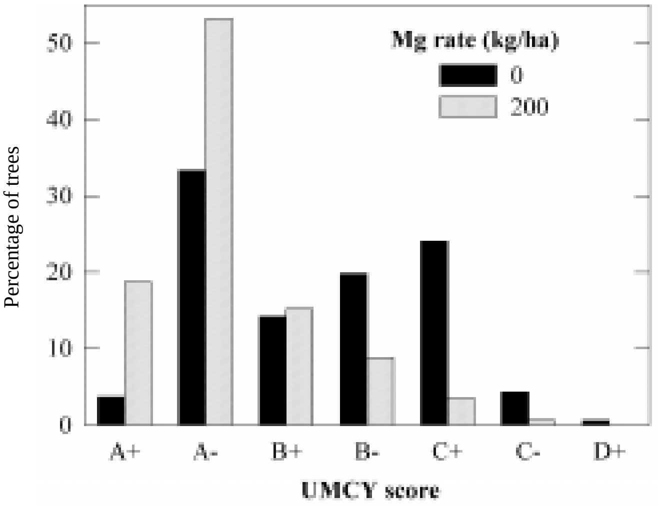

FIG. 6–Magnesium fertiliser affected the distribution of UMCY scores, assessed for 14-year-old *P. radiata*, 9 years after operational addition in Tauhara Forest.

In the untreated stand there were positive relationships between the UMCY value and tree height ($n = 163$, $r = 0.21$, $p = 0.007$), length of green crown ($n = 163$, $r = 0.18$, $p = 0.02$), and needle retention ($n = 163$, $r = 0.21$, $p = 0.007$). Taller trees with larger foliar crowns had higher UMCY values. These relationships were not significant for the trees receiving magnesium fertiliser.

The addition of magnesium did not significantly affect needle retention score in the lower half of the crown (mean of 2.0).

DISCUSSION

Relationships Between Magnesium Addition, UMCY, Cyclaneusma Needle-cast, and Tree Growth

An UMCY-affected tree does not reach its potential size because the foliage mass of UMCY-affected trees is less than that of healthy trees (Forest Research, unpubl. data). Beets & Pollock (1987) reported that leaf area index was correlated with above-ground production and mean dbh increased with leaf weights in *P. radiata*. It has also been found that magnesium-deficient needles have a reduced photosynthetic ability (Sun & Payn 1999).

The measurement of the Tauhara trial in 1993 did not identify any positive effect of the magnesium fertilisers on tree growth. Because of the presence of UMCY, and the reduction in its incidence and severity where magnesium fertiliser had been applied, it was expected that there may have been a growth response to magnesium. Other factors such as the presence of Cyclaneusma needle-cast, which was observed in the stand in 1993, may have had an overriding affect on tree growth as the trees aged at Tauhara. Cyclaneusma typically affects the 1-year-old foliage of trees aged 11 to 20 years and trees are usually resistant after about 15 years (Bulman 1993). In the Tauhara trial, the correlation between needle retention, a subjective assessment of the effect of Cyclaneusma in causing needle cast, and dbh measurement in 1993 was quite strong. Those trees with a high needle retention had larger dbh measurements. Bulman (1993) found a volume difference of 100 m^3/ha between 15-year-old healthy and Cyclaneusma-affected trees in Kaingaroa Forest.

As needle retention was not affected by the application of magnesium in the Tauhara trial, the effect of Cyclaneusma needle-cast in reducing the foliage mass in the tree crown, and therefore growth, may have masked the positive effect of the magnesium fertilisers. Once the effect of Cyclaneusma has passed, the relationship between UMCY and tree growth may become increasingly significant. It is anticipated that a re-measurement of the Tauhara magnesium fertiliser trial would show a positive effect of magnesium fertiliser on tree growth if UMCY symptoms were to worsen in the control plots and plots with low rates of magnesium addition.

In New Zealand there have been several reports of magnesium fertiliser addition promoting tree growth in young stands of *P. radiata* suffering from severe magnesium deficiency (Hunter *et al.* 1986; Hunter 1996). The growth response was an increase in dbh which occurred during the 3 to 4 years following application and may been a result of the improved photosynthetic capacity of the foliage (Sun & Payn 1999) and/or an increase in needle size (T. Payn, unpubl. data). In young trees, the above-ground response to added magnesium can occur quickly (Will 1966) but in trees of mid-rotation age transient growth responses to magnesium have been noted (Woollons & Will 1975). In the Tauhara trial, Hunter (1996) found that the addition of magnesium (55 kg/ha) as Epsom salts, kieserite, or coarsely ground calcined magnesite significantly and consistently increased basal area from 1985 to 1989.

