The Magnesium Requirements of Pastures in New Zealand: A review

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Abstract Magnesium (Mg) is an essential nutrient for plants and animals, and hypomagesaemia, a disorder associated with low blood Mg in ruminants, is a major problem in the New Zealand pastoral industry. This paper reviews the research conducted in New Zealand in the last 30 years to develop diagnostic criteria to predict, and strategies to manage, soil, plant and animal Mg. The Mg status of New Zealand soils is examined and it is concluded that most New Zealand topsoils have significant reserves of Mg, at least for optimal pasture production, for the foreseeable future. There is evidence, however, that soil Mg levels are slowly declining because, in the absence of fertiliser Mg inputs, most pastoral farms are in a negative balance with respect to Mg. The soils most vulnerable to developing Mg deficiency are the coarser textured soils used for dairying and under high rainfall (> 1200mm). Extreme deficiency resulting in the loss of production in legume-based pastures occurs if the soil Mg concentration is < 4-5 Quick Test Mg (QT Mg) units and the mixed herbage Mg concentration is < 0.10%. Achieving and maintaining soils at > QT Mg 8-10 ensures that the probability of Mg deficiency in respect to pasture production is small. The evidence shows that even the most extreme deficiencies can be eliminated with inputs of about 25 kg Mg ha^{-1} yr^{-1}, and balance studies indicate that soil Mg levels can be maintained with inputs of between 5 and 20 kg Mg ha^{-1} yr^{-1}, depending particularly on the type of operation (dairying or sheep & beef) and the leaching regime of the soil. The factors that affect soil Mg levels, plant uptake and pasture concentrations, such as inputs of potassium and lime, season and plant species are discussed.

Overcoming Mg deficiency in pastures does not, however, eliminate the risk of hypomagnesaemia in lactating ruminants. The evidence indicates that feed intake is the most important determinant of animal Mg status and milk production, but other factors can affect the ability of the animal to utilise Mg. Assuming an adequate feed intake, animal Mg requirements during early lactation can only be met if the pasture Mg concentration is > 0.20%. To achieve such concentration in spring requires that the soil Mg level is QT Mg 25-30 or above. On those soils in New Zealand with low soil Mg status such levels can only be achieved with large capital inputs of fertiliser Mg (> 100 kg Mg ha^{-1}). Strategies for managing pasture and animal Mg requirements are discussed in relation to the agronomic effectiveness of Mg fertilisers. The importance of Mg in the long-term sustainability of New Zealand pastoral system is emphasized and weaknesses in current knowledge are identified and highlighted for future research.

Keywords animals, fertiliser, hypomagnesaemia, magnesium, nutrient budgeting, pastures, soil fertility, sustainability.

INTRODUCTION

Magnesium (Mg) is an essential nutrient for both plants (Marschener 1995) and animals (Grace 1983), and has particular significance to New Zealand's pastoral industry because of hypomagnesaemia, a disorder associated with low blood Mg in ruminants (Grace 1983), particularly in lactating dairy and beef animals. According to O'Connor et al. (1987), hypomagnesaemia is a major cause of lowered milk production, affecting about 30-50% of dairy herds.

Metson (1974) published a major review on the factors governing the availability of soil Mg. He concluded that absolute Mg deficiency in crops occurs most frequently on light-textured, free-draining soils, but that induced deficiencies have been reported on heavier soils fertilised with NPK. After considering the likely inputs (from precipitation) and outputs (crop removal and drainage) of Mg, he predicted that, in the absence of fertiliser Mg, there is "an increased likelihood of Mg deficiency in the future."

Discussing the incidence of hypomagnesaemia, Metson (1974), noted that while it is widely accepted that there is a general relationship between soil Mg and the incidence of hypomagnesaemia, "The connection, if any, between the kind of soil and the incidence of grass tetany [hypomagnesaemia] is much more difficult to establish and indeed few, if any, direct or causal links have been established." He elaborated that this is because there are many factors, some of which, including climate and management, are independent of the soil and soil conditions, which affect the animals Mg status and hence the incidence of hypomagnesaemia.

The first pasture responses to Mg fertiliser were reported in the mid 1960s on coarse textured pumice soils, and for the next two decades much research on pastures was undertaken to (a) develop diagnostic tests and criteria to define and predict Mg deficiency (b) quantify the benefits of alleviating Mg deficiency (c) measure the agronomic effectiveness of various Mg fertilisers and d) quantify the optimal rates of Mg fertiliser to eliminate Mg deficiency and maintain soil Mg levels. Simultaneously, animal trials were undertaken to define diagnostic criteria and determine the most cost effective methods for eliminating hypomagnesaemia (Grace 1983).

Based on this body of research, Mg fertilisers (20-25 kg Mg $ha^{-1}yr^{-1}$) were recommended if the soil Quick Test Mg (Mg QT) levels were < 9, to eliminate pasture Mg deficiency and maintain soil Mg levels (O'Connor & Edmeades 1984). This criterion only applied to the Pumice soils because of their generally lower soil Mg status, and hence the routine use of Mg fertiliser has been largely restricted to these soils. The widespread use of Mg fertiliser was not regarded as an economic means to control hypomagnesaemia (McNaught et al. 1973a, b). This, it was argued, was best managed by direct supplementation of Mg to the animal as a drench, by dusting pasture, hay and silage, and by water treatment (Grace 1983).

