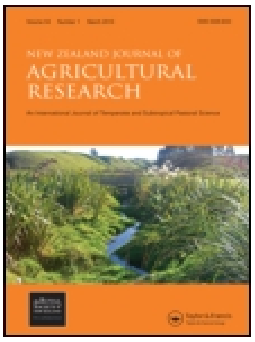

Taylor & Francis
Taylor & Francis Group

New Zealand Journal of Agricultural Research

ISSN: 0028-8233 (Print) 1175-8775 (Online) Journal homepage: http://www.tandfonline.com/loi/tnza20

Effect of serpentine rock and its acidulated products as magnesium fertilisers for pasture, compared with magnesium oxide and Epsom salts, on a Pumice Soil. 1. Dry matter yield and magnesium uptake

J. A. Hanly , P. Loganathan & L. D. Currie

New Zealand Journal of Agricultural Research, 2005, Vol. 48: 451–460
0028–8233/05/4804–0451

Effect of serpentine rock and its acidulated products as magnesium fertilisers for pasture, compared with magnesium oxide and Epsom salts, on a Pumice Soil. 1. Dry matter yield and magnesium uptake

J. A. HANLY
P. LOGANATHAN
L. D. CURRIE
Fertilizer and Lime Research Centre
Institute of Natural Resources
Massey University
Private Bag 11 222
Palmerston North, New Zealand
J.A.Hanly@massey.ac.nz

Abstract Low pasture magnesium (Mg) intakes by grazing dairy and beef cows is a main cause of hypomagnesaemia in these animals soon after calving. Magnesium fertiliser application to pasture can increase pasture mixed-herbage (hereafter "herbage") Mg concentration and reduce the risk of this disorder. However, the effectiveness of Mg fertilisers is variable depending on fertiliser type and soil properties. A 32-month Mg fertiliser field trial was conducted on dairy pasture on an Immature Orthic Pumice Soil (near Taupo, New Zealand; exchangeable Mg 0.4 $cmol_c\ kg^{-1}$, pasture Mg 0.13%) to compare the effectiveness of a range of Mg fertilisers in elevating herbage Mg concentration. The fertilisers used were ground serpentine rock, three acidulated serpentine rock products, Epsom salts, and E-mag (magnesium oxide). All fertilisers were applied at 100 kg Mg ha^{-1} at the start of the trial. The trial also had two treatments where Epsom salts was applied at 25 and 50 kg Mg ha^{-1} and a treatment where serpentine rock was reapplied during the second and third year at 100 kg Mg ha^{-1}. Magnesium fertiliser treatments did not affect pasture dry matter yield significantly at any harvest, however, the effect of treatments on herbage Mg concentration was highly significant ($P < 0.001$) at all harvests. The single application of serpentine significantly increased herbage Mg concentration at 10 harvests, with five of these harvests having Mg concentrations ≥0.20%, which is generally considered to be the minimum "threshold level" for stock health. In comparison, the Mg concentration in pasture not receiving Mg fertiliser remained below the minimum threshold level throughout the trial. Application of serpentine rock annually further increased herbage Mg concentration and accumulation. The herbage Mg concentrations for this treatment were similar to those of the Epsom salts (50 kg Mg ha^{-1}) treatment at the majority of the harvests. These results indicate that the annual application of serpentine rock may have potential as an alternative strategy to the application of more soluble Mg sources for raising herbage Mg concentration to levels considered adequate to meet stock health requirements. The more soluble Mg fertilisers—Epsom salts, the two serpentine-superphosphate products, and an acidulated serpentine rock plus reactive phosphate rock product—had the greatest effect on increasing herbage Mg concentration and accumulation. These treatments increased herbage Mg concentration to ≥0.20% within 3–6 months after application and for the majority of harvests over the rest of the trial period. The effect of E-mag on herbage Mg concentration was similar to that of serpentine rock during the first year, but the subsequent performance of E-mag was similar to the more soluble Mg fertilisers.

Keywords dairy pasture; fertiliser; hypomagnesaemia; magnesium; Pumice Soil; serpentine

INTRODUCTION

Magnesium (Mg) deficiency is a main cause of hypomagnesaemic grass tetany (hypomagnesaemia) that usually occurs in dairy and beef cows soon after calving, and less frequently in ewes pre- and post-lambing (Grace 1984). Hypomagnesaemia is a major cause of lower milk production affecting approximately 30–50% of dairy herds in the major dairying areas of New Zealand (O'Connor et al. 1987).

A05013; Online publication date 11 October 2005
Received 8 April 2005; accepted 1 September 2005

The incidence of hypomagnesaemia is associated with low concentrations of Mg in pastures and low feed intake. The lowest concentration of Mg in pasture in New Zealand typically occurs during spring (McNaught et al. 1968), the period of calving when stock requirements for Mg is greatest, increasing the risk of hypomagnesaemia.

Pasture mixed-herbage (hereafter "herbage") Mg concentration also depends on the concentrations of exchangeable soil Mg, calcium (Ca), and potassium (K) and is also influenced by soil pH. Pasture Mg uptake increases with increasing exchangeable soil Mg, but decreases with excessive levels of exchangeable Ca and K and with low soil pH due to competitive inhibition (Edmeades 2004). Nitrogen (N) fertiliser applications have also been shown to affect pasture herbage Mg concentration. McNaught et al. (1973) reported inconsistent effects of urea applications on pasture herbage Mg concentrations. Urea applications elevated herbage Mg concentrations in two of their experiments, but decreased Mg concentrations in a third experiment.