In forest stands, identifying relationships between UMCY severity and tree growth has been difficult because it depends on the proportion of trees with a high UMCY score in the stand and the longevity of severe symptoms. In the early stages, UMCY development appears to be associated with the faster growing trees and therefore the correlations between UMCY value and tree growth, particularly height, are positive. Because this relationship was found in the Tauhara trial, in the untreated trees in the operational area at Tauhara, and also in an untreated stand in southern Kaingaroa Forest (Forest Research, unpubl. data) it was hypothesised that the fastest growing young trees were more likely to develop UMCY because their demand for magnesium was greater than the soil supply and/or they had difficulties in transporting enough magnesium to the upper crown. When these trees progressed to severe UMCY symptoms (i.e., D class with the death of a number of whorls) the rate of annual diameter increment would be significantly reduced compared to healthy trees. In contrast, the initially smaller healthy trees would maintain their dbh increments and, at some point during the latter part of the rotation, would overtake the UMCY-affected trees in diameter size. Recent research at Puruki has confirmed that trees with severe UMCY symptoms (i.e., D class) have reduced current annual increments, at age 22, compared to unaffected trees of similar height (Forest Research, unpubl. data) and the difference was expected to increase as the stand aged. This relationship was not found in the Tauhara trial because the stand did not have trees severely affected by UMCY at age 14.

The operational addition of magnesium fertiliser at Tauhara did promote diameter growth. Without a history of measurements and assessments it is not possible to ascertain when this occurred. As this stand was the same age as the Tauhara trial, and UMCY had not yet affected growth, the increase in diameter was due to a positive effect of the added magnesium on the young trees (i.e., improved photosynthetic capacity and needle size) which were suffering from magnesium deficiency.

Magnesium Fertiliser Addition can Reduce UMCY

This study confirmed that magnesium fertiliser addition to a young *P. radiata* stand, exhibiting magnesium deficiency symptoms and with low foliar magnesium concentrations, can reduce both the incidence and severity of UMCY later in the rotation. This was highlighted by the distribution of UMCY scores in the trial (Fig. 2) and in the operational area (Fig. 6). At Tauhara, the minimum rate of magnesium required to substantially reduce UMCY was between 100 and 200 kg/ha (Table 1). In 1993, the application of Dol400 had not further reduced UMCY compared to Dol150, although Dol400 may have a greater long-term effect in maintaining low UMCY values because this treatment sustained foliar magnesium concentrations and soil magnesium above the control levels.

By comparison, in a study conducted in Kaingaroa Forest, magnesium fertiliser (dolomite at 25 kg Mg/ha) was applied to a 5-year-old stand of extremely magnesium deficient *P. radiata* which had foliar magnesium concentrations of 0.03%. By age 20, the UMCY value was 2.3 but in an adjacent non-treated stand it was 4.6 (Forest Research, unpubl. data). In this situation of severe magnesium deficiency on a site at high risk from UMCY development, a relatively small amount of magnesium had a large affect in reducing UMCY.

Pinus radiata stands can recover from UMCY. During the scoring of UMCY in the Tauhara trial, there was evidence that 10 magnesium-treated trees had recovered from UMCY as the trees had both a low current UMCY score (predominantly an A–) in the sub-apical zone and an historically worse UMCY score (B– to C+) below this zone. The trees recovering from UMCY were located in a range of treatments where different types of magnesium had been added at rates from 20 to 150 kg/ha. No recovery from UMCY was observed in the 400 kg Mg/ha or control treatment. These results suggest that rates of magnesium addition less than 400 kg/ha have taken longer to promote the magnesium status of the upper crown at this site. As only a small proportion of trees behaved this way, there may also be genetic considerations relating to the ability of the trees to access magnesium from the soil and transport it to the upper crown.