More recently, Roberts & Morton (1998) published anecdotal information suggesting that soil Mg levels on all soils groups have decreased over the period 1980 to 1990 and that the incidence of hypomagnesaemia may be increasing, observations consistent with Metson's prediction (Metson 1974). They suggested that these trends are to be expected given that the use of Mg has not become part of annual fertiliser programs, +except on the generally low Mg status pumice soils used for dairying, despite that fact that there are considerable losses of Mg from product removal and leaching.

This review updates and refines our understanding of the role and management of Mg in New Zealand pastoral agriculture and in particular focuses on the need for Mg fertilisers to ensure the sustainability of the pastoral system.

MAGNESIUM STATUS OF NEW ZEALAND SOILS

A single factor map of the exchangeable Mg content of untopdressed New Zealand topsoils (A horizon) was published in 1962 (Blakemore & Miller 1962). These maps indicated that in their virgin state most topsoils had exchangeable Mg levels of 1-3 cmol kg^{-1} (Quick Test Mg (QT Mg) units 23-71) or higher. The only soils with very low exchangeable Mg (< 0.3 cmol kg^{-1}, QT Mg < 7) were some recent Allophanic soils and Pumice soils in the North Island and highly weathered soils in the South Island.

Metson (1974) emphasised the importance of non-exchangeable Mg as a source of slowly available plant Mg. In subsequent work Metson & Brooks (1975) identified the New Zealand soil groups likely to be, or to become, Mg-deficient based on their concentrations of exchangeable and non-exchangeable Mg, after considering the leaching and weathering environments of the specific soil groups. The most vulnerable soils, relevant to the pastoral industry, included: the Podzols, Brown soils (sands), Oxidic soils (red and brown loams) and Granular soils (brown granular clays) of the upper North Island, and the Pumice and Allophanic soils (volcanic soils) of the central North Island. Further, they showed (Kidson et al. 1975), using an exhaustive pot trial technique, that plant dry matter, plant Mg concentration and plant Mg uptake were significantly correlated to soil exchangeable Mg, but that non-exchangeable Mg contributed to plant growth only in those few situations where the initial amount on non-exchangeable Mg was high (> 30 cmol kg^{-1}).

Smith & Cornforth (1982) published results from a survey of pasture concentrations of pasture herbage samples which had been collected for advisory purposes from 5862 sites from throughout the North Island, New Zealand. These results showed that the average mixed herbage Mg content ranged from 0.21% to 0.28%, depending on region, being lowest on the pumice soils and highest on the heavy clay soils in the Thames region. Across regions, the concentrations ranged from 0.10% up to 0.60%, due largely to the effect of season (Smith & Cornforth 1982). Only 2% of the samples had Mg concentrations < 0.15% and 80% had concentrations > 0.20%.

Similarly, Wheeler & Roberts (1997) analyzed soil test data (30,780 samples from dairy farms (63%) and sheep & beef farms (37%)) from a commercial soil-testing laboratory over the period 1988-1991. For the Pumice soils of the North Island, 2-3% (covering both farm types) of the samples had QT Mg < 5 and 28-33% had QT Mg < 10. For the North Island Allophanic soils the respective figures were 0-1% and 5-6%. None of the North Island sedimentary soils were < 5 QT Mg and 1% were < 10 QT Mg. In the South Island, 0-2% of the sedimentary soils had QT Mg < 5 and 2% of the samples from sheep & beef farms and 13% from the dairy farms had QT Mg < 10. The median values ranged from about QT Mg 15 to 25 depending on farm type and soil group.

In a more structured survey, Perrott et al. (1995) sampled topsoils from 98 developed pasture sites from throughout New Zealand (64% sedimentary soils, 22% Allophanic, 8% Pumice and 4% Organic). The distribution of the soil exchangeable Mg concentrations is given in fig 1. No sites had Mg levels < 5 QT Mg (0.21 cmol kg^{-1}), but four sites (4%) (two Pumice soils and two coarse Recent soils on the West Coast under high rainfall) had Mg levels < QT 10 (0.42 cmol kg^{-1}). The median value was 1.45 cmol kg^{-1} (QT Mg 34). These distributions suggest that there may be a slight negative bias relative to the survey data of Wheeler & Roberts (1997).

Collectively these survey data serve to emphasise the predictions made by Metson and coworkers. The soils most vulnerable to developing Mg deficiency are the coarser Pumice soils of the North Island and the coarse textured Recent soils under high rainfall on the West Coast of the South Island. But apart from these exceptions, the evidence indicates that most New Zealand topsoils have significant reserves of available Mg. However, recent data (Wheeler et al. 2003) shows that soil Mg levels in all major soil groups are decreasing, except for the Pumice soils under dairying (Fig 2) which is the only situation in which Mg has become part of the fertiliser program. These trends confirm earlier observations (Roberts & Morton 1998) and Metson's prediction.

