SOIL FACTORS AFFECTING MAGNESIUM AVAILABILITY IN PLANT-ANIMAL SYSTEMS: A REVIEW[1]

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ABSTRACT

Soils provide the support, water and most of the nutrient elements, including Mg, needed for plant growth. Magnesium uptake by plants depends largely on the amount, concentration and activity of Mg in the soil solution and the capacity of the soil to replenish Mg in the soil solution. The availability of Mg depends on the activity or proportion of Mg relative to soluble and exchangeable amounts of K, Ca, Na, Al and Mn. In humid regions, Mg losses from leaching are often greatest from agroecosystems receiving heavy N fertilization. Cool-season grasses produce nearly maximum growth at herbage concentrations of 1 to 1.5 g Mg/kg, 25 g K/kg and 30 g N/kg of dry matter. At these concentrations of N and K, herbage should contain about 2.5 g Mg/kg to avoid inducing hypomagnesemic grass tetany in ruminants. To increase herbage Mg concentration to this level often requires, except on sandy soils, an uneconomically large addition of Mg fertilizer. Adjusting soil conditions to produce grasses with a low-tetany potential may not always be possible physically. The risk of tetany can be reduced by a judicious program of well-timed N, K and Mg fertilizer applications. However, direct Mg supplementation of grazing ruminants is considered more cost-effective than is Mg fertilization to prevent grass tetany.
(Key Words: Grass Tetany, Magnesium Fertilizers, Soil Chemistry, Nutrient Cycles, Soil, Plant Nutrient Concentration.)

Introduction

Soils are reservoirs of nutrients and water for plant growth. Nutrient availability to plants depends on the concentration, content and activity of each nutrient in the soil. This paper reviews abiotic factors affecting availability of Mg for plant uptake and how these factors may affect hypomagnesemic tetany (defined as <2.0 mg Mg/dl blood serum) in grazing ruminants. A discussion of the Mg cycle describes the various pools and how this element moves from one pool to another.

Parent Materials

Magnesium, Ca, K and Na, on the average, make up 21, 36, 26 and 36 g/kg of the lithosphere, respectively (Baker and Risser, 1983). Magnesium is readily leached upon weathering from most Mg-bearing minerals. As a result, soils contain an average of only 5 g Mg/kg.

Soils formed from granites, sandstone and most shales are relatively low in total Mg. Soils formed from mafic igneous rocks contain substantial amounts of ferromagnesian minerals. Without severe weathering and leaching, soils derived from mafic igneous materials will have large amounts of available Mg (Ellis, 1979). Limestone contains from 30 to 120 g Mg/kg. Soils developed from serpentine parent material or those that may contain dolomite or magnesite have a relatively high concentration of Mg. However, the Mg composition of the soil cannot be predicted solely from the parent

material composition because of differences in the degree of weathering and leaching.

Clay Mineralogy

The structural and exchangeable Mg contained in soil is related to the clay minerals present. The exchangeable form of Mg is most important for plant nutrition. Soils containing mostly kaolinitic clays are highly weathered and have low Ca and Mg availability.

Chlorite, vermiculite, and montmorillonite clays have undergone intermediate weathering and still contain some Mg as part of their structure. These clays have a relatively high Mg content, in the order chlorite > vermiculite > montmorillonite, but the rate of Mg release may be very slow. Illite clays contain Mg in their structure, but it is not readily available. In illite, K is released much more easily than Mg, thus reducing Mg availability to plants and animals (Baker, 1972).

Vermiculite and montmorillonite are the predominant Mg-supplying clays in the southeastern (Baker, 1972) and western (Mayland and Grunes, 1974, 1979) parts of the U.S., respectively. In these areas, Mg is adequate for plant growth, but grass tetany still occurs in cattle grazing plants in these regions because of various and complex factors. More detailed information on Mg and clay mineralogy is available from Baker and Risser (1983), Christenson and Doll (1973) and Metson (1974).