High Magnesium Fertiliser Additions can Elevate Foliar and Soil Magnesium in the Long Term

A number of the magnesium fertiliser treatments elevated foliar magnesium concentrations and reduced foliar potassium/magnesium ratios nearly 10 years after their addition (Table 1). The rate of dolomite required was at least 150 kg Mg/ha. If magnesium addition elevates foliar magnesium concentrations, then the magnesium status of the upper crown has been improved and UMCY severity is likely to be reduced. The longevity of the beneficial effect of added magnesium is unknown and may depend on the type of fertiliser applied (i.e., slow- or quick-release) and the rate of addition. Other factors that may influence magnesium fertiliser dissolution include rainfall, native soil exchangeable magnesium, and the percentage magnesium saturation of the soil exchange (Mitchell 2000), indicating that soil type may affect the time required for added magnesium to have a significant impact on the soil exchangeable magnesium and potassium/magnesium ratio. At Tauhara, to sustain elevated exchangeable and acid-extractable magnesium in the soil and maintain satisfactory foliar magnesium concentrations for more than 10 years, a single application of a high rate of magnesium, such as Dol400, or a second application at lower rates may be required.

Kieserite was the only magnesium fertiliser applied at 55 kg Mg/ha which maintained foliar magnesium concentrations above the control 10 years after application. Kieserite is used when magnesium is required rapidly (Mengel & Kirkby 1987) and in the field is only slightly less soluble than Epsom salts (Andrew Mitchell, unpubl. data) resulting in a rapid increase in extractable magnesium (Heming & Hollis 1995). It was therefore surprising that this quick-release magnesium fertiliser could have a long-term benefit. There were no accompanying data to verify the effect of kieserite on soil magnesium.

Identifying Relationships Between UMCY and Foliage and Soil Nutrient Data

The key to managing UMCY in the future will be based on (a) the ability to identify sites at high risk for UMCY development, (b) the application of magnesium fertilisers to existing stands at high risk from UMCY or with visual symptoms of magnesium deficiency or UMCY, and (c) identifying *P. radiata* genotypes resistant to UMCY for the planting of new stands.

Detecting resistant genotypes would require the identification of links between UMCY in older trees and characteristics such as visual magnesium deficiency symptoms, foliar magnesium, or potassium/magnesium ratios, etc., in young trees of the same genotype. In the Tauhara trial, the 1984 health scores were only weakly related to UMCY in the same trees in the control plots. This may have been due an inadequate scoring system being used to describe “health”. Because UMCY is thought to be a form of magnesium deficiency in older trees, a link between early visual symptoms of magnesium deficiency (i.e., needle yellowing) and UMCY is believed to exist.

At Tauhara, there was a positive relationship between foliar magnesium and UMCY value but the data were variable and therefore did not provide any useful guidelines. Beets & Jokela (1994) found that UMCY tended to be more severe in trees with low foliar magnesium, and clones with foliar magnesium concentrations above 0.10% did not have UMCY. In the Tauhara trial, the concentration of foliar magnesium in the control plots was 0.11% (Table 1) which was satisfactory. In this study, the use of bulk foliage samples and mean UMCY values per plot, as well as the underlying genetic variation, did not assist in the identification of strong relationships on a site that may be considered at “medium” risk from UMCY.

Recent research into the link between foliar nutrients and UMCY suggests that the ratio between potassium and magnesium may be more important in determining the development of UMCY (Beets & Jokela 1994). Current foliar recommendations suggest that if foliar potassium/magnesium ratios are above 10, UMCY either will be present or is likely to develop, depending on the age of the stand when it was sampled (Forest Nutrition Laboratory, Forest Research, pers. comm.). At Tauhara, the potassium/magnesium ratio in the control plot was 9.8 and the addition of Dol400 reduced it to 6.1 (Table 1). These ratios corresponded to a relatively small range in UMCY values of 2.6 and 1.6 respectively. While Tauhara Forest does have UMCY, the values were not severe enough, particularly in the control plots, to provide meaningful relationships between foliar nutrients and UMCY when based on plot means.