FACTORS AFFECTING SOIL AND PLANT MAGNESIUM

Metson (1974) identified and reviewed three factors that adversely affected the ability of plants to take up Mg: excess soil K and Ca, and low soil pH. Certainly, there is much evidence to show that increasing the concentration of Ca^{2+}, K^{+} and H^{+} in the soil decreases plant Mg uptake (Metson 1974; Clarke 1984) due to competitive inhibition.

Morton et al. (2000) quantified the effect of increasing fertiliser K inputs, and hence the pasture K content, on pasture Mg concentrations. They found that most of the available data could be described by a simple non-linear relationship (r^2 = 0.62) -

pasture Mg decreased with increasing plant K, but the rate of decrease was greatest at low pasture K (< 2.0% K) concentrations (Fig 3). Once the pasture K concentration was above 3%, as is typically the case in New Zealand pastures adequately fertilised with K, the effect is small. In two further trials (Morton et al. 2000), in Northland (QT K 4, QT Mg 12) and Southland (QT K 12, QT Mg 15), these effects of K were greatest for spring- applied K, as distinct from autumn applied K, and for high K inputs (> 50 kg K ha^{-1}).

Over-riding these nutritional interactions in the plant there are those effects due to pasture composition and season. The results in Fig 6 demonstrate both effects, and McNaught et al. (1968b) and Edmeades et al. (1983) provide further examples. While clovers have a higher concentration of Mg than grasses, this effect is small in comparison with the seasonally induced changes in plant Mg, which are of the order of 50%-100%. Unfortunately, the lowest pasture Mg concentrations coincide with spring, and hence calving - the time of greatest Mg demand - in most New Zealand dairy herds. This has major implications for the management of soils, pastures and animals during the critical spring period. Some of this seasonal variability can be attributed to similar fluctuations in soil solution Mg (Edmeades et al. 1985b), but it is also likely that the stage of maturity of the plant plays an important role.

At the soil level, large inputs of all three cations Ca, K, and Na, change their ratios in the soil solution and hence the ratios of the exchangeable cations. The net effect, given sufficient inputs, is that Mg is ‘forced’ off the exchange complex into soil solution, increasing the potential for leaching. Over time, the rate of leaching of Mg can be increased and exchangeable Mg decreased. Metson (1974) gives numerous examples of this effect in respect to K applied as fertiliser or in urine. Additions of Ca as lime can have the same effect.

The effects of liming, however, cannot be predicted solely on the basis of its effect on increasing Ca^{2+} and decreasing H^{+}. Liming New Zealand soils has three effects in relation to Mg: it increases the preference (selectivity) of soils to absorb Ca (as exchangeable Ca), decreases the proportion of Mg/Ca in the soil solution and increases the effective cation exchange capacity (ECEC) (Edmeades & Judd 1980; Edmeades et al. 1983). The net result of these competing effects is that liming, given time, generally reduces soil exchangeable Mg by forcing it off the exchange surface and into soil solution thereby increasing the amount of Mg leached. However, on some soils, those with a large buffer capacity (> 15 cmol kg^{-1} increase in ECEC per unit increase in pH), the increase in new exchange surfaces is sufficient to offset the negative effects arising from the increased preference for Ca and the decrease in solution Mg/Ca, and exchangeable Mg increases with time (Edmeades et al. 1985a). There was no evidence from this work that increasing the soil pH decreased soil Mg solubility *per se*.

These effects have been observed in the field. On a volcanic soil with a large buffer capacity, liming increased exchangeable Mg but significantly decreased clover and grass Mg concentrations (Edmeades et al. 1983). This effect was greatest in the spring. In this case it was postulated that the apparently beneficial effect of liming on soil Mg was offset bya large increase in the soil solution Ca/Mg concentration and hence a decrease in pasture Mg uptake. On a Pallic soil with low buffer capacity, liming decreased exchangeable Mg (Wheeler 1997) but increased soil solution Mg

(Wheeler & Edmeades 1995). It appears therefore that while liming may increase or decrease soil Mg, depending on the soil buffer capacity, it always reduces pasture Mg uptake and concentration due to the increase in soil Ca/Mg ratio. .

When optimising spring pasture Mg concentrations to reduce the incidence of hypomagnesaemia, there is little that can be done about the large seasonal effect. However, inputs of Ca and K should be avoided during this critical period so that the already low Mg concentration is not suppressed further by competitive inhibition. Ongoing inputs of all Ca-containing fertilisers (lime, superphosphate, reactive phosphate rocks) and K-containing fertiliser, (potassium chloride, potassium sulphate) will, however, slowly and insidiously reduce soil Mg levels by increasing the rate of Mg leaching. This, together with the ongoing removal of Mg in products without inputs of fertiliser Mg, is the reason for the decline in soil Mg status in the New Zealand pastoral sector (Fig 2)

MAGNESIUM REQUIREMENTS FOR PASTURES

A total of 48 trials have been undertaken on pastures in New Zealand of which only 13 have been reported individually (Table 1). Most trials were designed to examine the effects of either rates or forms of Mg fertilisers on pasture production and soil and plant Mg levels. Only one trial specifically examined the effect of fertiliser Mg on animal production (Table 1).