Ion Movement in Soils

Ions move from the solid phase to the root by several mechanisms (Barber, 1984). Mass transport of ions occurs as ions are carried along with the soil water absorbed by plant roots. This process is driven by the evapotranspiration demand on plant foliage and is more important in situations of low rather than of high humidity. This mechanism supplies enough Mg and Ca at the root surface to satisfy plant requirements in most soils. It does not provide enough K or P to meet plant needs. The ion flow rate is determined by the evapotranspiration rate and the ratio of transpiring surface area to root absorbing surface.

Diffusion is another important mechanism of ion transport. It occurs when ions in the soil solution move from zones of high concentration to zones of lower concentration near or in the root rhizosphere (Barber, 1984). Diffusion

rates of K, Ca and Mg increase with soil water content, salt concentration and temperature (Schaff and Skogley, 1982).

Adding salt to the soil solution raises the effective diffusion coefficients for divalent cations, such as Mg, more than those for monovalent cations (Mullins and Edwards, 1987). This may explain the benefit of NaCl applications to pastures in Ireland where some believe that this practice reduces the incidence of grass tetany (Benians, 1985). Adding Na ions also may reduce the negative effects of K uptake on forage Mg concentrations.

Roots also might come into direct physical contact with the soil-particle surface and directly exchange H^+ for other soil sorbed ions like Mg. The chance of direct exchange of nutrients between the root surface and the soil particle is very low. This mechanism accounts for only insignificant amounts of Mg uptake by plants (Barber, 1984).

Potassium

The interaction of K on reducing Mg concentration in plant tops is well documented (Wilkinson, 1983). Heavy applications of K fertilizer to pastures increase the incidence of grass tetany. Ohno and Grunes (1985) investigated the K-Mg interactions and reported that increasing K supply depressed Mg concentrations in plant tops, but not in roots. They concluded that the K inhibits translocation of Mg from the root to the plant top.

Acid Soils

In acid soils, Mg uptake by plants is reduced by K, Ca, Al, H, Mn and NH_4. The critical soil Mg concentration for maximum crop yield is higher in acid than in neutral soils (Ferrari and Sluisman, 1955; Stenuit and Piot, 1958). Soluble or exchangeable Al in soil interferes with uptake of Ca and Mg more than that of K, thereby increasing $K/(Ca + Mg)$ values (D. L. Robinson, personal communication). Aluminum is not soluble in soils having pH 5.2 to 9.0, but it is increasingly soluble as soil pH falls below 5.2. Soluble Al is toxic to root growth of many crops and results in reduced cation uptake. Subsoils of Ultisols and Oxisols often have toxic concentrations of soluble Al (more than 2 mmol/kg).

Manganese is a toxic element in soils only rarely, because higher amounts of Mn than of Al are required to produce toxicity. Reducing

conditions and low soil pH can produce Mn toxicity, which usually affects shoots more than roots. Manganese can reduce Mg uptake in plants.

Ammonium N is antagonistic to the uptake of Mg by plants, whereas NO_3 fertilization often enhances Mg uptake (Mayland and Grunes, 1979). An interaction can occur with NO_3 fertilization that may result in NO_3 stimulating K uptake, which in turn inhibits Mg translocation to plant tops.

Calcareous or Alkaline Soils

Magnesium activity in alkaline soils is influenced by the proportions of competing ions, whether they be Ca, Na or K. Magnesium uptake in calcareous alkaline soils can be reduced by Ca, and sometimes by K. Gypsum applications reduce Mg concentrations in plants growing on alkaline soils.

Soil Organic Matter

Small amounts of Mg are adsorbed to soil organic matter. Increasing soil organic matter concentrations increases the exchangeable cation capacity and improves the Mg supply available for plant uptake. The organically complexed Mg is an important source of Mg in some soils (Mathan and Rao, 1982).

Soil Testing

Soil testing provides rapid assessment of season-long nutrient availability to crops. Two tests for soil Mg are commonly used in the U.S.: 1) extraction with a double acid (.05 N HCl in .025 N H_2SO_4) and 2) extraction with neutral, 1 N ammonium acetate. The extractant:soil ratios, shaking times and concentration and pH of the extractants vary (Nelson and Jones, 1972).

Results from the two extractants are similar for sandy soils. The ammonium acetate procedure extracts more Mg from soils with neutral to alkaline pH, high clay, or high organic matter concentrations than does the double acid procedure. The double acid procedure gives erroneously high results if the soil contains dolomitic limestone or other acid-soluble Mg.