A survey of soil Mg status of New Zealand soils conducted in early 1970s by Metson (1974) showed that Mg deficiency was not common. However, due to an estimated annual net loss of Mg from soils not receiving Mg fertiliser, Metson (1974) predicted that there was an increased likelihood of Mg deficiency occurring in the future. Edmeades (2004) cited recent New Zealand data that confirmed a decline in soil Mg levels in New Zealand pastoral soils from the 1980s to 2000. This was due to continued inputs of Ca and K fertilisers and the removal of soil Mg via leaching and transfer in animal products without sufficient inputs of fertiliser Mg.

One method of increasing the pasture herbage Mg concentration is by regularly applying Mg fertilisers. Ground serpentine rock (23% Mg) has been used successfully on pasture as a Mg fertiliser when incorporated with superphosphate (serpentine-superphosphate) (McNaught & Ludecke 1967; McNaught et al. 1968). A trial by Chittenden et al. (1964) showed that serpentine rock also had potential for use as a Mg fertiliser on its own. Their results, however, were not convincing because they used only two replicates of each treatment, and fertiliser treatments were compared on a fertiliser weight basis rather than on a Mg content basis. Later trials on serpentine conducted by McNaught et al. (1973) showed minimal pasture Mg concentration response from ground serpentine application, probably because these trials were conducted on sites with soils not considered deficient in Mg. Also, serpentine dissolution may differ depending on its source. A 3-month soil incubation study, comparing five ground serpentine rocks sourced from different locations in New Zealand, showed that serpentine from Pio Pio, near Te Kuiti, had the highest rate of Mg dissolution (Loganathan et al. 2001).

A recent field trial in the Manawatu region of New Zealand on a Pallic Soil (yellow-grey earth soil) compared the effectiveness of a ground serpentine rock from Pio Pio and two acidulated serpentine products (5:1 and 5:2 w/w rock:H_2SO_4 acid ratios) with some commonly used Mg fertilisers. The application of this ground serpentine rock showed

Table 1 Chemical properties of the soil (0–7.5 cm depth) at the trial site prior to Mg treatment. CEC, cation exchange capacity.

	pH (1:2.5 soil:water)	Olsen P	Exchangeable cations ($cmol_c\ kg^{-1}$)				CEC ($cmol_c\ kg^{-1}$)
			K	Ca	Mg	Na	
Mean*	6.3	15	0.44	10.9	0.4 (5.3)[†]	0.06	18.9
SE	±0.05	±0.42	±0.68	±0.03	±0.82	±0.03	±0.002

*Mean of eight samples from the trial site. [†]Value in parenthesis is the equivalent Quick Test value calculated using a conversion factor (Cornforth & Sinclair 1984).

Table 2 Nutrient concentration in herbage at the trial site prior to Mg treatment.

	%N	%P	%K	%Ca	%Mg
Mean*	3.60	0.26	2.38	0.40	0.13
SE	±0.018	±0.003	±0.040	±0.008	±0.002

*Mean of 48 samples; one collected from each of the 48 plots of the trial site.

potential as a slow-release Mg source for increasing pasture Mg concentration (Loganathan et al. 2001). However, as with the McNaught et al. (1973) study, the soil at this trial site was not deficient in Mg (pasture mixed-herbage Mg 0.20–0.30%, exchangeable soil Mg 1.04 $cmol_c$ kg^{-1}) and, therefore, the trial could not convincingly evaluate the effectiveness of serpentine rock.

The objective of the study presented in this paper was to compare the effectiveness of serpentine rock and a range of other Mg fertilisers in elevating pasture herbage Mg concentration on a soil with low Mg status. The dissolution rates and estimated leaching of fertiliser Mg are presented in Loganathan et al. (2005 this issue).

MATERIALS AND METHODS

Trial site

The trial was conducted on a pastoral dairy farm (Porinui Station, Taupo; NZMS 260 U19/960450; 38.950°S, 176.267°E; altitude 750 m) in the central North Island of New Zealand. Annual rainfall for the area was 1430 mm in 2001, 1350 mm in 2002, and 1370 mm in 2003. Pasture herbage composition at the site was a mixed sward of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). The soil at the site was classified as an Immature Orthic Pumice Soil (Hewitt 1993; Typic Udivitrand in US soil taxonomy classification system). The chemical characteristics of the soil and nutrient concentration in herbage at the trial site (11 May 2001) prior to Mg treatment are presented in Tables 1 and 2, respectively. Soil and herbage Mg concentrations (see later section for sampling procedures) indicated that the trial site had low Mg levels prior to commencement of the study. The pasture at this site just prior to commencement of the trial had an average Mg concentration of 0.13%, on a dry weight basis, and an average soil exchangeable Mg concentration of 0.4 $cmol_c$ kg^{-1} soil (Quick Test value of 5.3; Cornforth & Sinclair 1984).