Of the 13 individually reported trials, 8 were on soils with low soil Mg status (QT Mg 5 or less). The remainder were on sites with high soil Mg status (QT Mg > 20). Nine trials examined different forms of fertiliser Mg, and the balance measured the effect of different rates of fertiliser Mg.

No pasture production responses to Mg fertiliser have occurred on soils with QT Mg 6 or above, and of those trials on soils with QT Mg 5 or less, all were responsive to fertiliser Mg (Table 1). Similar results were obtained in the glasshouse on a range of soils (29) using white clover alone as the test plant (Table 2). The higher frequency of responses in this glasshouse study on soils with medium Mg status (Mg QT 4-7) is probably due to the more vigorous growing conditions and the use of a legume alone as the test plant – white clovers have a higher requirement for Mg than grasses (McNaught et al. 1968a).

Based on these results, the minimum level for maximum pasture production in legume-based pastures was set at QT Mg 8-10 (0.33 - 0.42 cmol kg^{-1}) (Roberts & Edmeades 1993). If pastoral soils were maintained at or above this level, the probability of Mg deficiency limiting pasture production was small. This is consistent with the data reviewed by Metson (1974) who concluded that most reports of absolute Mg deficiency in crops are associated with soils in which the exchangeable Mg is 0.2 - 0.3 cmol kg^{-1} (QT Mg 5 - 7). If the distribution of soil Mg given in Fig 1 is applied to these criteria, then approximately 2% of all New Zealand soils are Mg deficient for pasture production. Based on the data from Wheeler & Roberts (1997), the proportion of Mg-deficient sites may be as high as 30% on pumice soils, about 5% on Allophanic soils and 13% on sedimentary soils used for dairying in the South Island.

Three trials on Mg deficient soils have examined the effects of increasing rates of Mg fertiliser on pasture production and herbage Mg concentration (McNaught & Dorofaeff 1965, MAF SF 28/1 and MAF SF 1015/3, see Table 1). The relationships between fertiliser Mg applied and the average annual pasture production and pasture herbage concentrations are given in Figs 4 and 5, for the last two mentioned trials. These results suggest that, on these Mg-deficient soils, inputs of fertiliser Mg of about 25 kg Mg $ha^{-1}yr^{-1}$ are sufficient to eliminate Mg deficiency in pasture. The mixed herbage Mg concentrations associated with these inputs were about 0.20% suggesting that this is the critical minimum concentration for mixed herbage. McNaught & Dorofaeff (1965) reported no significant increases in pasture production to rates of fertiliser Mg > 12.5 kg Mg $ha^{-1}yr^{-1}$ on two coarse pumice soils. The associated Mg concentrations were typically in the range 0.13 - 0.20% for white clover and 0.10 - 0.15% for grasses.

Unfortunately there is very little information from the collective field trials on the soil Mg buffer capacity - the change in QT Mg per unit Mg applied. The available information comes from eight trials and suggests that, on average, eight kg Mg ha^{-1} is required to increase the QT Mg by one unit. However this data is variable (range 4-12) and has not been collected systematically (ie the soil Mg levels have not been measured at the same time after Mg fertiliser application). Furthermore, these trials were all on Pumice and Allophanic soils.

The information reviewed above has formed the basis of Mg fertiliser advice for pastoral soils in New Zealand (Roberts & Morton 1999). The general recommendation for optimal pasture production is to achieve soil Mg levels at or above QT Mg 8-10 with applications of about 25 kg Mg $ha^{-1}yr^{-1}$. The optimal concentration for mixed pasture is set at 0.18-0.22%.

It is important to emphasize that pasture Mg concentrations continue to increase with increasing inputs of fertiliser Mg, even though there is no further increase in pasture production (Figs 4 and 5). To the extent that increasing pasture Mg content increases animal Mg intake, this suggests that there is potential to decrease the incidence of hypomagnesaemia through the use of fertiliser Mg.

MAGNESIUM REQUIREMENTS FOR ANIMALS

Grace (1983) has reviewed and summarized the dietary requirements of sheep and cattle. A summary of the data he complied is given in Table 3. In discussing these requirements he emphasized that, "it is the total amount of Mg that is ingested *and absorbed* [authors emphasis] which is important, not just the Mg intake." Comparison of the data in Table 3 with the survey results of Smith & Cornforth (1982) would suggest that the incidence of hypomagnesaemia in New Zealand should be low. This is not the case, as noted by O'Connor et al. (1987), and serves to highlight that the causes of hypomagnesaemia are complex and that pasture Mg concentration is only an approximate measure of Mg absorption by the animal.

Part of this complexity arises because of the interactions between Mg on the one hand and K and Ca on the other. These interactions not only occur at the soil-plant level, as has already been discussed, but also within the animal (Grace 1983; Morton et al. 2000). Grace (1983) listed some of the factors which restrict Mg absorption in animals including: organic acids, carbohydrates, protein, and long chain fatty acids, but emphasized that K intake "has by far the greatest effect on reducing the absorption of Mg in the grazing ruminant." He cited an example where a twofold increase in K intake reduced Mg absorption from 41% to 35%.