Baker's (1971) approach to soil testing was to equilibrate a soil sample with an idealized soil solution. The nutrient composition of this solution was assumed to provide good plant growth. He then determined the sorption or desorption of cations from the sample and used the information to develop fertilizer recommendations.

Agronomic practices have intensified over the last three decades. Today more N, P and K fertilizers are applied to meet crop requirements. Plant responses to Mg fertilization are measured more frequently now. Critical Mg soil test levels, for plant requirements, will range from 25 to 100 mg Mg/kg soil, depending on the soil and soil testing procedure used (Nelson and Jones, 1972).

Plant response to Mg soil test level is related to the exchange capacity (CEC) ratio of Mg to total soil cation. When the percent base saturation of Mg decreases to 5%, plant Mg deficiencies are likely to occur.

Animals require a higher dietary Mg concentration than is needed for plant growth (Wilkinson et al., 1987). Mayland (1983) noted that the critical concentration of Mg for adequate plant growth in cereal and forage grass was <1.3 mg Mg/g. This is less than the 2.5 mg Mg/g of forage required by animals during the grass tetany season (Prins et al., 1986). Thus, fertilization should be employed to raise soil-Mg test levels to 10% of base saturation or higher.

Plant availability of soil Mg and other cations also is related to the cation activity ratios in the soil solution. The approximate critical activity ratio for Mg/K (molar basis) should be .5 for good growth (Beckett, 1972). Beringer (1985) noted that only 10% of the K taken up by plants was supplied by mass flow. Larger quantities of Mg and Ca moved toward the root than were absorbed, resulting in the accumulation of these two cations near the root surface.

Under some conditions, the K moving by mass flow is high enough to exceed root absorption. This may occur in soils having high K concentrations or low CEC values and adequate soil moisture allowing maximum evapotranspiration. Ohno et al. (1985) showed that K uptake is regulated primarily by K diffusion from the soil to the plant root and that Mg uptake is regulated by active plant uptake rather than by nutrient transport through the soil solution.

The electro-ultrafiltration technique determines relative solubility of soil nutrients by using an electrical field to separate soil

nutrients from a soil suspension. Voltage is increased during separation. Nutrients obtained at lower voltages represent available nutrient fractions, and those obtained only at higher voltages have lower availability. The technique, now under intensive evaluation in Europe, has received little attention in the U.S. According to Loch (1985), the technique is gaining acceptance in assessing nutrient status. Plant uptake of Mg is related to Mg in electro-ultrafiltration extracts, but improvement still is expected in the extraction procedure.

Magnesium Fertilizers

Effectiveness of Mg fertilizers is determined primarily by their particle size and water solubility. Magnesium fertilizer sources include the oxide, sulfate, carbonate, nitrate, chloride, phosphate or silicate forms. Selected Mg fertilizers are described in Table 1. Wilkinson (1983) presents a more comprehensive listing of Mg fertilizers.

Mortvedt and Kelsoe (1988) found that $MgSO_4$, MgO, $MgCO_3$ and Mg oxysulfate (MgO partially acidulated with H_2SO_4 to contain 36% Mg and 6% S) all gave similar forage yields with particle sizes less than .2 mm. Granular MgO and Mg-oxysulfate produced corn forage yields similar to those obtained with particles less than .2 mm in size when granular size was small (1.4 to 2.0 mm). However, Mg solubility decreased as granule size increased. Nevertheless, residual effects for subsequent crops are greater for the larger granule sizes.

Particle size and water solubility are two factors that can be regulated to control release rates of available Mg to soil solution. For example, formulating fertilizers with large particle sizes of high solubility material or very fine particle sizes with low solubility material might be useful in controlling release rates of soluble Mg to soil solution.