Fertilisers

The fertilisers used in the trial are shown in Table 3. The serpentine rock (a hydrated magnesium silicate) was obtained from a deposit at Pio Pio near Te Kuiti, New Zealand. It was ground to <500 μm and applied either on its own or as a mixture with an equal weight of lime. The serpentine rock-lime mixture is applied to soil by some New Zealand

Table 3 Magnesium and P concentrations and application rates of fertilisers.

Treatment names	Total Mg in fertilisers (%)	Water-soluble Mg in fertilisers (%)	Rate of Mg application (kg Mg ha^{-1})	Fertiliser P concentration (%)	P applied in Mg fertiliser (kg P ha^{-1})	P supplemented with "Super 10"* (kg P ha^{-1})
Control	0	0	0	0	0	140
Lime-control†	0	0	0	0	0	140
Epsom salts	10.3	10.0	25	0	0	140
Epsom salts	10.3	10.0	50	0	0	140
Epsom salts	10.3	10.0	100	0	0	140
Serp-super A	6.1	1.3	100	7.0	116	24
Serp-super B	4.7	3.1	100	6.6	140	0
ASRPR	4.2	4.0	100	5.1	121	19
E-Mag	57.3	0.4	100	0	0	140
Serpentine rock	23.1	0.1	100	0	0	140
Serpentine rock (annual application)	23.1	0.1	100	0	0	140
Serpentine rock:lime mix†	11.5	–	100	0	0	140

*"Super 10" superphosphate has a P content of 9.54%.

†Serpentine rock:lime mix and lime-control treatments received an application of lime at a rate of 430 kg lime ha^{-1}. Potassium chloride was also applied to every plot at treatment application (3 July 2001) at a rate of 50 kg K ha^{-1}.

farmers and growers as a Mg source and also to correct soil acidity. All serpentine rock products were supplied by Rorison Mineral Developments Ltd, New Zealand. The two serpentine rock-superphosphate products (Serp-super A and Serp-super B) were made by the addition of ground serpentine rock at different stages during the process of superphosphate manufacture. E-mag (magnesium oxide) is a chip calcined magnesite. The serpentine-super and E-mag products were obtained from Ballance Agri-Nutrients Ltd, New Zealand. The acidulated serpentine rock plus reactive phosphate rock (ASRPR) product was made at Massey University by mixing Kossier phosphate rock with a partially acidulated serpentine rock.

The total and water-soluble Mg contents of the fertilisers are given in Table 3. The water-solubility of the fertilisers in order of highest to lowest solubility are: Epsom salts, ASRPR, Serp-super B, Serp-super A, E-mag, and serpentine.

Total fertiliser Mg and solubility

Total fertiliser Mg content was determined by heating 0.1 g of ground fertiliser with 10 ml of 1 *M* HCl at 70°C on a hot plate and analysing Mg in the solution by atomic absorption spectrometry. The fertiliser Mg solubility in water was determined by shaking 2 g as-received fertiliser with 100 ml water for 16 h, centrifuging and filtering the suspension and determining Mg concentration in the filtrate by atomic absorption spectrometry.

Trial design and treatments

The trial consisted of a randomised complete-block design, consisting of 10 Mg treatments and two control treatments each replicated four times. The Mg contents of the fertilisers and their rates of application are shown in Table 3. Plot size for each treatment was 3 × 2.5 m (7.5 m^2). The entire area was fenced with an electric wire to prevent grazing by stock. All fertilisers were applied on 3 July 2001 after a pre-treatment harvest was collected by mowing the trial area. The serpentine annual-application treatment was reapplied at 100 kg Mg ha^{-1} on 10 July 2002 and on 22 July 2003, giving a total application rate of 300 kg Mg ha^{-1}.

Phosphorous (P) and sulphur (S), as "Super 10" single superphosphate, were applied to some treatments at the start of the trial to balance the quantities of these nutrients in all treatments (Table 3). A total of 17 post-treatment harvests were made from the trial over a duration of 32 months (July 2001–February 2004).

Urea and potassium sulphate were applied at various times during the trial period to compensate for N, K, and S being transferred out of the trial site area due to removal of pasture herbage at each harvest. Urea was applied 12 times at an average rate of 46 kg N ha^{-1} per application, and potassium sulphate was applied eight times to provide average rates of K and S of 6 and 7 kg ha^{-1}, respectively, per application. These applications were mostly made from late winter to early summer.

Herbage and soil sampling

Herbage dry matter (DM) accumulation was assessed at each harvest, including a pre-treatment harvest (collected 3 July 2001), by mowing two strips (total area 1.8 m^2) of pasture from each plot and weighing after drying at 60–70°C. Harvests were made every 5–12 weeks, depending on pasture growth rates (Table 4). At each harvest, a second herbage sample was collected from each plot by cutting a strip of pasture from the centre of each plot with a hedge-trimmer, which was dried at 60–70°C and then ground for chemical analysis.

Soil samples were collected on 11 May 2001 by taking 12 soil cores (2 cm diameter) per one-half block (six plots per sample) and bulking the 12 cores together to make one sample. A total of eight one-half block samples were collected. The samples were air-dried, ground to pass through a 2 mm sieve and stored for chemical analysis.

Table 4 Herbage harvest numbers and dates.