Feyter et al. (1986a,b) surveyed 119 dairy farms in the Waikato and found that herd Mg status in spring was positively related to herd feeding level and animal breed, and negatively related to topography and potassium inputs. This would seem to confirm that K inputs reduce animal Mg status. In subsequent work they found that milk production was positively related to K inputs, an effect they argued was coincidental rather than causative. However, the important practical finding from this work was that the level of feeding, and hence total Mg intake, is the most important determinant of animal Mg status and milk production.

In a trial in Taranaki (Thomson 1981), the application of lime (5 tonnes ha^{-1}) in early spring increased the incidence of hypomagnesaemia. The cause of this effect is not clear. It may have resulted from liming decreasing herbage Mg, as has been discussed and hence decreasing animal Mg intake. Alternatively, it could been a consequence of suppressed absorption of Mg by the animals resulting from an increase in Ca intake, either from the higher internal pasture Ca content or from lime adhering to the pasture.

Thus, while there is a need to be cognisant of the potential effects of K and lime on the absorption and utilization of Mg by animals, optimal feeding of animals, particularly in early lactation, appears to be the best protection against hypomagnesaemia. This is also a further reason to suggest that inputs of K and lime should be avoided until late spring after calving has been completed.

McNaught et al. (1973a) determined the relationship between soil Mg and the Mg concentration of mixed pasture in the early spring on an Allophanic soil. From this they calculated the amount of fertiliser Mg, and the associated soil QT Mg level, to achieve successive incremental increases in spring pasture Mg concentrations of 0.03% (Fig 7). These calculations demonstrate the logarithmic relationship bettween pasture and soil Mg. The first incremental increase in spring pasture Mg from 0.14% to 0.17%, required an input of 25 kg Mg ha^{-1}. However, 90 kg Mg ha^{-1} was required to increase plant Mg from 0.28% to 0.31%. In other words, as the soil Mg status increases, increasingly greater inputs of Mg are required to achieve the same incremental increase in plant Mg. Such results demonstrate that large inputs of fertiliser Mg, over and above that required to overcome pasture Mg deficiency, are required to provide protection against hypomagnesaemia. Accordingly, McNaught et al. (1973a,b) argued that fertiliser Mg was not as cost-effective as other remedial options, such as pasture dusting, drenching or adding Mg to the drinking water.

O'Connor et al. (1987) set out to test this hypothesis. On a soil with medium soil Mg status (Mg QT 20), they measured the incidence of hypomagnesaemia in dairy cows at three levels of Mg fertiliser input: 0, 60 and 120 kg Mg ha^{-1} (applied as MgO). They found that 120 kg Mg ha^{-1} significantly increased soil (45%), plant (24%) and animal Mg status (32%), and accordingly, reduced, although did not eliminate, the incidence of hypomagnesaemia. The lower input (60 kg Mg ha^{-1}) had a similar effect in the first year, but this was not sustained in year 2. Unfortunately this trial was terminated after 2 years so that the longevity, and hence the economic benefits of the effects of single high inputs of fertiliser Mg could not be quantified. Nevertheless, this experiment showed that, in theory at least, hypomagnesaemia could be managed, although not eliminated entirely, by increasing the soil Mg status to QT Mg 25-30.

In practice, the data in Table 3, taken together with the results of McNaught et al. (1973b) and O'Connor et al. (1987), have been interpreted to mean that a minimum mixed herbage Mg concentration in the spring of 0.18%-0.20% is required to meet the animal dietary requirements, at least for lactating dairy and beef animals (Roberts & Morton 1999), and that soil Mg levels of QT 25-30 (exchangeable Mg 1.05 to 1.26 cmol Mg kg^{-1}) are required to achieve such mixed herbage pasture concentrations. Applying this criteria to the distribution data in Fig 1 would suggest that about 30% of New Zealand soils are Mg deficient in respect to meeting the lactating animal's spring pasture requirements. This is similar to O'Connor's estimate that 30-50% of New Zealand dairy herd is affected by hypomagnesaemia.

MAGNESIUM BALANCE IN PASTURES

Metson (1974) concluded that it was difficult to construct Mg balance sheets because of the difficulty of measuring some components, notably Mg leaching losses. From the available data he could only conclude qualitatively that, in the absence of fertiliser Mg, outgoings (leaching, product removal) typically exceed inputs (rainfall).

Monaghan et al. (2000) measured leaching losses of Mg over a four-year period on a poorly drained Pallic soil (rainfall 1000 mm) under intensive grazing (2-3 cows ha^{-1})

in Southland. The average annual loss was 9 kg Mg $ha^{-1}yr^{-1}$. This is consistent with the data reviewed by Metson (1974) who concluded that Mg leaching losses were typically 8-15 kg Mg $ha^{-1}yr^{-1}$. However, under more intensive conditions in the Waikato on an Allophanic soil (rainfall 1200mm, 3-4 cows ha^{-1}) leaching losses were higher (21-46 kg Mg $^{-1}$ha yr^{-1}) and were related to the total drainage (Rajendram et al. 1998). Given that inputs of superphosphate, potash and lime, together with urine deposition, exacerbate Mg leaching, as discussed earlier, it is reasonable to suggest that leaching losses of Mg increase with intensification.