Magnesium deficiencies are most likely to occur on acid, sandy soils in humid regions and on soils with very high to excessive K availability. Some organic soils, and soils with shallow rooting depths, also may suffer from Mg deficiencies, especially when they are liberally fertilized with K fertilizer. Foliar or soil application of Mg fertilizer is recommended where Mg deficiencies occur in plants. Applying larger amounts of Mg to soil to increase forage Mg to concentrations required

TABLE 1. SOME MAGNESIUM FERTILIZER SOURCES

Name	Water solubility	% Mg	Remarks
Magnesia (Calcined magnesite) (MgO)	Slightly soluble	56	Very effective source for acid soils under moderate to high rainfalls (>900 mm)
Epsom's salts ($MgSO_4 \cdot 7H_2O$)	Very soluble	10	Expensive, very effective, especially for calcareous or high pH soils
Kieserite ($MgSO_4 \cdot H_2O$)	Soluble	16	Effective
Potassium-magnesium sulfate ($K_2SO_4 \cdot MgSO_4$)	Soluble	11	Sol-PO-Mag or K-Mag not recommended where low Mg concentration in plants is associated with high soil K
Serpentine ($Mg_6Si_4O_{10}(OH)_8$)	Insoluble	22	Effective only at high rates in acid soils when finely ground
Dolomite	Insoluble	16	Finely ground material is necessary to achieve rapid effects. An amendment to increase pH of acid soils, as well as to supply Mg
Mg oxysulfate	Soluble to slightly soluble	36	MgO partially acidulated with H_2SO_4 to contain 6% S. Seventeen percent of the Mg is $MgSO_4$, which is readily soluble whereas the remaining MgO form provides slow continual release

by animals often is considered uneconomical except on coarsely textured soils.

Magnesium deficiency in grasses occurs when leaf Mg concentrations decrease below 1.3 mg Mg/g, whereas safe Mg concentrations to prevent grass tetany may require 2.5 mg Mg/g, or greater, concentrations. Prins et al. (1986) suggests that when grass contains 40 mg N/g and 35 mg K/g, herbage Mg concentration should be 2.5 mg/g. It is likely that 2.0 mg Mg/g would be enough in more mature grass containing less than 32 mg N/g and 30 mg K/g. Prins et al. (1986) also suggest that herbage K should increase with herbage N to avoid a reduction in dry matter yield. For example, herbage containing 24 mg N/g required 27 mg K/g for maximum yield, whereas forage containing 48 mg N/g required 39 mg K/g.

Magnesium fertilization studies have been reviewed extensively (Ellis, 1979; Wilkinson and Stuedemann, 1979). Potassium and N fertilization and N and K concentrations in herbage are key factors for pasture management to prevent grass tetany (DeGroot, 1970; Hodge and Bell, 1983; Prins et al., 1986). Fertilization to prevent hypomagnesemic grass tetany also must provide adequate N and K for desired herbage growth, but without diminishing Mg uptake. This subject is discussed specifically for humid-region pastures by Wilkinson (1983).

Fertilization with Mg only may prevent Mg deficiency in plants, but reaching Mg concentrations in herbage that are safe for ruminants may require changing the N and K pasture fertilization practice. Dolomitic limestone is the recommended Mg source when soil pH must be increased. Soluble Mg fertilizers or MgO are recommended when soil pH needs no adjustment. Magnesium sulfate and K-Mg sulfate fertilizers (Langbeinite) are recommended for calcareous or saline soils. High Mg fertilizer rates may be required on Mg-deficient, alkaline soils because of the large amounts of Ca, Na and K present.

Surface placement of soluble Mg fertilizers is satisfactory, but soil incorporation is recommended for less-soluble Mg sources. Effectiveness of surface applications of insoluble, or slightly soluble, materials depends on particle size.

Dolomitic limestone must be ground to at least 60 mesh (.4 mm) to be effective in neutralizing soil acidity. Dolomitic limestone coarser than 20 mesh (1.3 mm) is ineffective for changing soil pH or supplying Mg to plants. As a source of Mg, dolomitic limestone is more effective at pH below 6.0 than above 6.0 and is more effective when incorporated into the soil.