To identify sites with a high risk of UMCY, an assessment of the soil exchangeable potassium and magnesium may provide the best information. The results from the Tauhara trial identified relationships between soil exchangeable potassium/magnesium ratios and UMCY (Fig. 3) which were stronger than the relationships with foliar magnesium or foliar potassium/magnesium ratio. New planting sites with high soil exchangeable potassium/magnesium ratios may be at high risk from UMCY development in *P. radiata*. Identifying the critical range would require a larger data set from a wide range of New Zealand soils. Based on the data from the Tauhara trial, a soil exchangeable potassium/magnesium ratio greater than 1.5 (0–10 cm depth) was associated with UMCY values over 2 (Fig. 3), foliar magnesium concentrations less than 0.12% (Fig. 4), and foliar potassium/magnesium ratios of about 10 (Fig. 5). These relationships highlight the fact that UMCY development at Tauhara was not severe.

Excess potassium can interfere with magnesium uptake from the soil (Mengel & Kirkby 1987) and mobilisation from the roots to the shoots (Sun & Payn 1999). In the agricultural literature, the soil potassium/magnesium ratio has been more successful as an indicator of magnesium availability than the amount of exchangeable magnesium (Hagstrom 1992). In this study stronger relationships were found between foliar magnesium and the soil exchangeable potassium/magnesium ratio than with exchangeable or acid-extractable magnesium (Fig. 4). In New Zealand, high foliar potassium/magnesium ratios are likely on sites where the soil exchangeable potassium/magnesium ratio is high and high foliar magnesium in 1-year-old needles was found to be strongly related to the soil exchangeable potassium/magnesium ratio (P. Beets, unpubl. data). Lowe (1999) found that the potassium/magnesium ratio in *P. radiata* seedlings reflected the potassium/magnesium ratio of the nutrient solution they were grown in. Given these findings, there are good reasons for considering both soil magnesium and potassium in the development of UMCY because a measure of soil magnesium indicates how much magnesium is available for tree uptake while soil potassium supply may indicate how much of the magnesium taken up by the tree is available for transport to the foliage.

CONCLUSIONS

A young *P. radiata* stand suffering from visual magnesium deficiency symptoms and with low foliar magnesium concentrations can develop UMCY if the magnesium status is not improved by adding magnesium fertiliser. The studies at Tauhara found that the addition of magnesium fertiliser to a young stand significantly reduced the incidence and severity of the UMCY symptoms by age 14. At this site, the minimum effective rate of magnesium addition was 100 to 200 kg/ha.

In the Tauhara trial, the link between early health scores and UMCY was weak. An improved system for scoring magnesium deficiency based on the length of needle affected by yellowing has been developed and may be useful in identifying a relationship between magnesium deficiency in young trees and UMCY in older trees.

The level of UMCY development at Tauhara was not severe enough to reduce tree growth to any significant degree by age 14. Evidence suggested that the widespread presence of Cyclaneusma needle-cast in the stand had affected dbh growth and made the task of identifying possible relationships between UMCY and dbh difficult. A reassessment of the trial prior to harvest would identify stronger relationships between UMCY severity, magnesium fertiliser addition, and dbh measurements if trees with severe UMCY symptoms were compared to unaffected trees of similar height. The operational application of magnesium at Tauhara, in a stand adjacent to the experiment, improved dbh growth by 5% and was credited with the improvement of the magnesium status of the young trees.

Analysing foliage for magnesium and potassium could identify existing stands at high risk of developing UMCY where foliar magnesium concentrations are low and foliar potassium/magnesium ratios are above 10. Identifying “medium-risk” stands may be more difficult using foliage analysis. Where UMCY is a concern or already present in a stand, periodic scoring of visual symptoms in permanent sample plots should be used to develop a database for assessing UMCY development.

New planting sites with high soil exchangeable potassium/magnesium ratios are high-risk sites for UMCY development in *P. radiata*. While critical soil values have yet to be clearly defined, soils from the Dol400 treatment had a soil exchangeable potassium/magnesium ratio of 0.13 in the 0 to 10 cm depth.

ACKNOWLEDGMENTS

This work was carried out as part of the UMCY Research Programme which was funded by Carter Holt Harvey Forests Ltd, City Forests Ltd, Ernslaw One Ltd, Fernz Chemicals NZ Ltd, Fletcher Challenge Forests Ltd, Ministry of Agriculture and Forestry, Rayonier New Zealand Ltd, Timberlands West Coast Ltd, and Wenita Forest Products Ltd. The authors would like to thank the following people for their assistance: Doug Graham, Francis Groenendijk, Jessica Hunter-Smith, Andrew Mitchell, Jean Prince, and Liz Weatherby.

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