From these and other data, Roberts & Morton (1998) and Monaghan et al. (2002) constructed Mg balances for typical dairy farms in Southland and the Waikato. Measured inputs of Mg via rainfall (3 and 5 kg Mg $ha^{-1}yr^{-1}$ at the Southland and Hamilton sites respectively) were consistent with the data reviewed by Metson (1974) who reported inputs ranging from 3-19 kg Mg $ha^{-1}yr^{-1}$ depending on proximity to the coast. In both examples there were significant inputs of Mg via the drenching of cows and dusting of pastures, two widespread management practices used in New Zealand dairy farming to alleviate hypomagnesaemia. Also, small inputs of Mg occur because Mg is a contaminant in the superphosphate, the commonly used source of P and S in New Zealand.

Using these and other data, Carey and Metherell (2002) have developed a Mg nutrient model for pastoral agriculture. In particular it contains sub-models for predicting Mg inputs from rainfall and weathering of soil minerals, and Mg losses as leaching and transfer to non-productive areas. The inputs from rainfall were based largely on data from Southland and, assuming a rainfall of about 1000 to 1200 mm, predicted inputs of about 10-12 kg Mg $ha^{-1}yr^{-1}$ at the coast, reducing to <1 kg Mg $ha^{-1}yr^{-1}$ at distances > 100km, consistent with the measured inputs reviewed above.

The input of Mg from weathering was estimated by modifying a soil-weathering model to New Zealand conditions. This suggested very small inputs of Mg from "nothing to a few kilograms," but they noted the model was very unstable in the sense that small additions of easily weathered Mg minerals greatly increased the amount of available Mg from this source. This is perhaps a reiteration of Metson and coworkers's finding (Kidson et al. 1976) that non-exchangeable Mg contributed to exchangeable Mg only where its level in the soil was high. Carey and Metherell (2002) derived an empirical model for predicting Mg leaching losses, which accounted for 72% of the variance in the available measured data. It depended on three factors: the quantity of drainage, the soil group, and the proportion of exchangeable Mg on the exchange complex.

Using this model they constructed Mg nutrient budgets for four pastoral farming scenarios (Table 4). In the absence of inputs from fertiliser the Mg balance was negative under dairying on volcanic and sedimentary soils. This would explain why there has been a gradual decline in soil Mg levels (Fig 3) on these soil groups. On the pumice soils there is small a positive Mg balance, but only given maintenance inputs of fertiliser Mg. This also is consistent with the data in Fig 3. Under intensive sheep farming there is a small positive balance of Mg, but this is only the case where there is significant input of Mg via irrigation. For example, intensive sheep farming is practiced in Southland under natural rainfall. Under these circumstances a negative Mg balance is predicted.

This evidence suggests, therefore, that under dairying the net losses of Mg are typically in the range from 5 to 20 kg Mg $ha^{-1}yr^{-1}$ depending particularly on the degree of intensification (i.e. inputs of superphosphate, potash, lime and deposition of urine), rainfall, soil texture and proximity to the coast. The situation in sheep and beef operations will differ from this only in as much as they are generally, but not always, less intensive than dairying. Thus, in the absence of fertiliser Mg, it appears that most of the soils used for dairy and a large proportion (based on stock units carried) of those used for sheep and beef farming are in a negative balance with respect to Mg. The use of Mg fertiliser must increase if these land uses are to be sustainable at current production levels.

If it is assumed that 1 QT Mg unit is equivalent to 0.29 kg Mg ha^{-1}75 mm^{-1} depth (Cornforth & Sinclair 1984) then a net loss of 5 - 20 kg Mg ha^{-1}75$mm^{-1}yr^{-1}$ will represent a decrease of approximately 1.5 - 6.0 QT Mg units yr^{-1}, assuming that non-exchangeable Mg makes no contribution to exchangeable Mg over time. On this basis, for a soil currently at QT Mg 20 it would take about 2-7 years, depending on the actual rate of net loss, for the soil to become depleted in Mg such that pasture production would be affected. More typically, the average New Zealand soil has a Mg concentration equivalent to QT Mg 35 (Fig. 1). If the average rate of net loss of Mg was 10 kg Mg $ha^{-1}yr^{--1}$ then it would take about a decade before the soil Mg reserves were depleted to the extent that significant losses in pasture production would occur (QT Mg < 5). In practice, it appears the rate of depletion of soil Mg reserves may not be as fast as this. For example the rate of decline in QT Mg derived from the linear part of Fig. 3 suggests an average depletion rate of QT Mg 0.5 yr^{-1}. This would suggest there are sufficient Mg reserves for about 20 years. Whatever the exact figure, it is clear that Mg fertiliser must become part of normal fertiliser practice on many farms in New Zealand pastoral industry.