Foliar sprays made from soluble Mg salts ($MgSO_4$, $MgCl_2$, $MgNO_3$, Mg chelate) may be effective in correcting crop Mg deficiency, but sprays usually must be repeated to maximize yield. It is difficult to raise Mg concentrations to safe levels of 2.0 to 2.5 mg Mg/g when pasture herbage contains 30 mg K/g. Foliar dusting with 20 to 50 kg MgO/ha has been used in the Netherlands, Ireland and New Zealand to achieve the concentrations of Mg intake in cattle necessary to prevent hypomagnesemic grass tetany. A 4- to 6-d protection period was noted for rotational grazing and up to 3 wk was noted for continuous grazing (summarized by Wilkinson et al., 1973). The effective period of MgO dusting depends on intensity of rain or wind, density of herbage at time of dusting, herbage growth rate and forage utilization rate.

Dusting tall fescue pastures with MgO was investigated at the Southern Piedmont Conservation Research Center, Watkinsville, GA. Dusting was effective only when enough grass was available at the time of dusting to provide grazing for two or more weeks and when rainfall did not wash the MgO from the leaves. This practice was not satisfactory in North Georgia because of the greater rainfall frequency during the tetany season. Therefore, a MgO-bentonite-water slurry was applied to the grass at a rate of 26 kg MgO/ha with a suspension-fertilizer applicator. The technique was highly effective in preventing outbreaks of grass tetany. Drawbacks include the need to maintain suspensions and their application cost (Wilkinson and Stuedemann, 1979). Suspensions of MgO now are available for easy addition to liquid fertilizers.

Liming

Liming (CaO) of acid soils to near-neutrality is a factor that reduces Mg available to the plant in acid soils containing 10 to 80 mmol/kg exchangeable Al (Myers et al., 1988). Upon liming, the added Ca displaces some of the exchangeable Mg and Al, reducing available Mg. The mechanism is thought to be an occlusion or coprecipitation of Mg with Al.

TABLE 2. DISTRIBUTION OF MG IN SURFACE SOILS COLLECTED FROM THREE CONTINENTS

Reference and measurement	Mineral Mg	Acid-soluble Mg	Exchange Mg	Organic complex Mg	Total Mg
	meq/100 g[a] (% of total Mg)				
Mokwunye and Melsted (1972)					
Mean	9.0 (56%)	4.2 (26%)	2.6 (16%)	.17 (1%)	16 (100%)
Range	1.0 to 28	.49 to 13	.40 to 11	.05 to .71	2.9 to 45
Mathan and Rao (1982)					
Mean	2.1 (28%)	1.8 (24%)	1.9 (26%)	1.6 (22%)	7.4 (100%)
Range	1.2 to 5.3	.6 to 3.3	.2 to 7.1	.3 to 2.8	2.0 to 13

[a]1 meq/100 g is equivalent to 120 ppm Mg.

This phenomenon is especially critical in highly acidic soils with low levels of native exchangeable Mg. Magnesium fixation occurs primarily in soils with a pH-dependent charge, as in some Ultisols (Myers et al., 1988). Liming with calcitic materials also displaces Mg into soil solution and enhances leaching of Mg (Edmeades et al., 1985). This may be particularly noticeable in pastures where hypomagnesemia in grazing cattle is a problem.

Magnesium Cycling

The Mg cycle describes the quantities of Mg moving into (gains) and out of (losses) various parts (pools) of the ecosystem. Magnesium is not volatile, so it cycles by water-mediated biological and physical means. It is therefore integrally involved with the hydrologic cycle.

Magnesium pools, in a pasture system, consist of Mg in water, soil, plants and animals. The plant pools are further subdivided into roots and residues of plant parts not harvested or grazed. The animal pools are partitioned into animals and their fecal and urinary residues. The soil pools may be subdivided into an available pool (exchangeable and water soluble) and the very slowly available pool in the rooting zone. The unavailable pool includes the nonexchangeable and water-insoluble Mg precipitates and Mg minerals.

Most Mg in the agro-ecosystem is in the soil, with only a small proportion in rapidly cycling pools that include plants, animals, residues and available soil Mg. Soil Mg has been described chemically as occurring in four fractions: the exchangeable and water-soluble, the acid-soluble, the organic complexed, and the mineral Mg fractions. Average Mg concentrations in different soil fractions are given in Table 2. The nonexchangeable fraction is composed of mineral, acid-soluble and organic complexed Mg. These forms often account for most of the Mg in the soil. Acid-soluble Mg may be considered as a Mg reserve and may supply appreciable Mg for crop use. Organically complexed Mg, or immobilized Mg, usually is a small proportion of the total Mg and is not considered an important factor in Mg nutrition of pasture plants. Soils from India (Mathan and Rao, 1982) consistently contained more organically complexed Mg than did the other soils. The amount of Mg contained in soil is influenced by the Mg content of the parent material and the duration and degree of weathering.