Harvest number	Harvest date
Pre-treatment	3 Jul 2001
1	19 Sep 2001
2	25 Oct 2001
3	26 Nov 2001
4	8 Jan 2002
5	21 Feb 2002
6	10 Apr 2002
7	10 Jul 2002
8	17 Sep 2002
9	14 Nov 2002
10	20 Dec 2002
11	30 Jan 2003
12	19 Mar 2003
13	30 Apr 2003
14	23 Sep 2003
15	6 Nov 2003
16	18 Dec 2003
17	27 Feb 2004

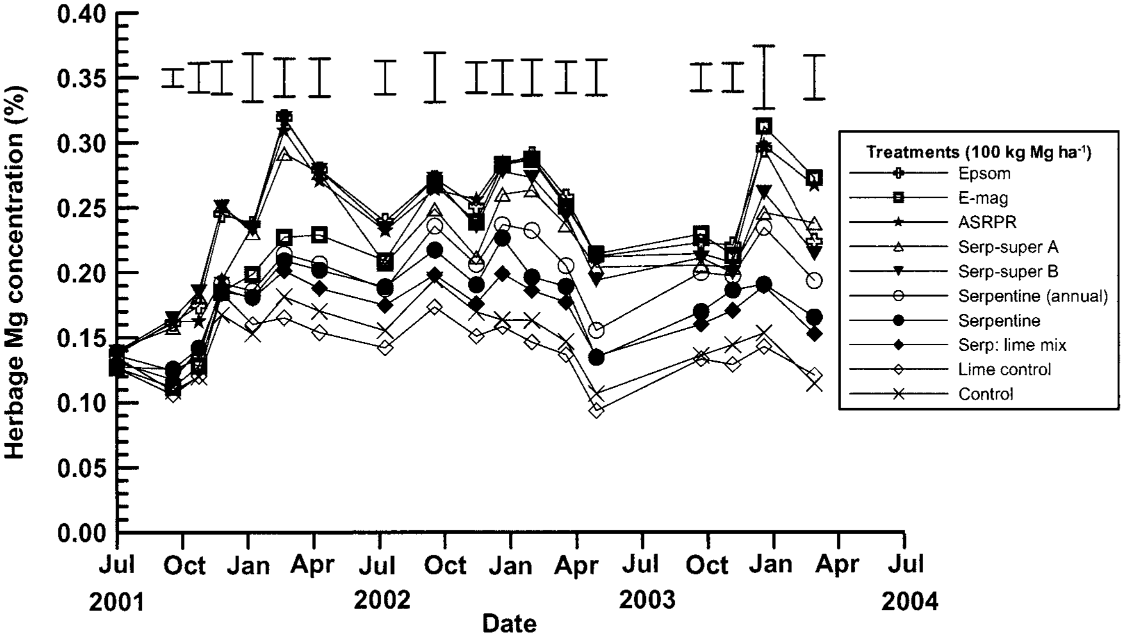

Fig. 1 Effect of fertilisers at 100 kg Mg ha^{-1} on herbage Mg concentrations from July 2001 to February 2004. Vertical bars represent LSD ($P < 0.05$) values.

Herbage and soil analysis

Magnesium concentrations in herbage were determined by digesting a subsample of ground herbage with concentrated nitric acid (69%) and measuring Mg concentrations in the digest using atomic absorption spectroscopy. Soil samples were analysed using methods described by Blakemore et al. (1987).

Statistical analyses

Data from the trial was statistically analysed using an analysis of variance (ANOVA). A least significant difference (LSD) test, at a 5% confidence level, was used to group Mg fertiliser treatments at harvests where the effects of Mg treatments were significant. Covariance analysis of DM yield at each cut was conducted using the yield data from the pre-treatment harvest.

RESULTS AND DISCUSSION

Pasture yield

Magnesium fertiliser treatments did not significantly affect herbage dry matter (DM) yields at any harvest except one. Only at Harvest 9 was there some evidence ($P = 0.011$) of a DM yield response. However, the measured DM yield differences between Mg treatments at this single harvest should be considered with caution as the treatment effects were not consistent with DM yield differences between treatments in previous and subsequent harvests.

Pasture DM yield is unlikely to respond to Mg fertiliser on Pumice Soils when the soil Mg Quick Test is ≥5 or herbage Mg concentration is ≥0.12% Mg (Toxopeus 1979). As the soil at the start of the study had an average soil Mg Quick Test value of 5.3 (exchangeable soil Mg of 0.4 $cmol_c\ kg^{-1}$) and a herbage Mg concentration of 0.13%, a pasture DM yield response to Mg addition was unlikely.

Total DM yields for the control plots on average were 10 749 kg DM ha^{-1} during the first 12 months of the study, 10 193 kg DM ha^{-1} between 12 and 24 months, and 5518 kg DM ha^{-1} between 24 and 32 months.

Magnesium concentrations in herbage

Magnesium concentrations in herbage showed a strong seasonal variation, being lowest during late winter and spring and highest during summer (Fig. 1). A similar trend was reported by McNaught et al. (1973) from many Mg field trials conducted in New Zealand, and by Loganathan et al. (2001) for a field trial conducted in the Manawatu region of New Zealand.