MAGNESIUM FERTILISERS

Agronomic effectiveness

There are many sources of Mg suitable for use as fertilisers, and Metson (1974) has exhaustively described and discussed their chemistry and other characteristics. These range from soluble materials, such as the magnesium sulphates, to the sparingly soluble carbonates and oxides, and then the generally insoluble silicate minerals. There have been many field trials in New Zealand designed to examine the relative effectiveness of these various sources of Mg fertiliser (Table 1). Unfortunately this work has not been systematic. For example, there have been no trials on Mg-deficient sites that have compared the whole range of products available. Nevertheless some broad conclusions are possible from the available field data.

For example, the results in Fig. 8 (McNaught et al. 1973a) shows that MgO has its maximum effect on plant Mg concentrations within 6 months whereas dolomite does not achieve its maximum effect until 24 months after application. Similarly, the results of McNaught et al (1968b) show that serpentine super is quicker acting than dolomite. Hogg & Karlovsky (1968) compared a number of Mg sources by measuring pasture Mg uptake over a 2-year period on a deficient soil. Their essential results are given in Table 5. These results demonstrate that serpentine superphosphate is as effective as kieserite when compared on an equal weight of soluble Mg, and is more effective than dolomite even when finely ground. Interestingly, dolomite-reverted superphosphate was less effective that dolomite. Hogg & Karlovsky (1968) and later Hogg & Dorofaeff (1976) suggested that this unusual result was due to the greater leaching of P due to the formation of soluble magnesium phosphate.

The least effective materials appear to be magnesite, serpentine and dunite (McNaught et al. 1973b), but Chittenden et al. (1967) suggested that serpentine rock and dunite were as effective as dolomite and magnesite. This work is, however, not convincing because of the lack of experimental replication. More recently, Loganathan et al. (2001) compared an unacidulated and acidulated serpentine with Epsom salts, dolomite and a proprietary product Granmag (granulated MgO) in a field trial and in laboratory incubation experiments. The pasture yields and pasture Mg concentrations from the serpentine-treated pastures were similar to the other treatments, and from this they suggested that unacidulated serpentine may be a useful source of Mg for pastures. However, the site of the field trial had a high Mg status (1 cmol Mg kg^{-1}, QT Mg 24) and therefore it was impossible to draw conclusions regarding the relative effectiveness of various sources of Mg. Similarly, results from closed incubation-type experiments can be ambiguous because of the non-removal of dissolution products, common ion effects and the inability to control pH.

Perrott & Kear (1999, 2000) have developed a laboratory method for comparing the rate of release of nutrients from fertiliser products using a continuous leaching system at a controlled pH, thus overcoming the problems arising from the accumulation of dissolution products and common ion effects. This method gives results which are more closely related to field performance that the batch extraction and incubation-type techniques. Using this technique they have compared the rate of release of Mg from a wide range of products (Table 6) under standard controlled conditions.

These results are consistent with much of the field work, and taken together with it suggest the following order in terms of their speed of reaction in the soil, and hence the speed at which they can effect changes in the soil and plant Mg concentrations:

Epsom salts = kieserite > fine calcined magnesite = serpentine super > coarse calcined magnesite >> calcined brucite = dolomite > dolomite reverted super >> magnesite, serpentine and dunite.

This reactivity sequence follows approximately the solubility of these materials in water or dilute acid, but other product-specific factors, such as particle size and degree of acidulation, and some site-specific factors including soil pH and the drainage of water through the soil, may modify this sequence, at least for the less soluble materials. Also, the position of serpentine superphosphate in this sequence depends on it being compared on soluble Mg basis and not on its total Mg content. Hogg & Karlovsky (1968) and McNaught et al. (1968b) have shown that 70% (range 66%-75%) of the total Mg in serpentine superphosphate is plant available, the remainder (30%) is assumed to have the same availability as serpentine rock.

In practice this sequence can be divided into 3 categories; the more soluble materials such as epsom salts, kieserite, calcined magnesite and serpentine superphosphate, whose effects are immediate (0-6 months) and independent of the product and soil properties; the less reactive materials (dolomite, dolomite-reverted super) which require between 12-24 months to reach their maximum effect, which may be dependant on product and site factors; and the materials which are largely ineffective.

There is, of course, a trade-off between the speed of the effect and its longevity - the more soluble the material the shorter its influence on soil and plant Mg concentrations. This is demonstrated in the results from the only trial that has examined the residual value of some Mg fertilisers (Fig. 8). Accepting that some of these products are too expensive for use in pastoral agriculture, or not available commercially (eg epsom salts and kieserite), and others are ineffective (serpentine and dunite), the remaining products can be categorized, in terms of their Mg availability, as shown in Table 7.

Fertiliser Magnesium Strategies

There are several reasons for applying Mg fertilisers and, apart from price, the choice of Mg fertiliser should depend on the particular purpose (Table 8). In the extreme, if there is an urgent need to eliminate Mg deficiency one of the more quick-acting products, such as kieserite, MgO or serpentine super should be used. The latter would be used if there was also a need for the nutrient P and S. If a large capital input of Mg was required, such as would be the case to raise the soil Mg level to QT Mg 25-30, MgO would be more suitable. An input of serpentine super sufficient to apply 100 kg Mg ha^{-1} would result in excessive inputs of P and S for most situations. However, where the intention is to maintain soil Mg levels or increase them slowly over many years, slow release materials such as dolomite will also be effective.