Table 5 Number of harvests where treatment herbage Mg concentrations were higher than that of the control treatment and ≥0.20% Mg.

Treatment (kg Mg ha^{-1})	No. of harvests, out of 17, where herbage Mg concentration was significantly ($P < 0.05$) higher than the control	No. of harvests, out of 17, with an average herbage Mg concentration ≥0.20% Mg†	No. of harvests, out of 3 made in spring 2001, with an average herbage Mg concentration ≥0.20% Mg†	No. of harvests, out of 2 made in spring 2002, with an average herbage Mg concentration ≥0.20% Mg†	No. of harvests, out of 2 made in spring 2003, with an average herbage Mg concentration ≥0.20% Mg†
Control	N/A	0	0	0	0
Lime-control	0	0	0	0	0
Epsom (25)	12	7	1	1	0
Epsom (50)	17	14	1	2	2
Epsom (100)	17	15	1	2	2
Serp-super A (100)	17	15	1	2	2
Serp-super B (100)	17	14	1	2	2
ASRPR (100)	17	14	0	2	2
E-Mag (100)	14	13	0	2	2
Serpentine rock(100)	10	5	0	1	0
Serpentine rock (100 annual)	14	10	0	1	2
Serpentine rock:lime mix (100)	6(10)*	3	0	1	0

*Value in parenthesis is the number of harvests where the serpentine rock:lime mix treatment resulted in herbage Mg concentration significantly ($P < 0.05$) higher than the lime-control treatment.

†A "threshold level" of 0.20% Mg in mixed-herbage was used to identify when pasture Mg concentrations were at levels where the risk of hypomagnesaemia is considered to be appreciably reduced.

For the current study, the effects of Mg fertiliser treatments on herbage Mg concentration and Mg accumulation were highly significant ($P < 0.001$) at all harvests (Fig. 1). The Epsom salts treatments demonstrated that herbage Mg concentration was responsive to increasing rates of Mg fertiliser (Fig. 3). The lowest rate of Epsom salts (25 kg Mg ha^{-1}) resulted in increased herbage Mg concentrations at 12 harvests, including the final harvest, while the two higher rates of Epsom salts (50 and 100 kg Mg ha^{-1}) increased concentrations at all harvests compared to the control. The 50 kg Mg ha^{-1} rate of Epsom salts increased Mg concentrations above the 25 kg Mg ha^{-1} at 10 harvests, including the last 3 harvests. The 100 Mg ha^{-1} rate further increased Mg concentrations above the 50 kg Mg ha^{-1} rate at 7 harvests, but not during the final 5 harvests. These results show that all three rates continued to be effective at elevating herbage Mg concentrations over the entire duration of the trial with the two higher rates performing consistently better than the lowest. However, after the first 24 months of the trial the two higher rates did not perform differently from each other. The reduction in the difference between the effects of the two higher rates of Epsom salts may partly be due to the 100 kg Mg ha^{-1} rate having higher estimated Mg leaching losses (Loganathan et al. 2005).

At an application rate of 100 kg Mg ha^{-1}, the more soluble fertilisers (Epsom, Serp-super A, Serp-super B, ASRPR) all resulted in significantly increasing herbage Mg concentrations at all 17 harvests, compared to the control (Table 5). These treatments also tended to have the highest herbage Mg levels at most harvests over the duration of the trial (Fig. 1).

Plant availability of Mg from E-mag appeared to have increased during the experiment, which was probably due to the rate of Mg dissolution increasing as the particle size of E-mag reduced over time (Mitchell et al. 2000). The E-mag treatment elevated herbage Mg concentrations at 14 harvests (Harvests 4–17) compared with the control. At most harvests during the second and third year of the trial, E-mag

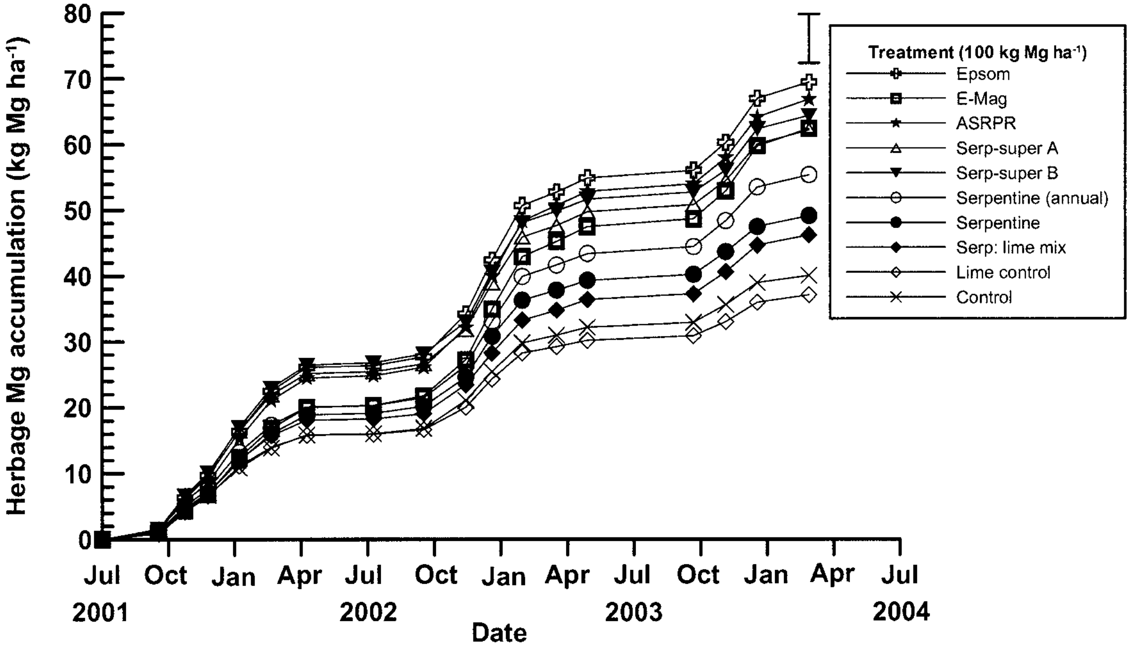

Fig. 2 Effect of treatments on cumulative herbage Mg accumulation from July 2001 to February 2004. Vertical bar represents the LSD ($P < 0.05$) value.

produced herbage Mg concentrations similar to the more soluble fertilisers and had the highest herbage Mg concentrations at the last two harvests (Fig. 1).

During the first year of this study (Harvests 1–7), the three non-acidulated serpentine rock treatments achieved identical herbage Mg concentrations. However, over time the annual application of serpentine rock produced higher herbage Mg concentrations than the other serpentine rock treatments.

Of the 17 harvests made during the trial, the serpentine rock annual-application treatment increased mixed-herbage Mg concentrations at 14 harvests, the serpentine rock single application treatment at 10 harvests and the serpentine rock:lime mix treatment at 6 harvests, compared with the control. The lower effectiveness of serpentine rock when mixed with lime, compared to serpentine rock applied alone, may be due to the lime reducing soil acidity, and hence, lowering serpentine rock dissolution. It may also be partially due to the effect that Ca in lime has on increasing Mg loss from the soil. At most harvests the lime-control tended to have lower herbage Mg concentrations than that of the control with no lime. This may be due to Ca in the lime being preferentially adsorbed by the soil and releasing Mg from the soil-exchange sites into soil solution, thereby increasing the amount of Mg leached (Edmeades 2004). It may also be due to Ca from the lime reducing Mg uptake by plants (Wild & Jones 1988).

Magnesium accumulation in herbage

Magnesium accumulation in herbage at each harvest over the trial period with the 100 kg Mg ha^{-1} treatments and the serpentine rock annual-application treatment is presented in Fig. 2. Total Mg accumulation in harvested herbage at the end of the trial is presented in Table 6. As with herbage Mg concentrations, the more soluble Mg fertilisers (Epsom salts, Serp-super A, Serp-super B, and ASRPR) and E-mag achieved the highest Mg accumulation levels, ranging from 61.9 to 69.4 kg Mg ha^{-1}, being 55.1–73.9% higher than the control level of 39.9 kg Mg ha^{-1}. The serpentine rock single-application and serpentine rock annual-application treatments resulted in Mg accumulation values of 23.1 and 38.6% higher than the control, respectively.

Herbage Mg concentration and animal health

The concentration of Mg in herbage is a major factor in the incidence of hypomagnesaemia. Every (1981) reported that various researchers have suggested that the safe concentration of Mg in pasture, for protection against hypomagnesaemia in critical periods, ranged from 0.20% to as high as 0.30%. Reviewing the work conducted on the Mg requirements of pastures in New Zealand, Edmeades (2004) reported that, assuming an adequate feed intake, ruminant Mg requirements during early lactation can only be met if the pasture Mg concentration is >0.20%. Therefore, a "threshold level" of 0.20% Mg in herbage was used in the current study to identify when pasture herbage Mg concentrations were at levels at which the risk of hypomagnesaemia is considered to be appreciably reduced. Throughout the current trial, the average herbage Mg concentrations from the two control treatments (control, lime-control) remained below 0.20%. This indicates that at this site, there is likely to be a risk of hypomagnesaemia without the addition of fertiliser Mg or Mg supplements given directly to stock. A fertiliser rate of 25 kg Mg ha^{-1} is commonly considered adequate to correct Mg deficiency in respect to pasture production (Edmeades 2004), whereas, fertiliser rates greater than 100 kg Mg ha^{-1} have been reported to be required to elevate Mg concentration in herbage to levels that meet animal Mg requirements (Edmeades 2004).

The application of more soluble Mg fertilisers (Epsom salts (50 and 100 kg Mg ha^{-1}), Serp-super A, Serp-super B, and ASRPR) resulted in herbage Mg concentrations ≥0.20% at 14–15 out of the 17 harvests made (Table 5). E-mag produced herbage Mg concentrations ≥0.20% at 13 harvests. More importantly, these treatments resulted in Mg concentrations ≥0.20% at all spring harvests (Harvests 7, 8, 14, and 15) in the second and third year of the study. In addition, the Epsom salts (50 and 100 kg Mg ha^{-1}), Serp-super A, and Serp-super B treatments resulted in herbage Mg concentrations ≥0.20% at one spring harvest (Harvest 3) in the first year of the trial.