CONCLUSIONS

Considerable progress has been made since Metson's (1974) review, particularly in respect to refining the criteria for diagnosing and managing Mg deficiency in soils, pastures and animals. Extreme deficiency resulting in the loss of production in legume-based pastures occurs if the soil Mg concentration is < QT Mg 4-5 and the mixed herbage Mg concentration is < 0.10%. Achieving and maintaining soils at > QT Mg 8-10 ensures that the probability of Mg deficiency in respect to pasture production is small. The evidence shows that even the most extreme deficiencies can be eliminated with inputs of about 25 kg Mg ha^{-1} yr^{-1}, and balance studies indicate that soil Mg levels can be maintained with inputs of between 5-30 kg Mg ha^{-1} yr^{-1} depending particularly on the type of operation (dairying or sheep and beef) and the leaching regime of the soil. Cost-effective Mg fertilisers are available in either readily available or slow release forms for capital and maintenance inputs.

Overcoming Mg deficiency in pastures does not, however, eliminate the risk of hypomagnesaemia in lactating ruminants. The evidence indicates that, assuming an adequate feed intake, animal Mg requirements during early lactation can only be meet if the pasture Mg concentration is > 0.20%. This is possible if the soil Mg level is QT Mg 25-30 or above, but such levels can only be achieved on many New Zealand soils with large capital inputs of fertiliser Mg (> 100 kg Mg ha^{-1}). Further research is required to quantify the economics of this approach. Such work need not require the measurement of pasture and animal production. Simple trials covering a range of soil groups which measure the longevity of the effects of large capital inputs of fertiliser Mg on soil and pasture Mg levels, and the change in soil Mg per unit fertiliser Mg applied, will be sufficient to apply simple economic theory. Until such calculations are made there can be no resolution to the perennial question: are the most common methods used in New Zealand for minimizing the risk of hypomagnesaemia (eg direct supplementation via drenching, pasture dusting and water treatment), the cheapest options?

Progress has been made in understanding those factors which affect pasture Mg concentrations including: pasture species, season and the interactions with inputs of Ca and K. This work collectively has provided a qualitative understanding of the those factors which are important in the management of soil and plant Mg and have resulted in refinements to management practices, especially related to the timing of soil nutrient and lime inputs and animal supplementation. It would be desirable, however, to develop pasture cultivars which have inherently higher Mg concentrations that are less affected by these factors. A greater understanding of these processes at the physiological level of the plant, coupled with modern gene technologies may provide the means for this advancement.

Recent nutrient-budgeting studies suggest that most pastoral soils, and particularly those under dairying, are in a negative balance with respect to Mg. This is supported from survey data showing that soil Mg levels are declining, except where the use of fertiliser Mg has become routine, such as on the Pumice soils. This has important implications for the sustainability of New Zealands pastoral system. Most New Zealand soils currently have significant reserves of Mg, as both exchangeable and non-exchangeable Mg, but it is inevitable that, in the absence of fertiliser Mg inputs, the incidence of Mg deficiency in pastures and animals will increase within the next few decades. This scenario can be managed to some extent with existing knowledge and technology by regular monitoring of soil Mg levels and nutrient budgeting, but the limitation in this approach is the lack of information about rate of release of Mg from soil minerals - that pool of Mg best defined as non-exchangeable but slowly available Mg. In this respect very little progress has been made, or as Meston (1974) noted; “This points again to the need for methods of assessing the rate of replenishment of magnesium from non-exchangeable sources.”

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CAPTIONS FOR FIGURES

Fig 1 The cumulative frequency distribution of soil magnesium concentrations (cmol kg^{-1}) from 97 topsoils under developed pasture (from Perrott et al. 1995).

Fig 2 Trends in soil magnesium concentrations (Quick Test Mg) over time on sheep and beef and dairy farms (Wheeler et al. 2003).

Fig 3 The effect of inputs of potassium on pasture magnesium concentrations (Morton et al. 2000).

Fig 4 Effect of fertiliser magnesium on pasture production and pasture magnesium concentration on a Pumice soil (mean of 2 years) (AgResearch Ltd unpublished trial number MAF 1015/3, see Table 1 for trial description).

Fig 5 Effect of fertiliser magnesium on pasture production and pasture magnesium concentration on a Pumice soil (mean of 5 years) (AgResearch Ltd unpublished trial number MAF 1015/3, see Table 1 for trial description).

Fig 6 Effect of season and serpentine superphosphate on the magnesium concentration in clover and grasses (McNaught et al. 1968a).

Fig 7 Fertiliser magnesium inputs required to achieve incremental increases in spring pasture magnesium concentration and soil magnesium status (from McNaught et al. 1973a)

Fig 8 Effect of fertiliser magnesium and time after application on pasture magnesium uptake (McNaught et al. 1973a).