The serpentine rock annual-application and the serpentine rock single-application treatments elevated herbage Mg concentrations to levels ≥0.20% at 10 and 5 harvests, respectively (Table 5). At 4 harvests (Harvests 11, 14, 16, and 17) during the latter part of the trial the serpentine rock annual-application had herbage Mg concentrations significantly ($P < 0.001$) higher than the serpentine rock single-application. During the second and third year of the trial (Harvests 8, 14, and 15) the serpentine rock annual-application also produced herbage Mg concentrations of ≥0.20% Mg in the period when cows are in early lactation. These results indicate that, after an initial lag period in the first year after application, an annual re-application of serpentine rock of 100 kg Mg ha^{-1} yr^{-1} can be an effective source of Mg to elevate and maintain herbage Mg concentrations to levels considered adequate to meet stock health requirements. However, the cost effectiveness of the repeated application of high rates of serpentine rock needs to be considered when adopting this fertiliser practice. For soils with very low Mg status, a more soluble form of Mg may be required initially to adequately raise the soil Mg availability.

Table 6 Effect of treatments on total Mg accumulation in pasture herbage (Harvests 1–17; July 2001–February 2004).

Treatment (kg Mg ha^{-1})	Total Mg accumulation (kg Mg ha^{-1}) in herbage Jul 2001–Feb 2004	Percentage increase above the control value (%)*
Control	39.9	–
Lime-control	37.1	–
Epsom (25)	51.7	29.6
Epsom (50)	60.8	52.4
Epsom (100)	69.4	73.9
Serp-super A (100)	61.9	55.1
Serp-super B (100)	64.3	61.2
ASRPR (100)	66.8	67.4
E-Mag (100)	62.3	56.1
Serpentine rock (100)	49.1	23.1
Serpentine rock (100 annual)	55.3	38.6
Serpentine rock:lime mix (100)	46.1	24.3*
LSD ($P < 0.05$)	7.4	

*Percentage increase for the serpentine rock:lime mix treatment was calculated using the lime-control as the comparison.

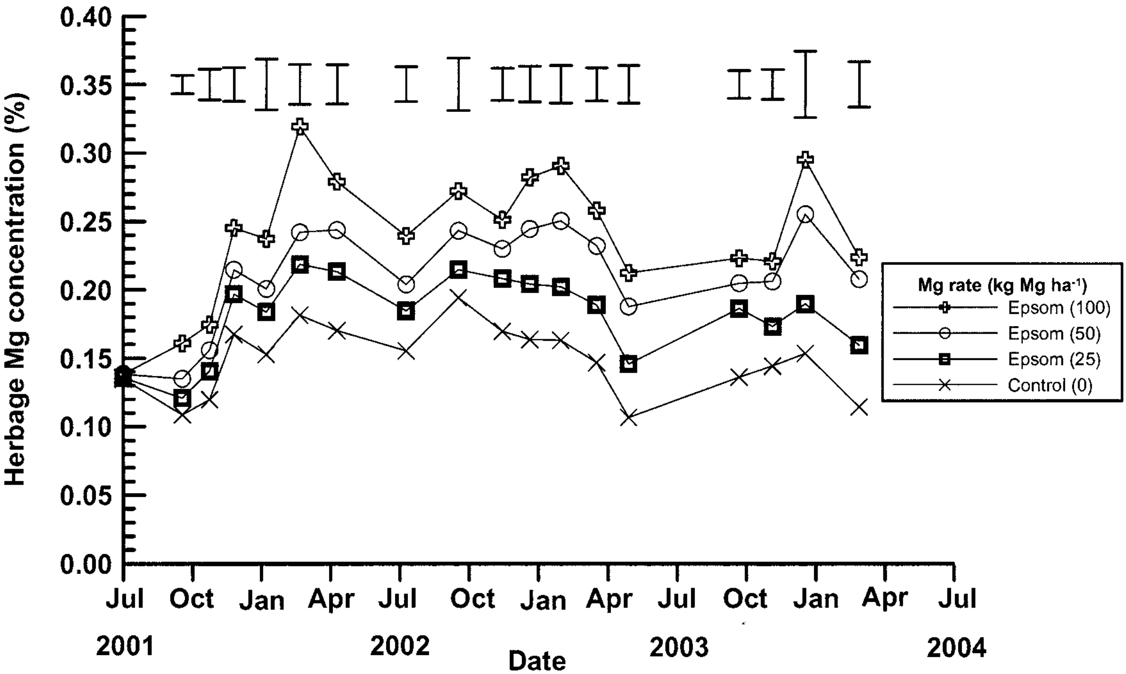

Fig. 3 Effects of Mg rate, applied as Epsom salts, on herbage Mg concentration from July 2001 to February 2004. Vertical bars represent LSD ($P < 0.05$) values.

CONCLUSIONS

The trial results have demonstrated that an application of serpentine rock (<500 µm particle size), at 100 kg Mg ha^{-1} to an Immature Orthic Pumic Soil, can increase herbage Mg concentrations above a control pasture after an initial lag period. Serpentine rock application elevated herbage Mg concentrations to ≥0.20% at 5 harvests made over the 32-month trial. In comparsion, the Mg concentration in pasture that received no Mg fertiliser remained below this threshold level throughout the trial. Re-application of serpentine rock annually (100 kg Mg ha^{-1} yr^{-1}) further increased herbage Mg concentration and accumulation. In the second and third year of the trial this treatment elevated Mg concentrations to ≥0.20% at 10 harvests, including 3 of the 4 harvests made during the critical period when cows are in early lactation. The results indicate that the annual application of serpentine rock may have potential as an alternative strategy to the application of more soluble Mg sources for raising pasture mixed-herbage Mg concentration to levels considered adequate to meet stock health requirements.

The more soluble Mg fertilisers (Epsom salts, Serp-super A, Serp-super B, and ASRPR) had the greatest effect on increasing mixed-herbage Mg concentration and accumulation. The effect of E-mag on mixed-herbage Mg concentration was similar to that of serpentine rock during the first year of the trial, but subsequently it performed as well as the more soluble Mg fertilisers.

The lack of dry matter yield response to Mg addition in this trial was likely to be due to the soil supplying sufficient Mg for pasture production.

ACKNOWLEDGMENTS

The authors are grateful for the financial assistance and fertilisers provided by Rorison Mineral Development Ltd and Balance Agri-Nutrients Ltd, and thank Mike Hedley for helpful advice on the experimental design of the trial; Mike Bretherton, Bob Toes, and Ross Wallace for helping with field work; Glenys Wallace and Andrew Mitchell for conducting fertiliser, herbage, and soil analyses, and Paul Gregg for reviewing the paper and making valuable comments.

REFERENCES

Blakemore LC, Searle PL, Day BK 1987. Methods for chemical analysis of soils. DSIR, Lower Hutt, New Zealand Soil Bureau Scientific Report 80.

Chittenden ET, Watson J, Hodgson L 1964. Magnesium uptake by pasture and apple leaves from top-dressing of ground serpentine and dunite. New Zealand Journal of Agricultural Research 7: 28–31.

Cornforth IS, Sinclair AG 1984. Fertiliser and lime recommendations for pastures and crops in New Zealand. Wellington, New Zealand, Ministry of Agriculture and Fisheries.

Edmeades DC 2004. The magnesium requirements of pastures in New Zealand: a review. New Zealand Journal of Agricultural Research 47: 363–380.

Every JP 1981. The effect of magnesium fertiliser applied to a pumice soil on magnesium concentration in grass herbage. New Zealand Journal of Agricultural Research 9: 251–254.

Grace ND 1984. Magnesium (Mg). In: Grace ND ed. The mineral requirements of grazing ruminants. New Zealand Society of Animal Production. Occasional Publication No. 9. Keeling and Mundy Ltd, Palmerston North, New Zealand. Pp. 92–99.

Hewitt AE 1993. New Zealand soil classification. Landcare Research Science Series No. 1. Lincoln, New Zealand, Manaaki Whenua-Landcare Research New Zealand Ltd.

Loganathan P, Hanly JA, Currie LD, Wallace GC 2001. Serpentine and its acidulated products as potential magnesium fertilisers for pasture. In: Currie LD, Loganathan P ed. Precision tools for improving land management. Occasional Report 17. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp. 239–250.

Loganathan P, Hanly JA, Currie LD 2005. Effect of serpentine rock and its acidulated products as magnesium fertilisers for pasture, compared with magnesium oxide and Epsom salts, on a Pumice Soil. 2. Dissolution and estimated leaching loss of fertiliser magnesium. New Zealand Journal of Agricultural Research 48: 461–471 (this issue).

McNaught KJ, Ludecke TE 1967. Effect of soil type on uptake of magnesium by pasture plants. New Zealand Society of Animal Production 27: 121–125.

McNaught KJ, Dorofaeff FD, Karlovsky J 1968. Effect of magnesium fertilisers and season on levels of inorganic nutrients in a pasture on Hamilton clay loam. 1. Magnesium and calcium. New Zealand Journal of Agricultural Research 11: 533–550.

McNaught KJ, Dorofaeff FD, Karlovsky J 1973. Effect of some magnesium fertilisers on mineral composition of pasture on Horotiu sandy loam. New Zealand Journal of Experimental Agriculture 1: 349–363.

Metson AJ 1974. Magnesium in New Zealand soils. 1. Some factors governing the availability of soil magnesium. New Zealand Journal of Experimental Agriculture 2: 277–319.

Mitchell AD, Loganathan P, Payn TW, Tillman RW 2000. Magnesium fertiliser dissolution rates in pumice soils under *Pinus radiata*. Australian Journal of Soil Research 38: 753–767.

O'Connor MB, Pearce MG, Gravett IM, Towers NR 1987. Fertilising with magnesium to prevent hypomagnesaemia (grass staggers) in dairy cows. Proceedings of the Ruakura Farmers Conference. Pp. 47–49.

Toxopeus MRT 1979. Treating magnesium deficiency in pasture. New Zealand Fertiliser Journal. Pp. 8–10.

Wild A, Jones LHP 1988. Mineral nutrition of crop plants. In: Wild A ed. Russell's soil conditions and plant growth. England, Longman Scientific & Technical. Pp. 69–112.