Production of 10,000 kg/ha of herbage may involve uptake of 30 kg Mg/ha, of which 23 kg might be consumed by grazing livestock. The animals would retain less than 1 kg Mg in their body tissues but would return to the pastures about 3 kg Mg in urine plus 19 kg Mg in feces. Within the plant segment, 7 kg/ha might be distributed in ungrazed herbage and litter fall. Magnesium contained in animal and plant residues then cycles back to the available and unavailable soil compartments. The availability of this recycled Mg to plants is affected by availability of K.

The same 10,000 kg/ha of herbage may involve uptake of 250 kg K/ha, of which 188 kg K would be consumed by grazing livestock and be recycled, mainly as urine. Urine spots in pastures are high in N and K and have lower Ca and Mg soil test values than areas where urine has not been recently deposited. Joblin and Keogh (1979) found that perennial ryegrass herbage, affected by urine return, had 27% higher N and 28% higher K concentrations. The Ca and Mg concentrations were 20% and 10% lower than ryegrass herbage and thus were not affected by urine return. Fecal

residues are readily mineralized, releasing 97, 62 and slightly less than 62% of the K, Mg and Ca, respectively, to the soil solution.

A similar relative availability exists for return of K, Ca and Mg from vegetation. Potassium turns over rapidly in pasture systems, and this may perpetuate an herbage imbalance in K/(Ca + Mg). By contrast, in a Ghana forest, turnover from vegetation was 35% of the K returned to the soil each year, with 20% of the Mg returned each year (Bennema, 1977). Blair (1988) found that 91% of the K and 58% of Mg in deciduous forest leaves is released to the soil within 2 yr.

Removal of Mg in animal products in inconsequential as far as ecosystem losses are concerned. However, this is not true for leaching losses of Mg. Leaching losses in humid regions frequently are greater than losses due to crop removal. The amount of Mg leached depends on the amount and rate of percolating water, the quantity and form of Mg present in the upper soil layer, and soil type (clay mineral present and texture). The predominant anion present in soil solution, whether it be HCO_3, SO_4, NO_3, Cl or H_2PO_4, also affects ease of leaching because anions move with cations in soil solution. For example, the downward mobility of Ca and Mg with percolating waters decreases in association with anions in the following order: $NO_3 > Cl > SO_4 > PO_4$.

Application of ammonical-nitrogen fertilizers promotes downward mobility of cations, especially of Mg. Leaching losses from ecosystems well-supplied with Mg capable of sustaining soil solution Mg concentrations of 30 mg/liter (1.25 mmol/liter) and 25 cm percolating water per year could lose as much as 75 kg Mg/(ha·yr). Magnesium losses for crops removed from agricultural watersheds or tree harvest in forested watersheds were less than losses to subsurface flow (Lowrance et al., 1985; Johnson et al., 1988). Similar conclusions were reached in Mg balance calculations for intensive pasture production systems in Georgia (Wilkinson and Lowrey, 1973). Nitrate and SO_4 in acid rain may accelerate leaching losses of bases and thereby enhance the potential for hypomagnesemic tetany.

Gains of Mg from precipitation range from 1 to 10 kg/(ha·yr) (Lowrance et al., 1985; Johnson et al., 1988). Fertilizer Mg usually is applied with liming materials. Because most cool-season grass species are somewhat insensitive to soil acidity, liming inputs are postponed or omitted in the interest of economy.

Conclusions and Recommendations

The following factors affect the Mg cycle in grazed cool-season pasture systems: 1) Mg losses due to leaching, 2) use of high-N and -K fertilizers to optimize plant herbage production and 3) acid rain, which increases mobility of soil cations. These should be considered in developing economical fertilizer programs for best yields while still producing a quality forage that carries a minimum risk of producing hypomagnesemic grass tetany.

Further research is needed on the interactions of lime, Al, K and Mg in the production of both cool- and warm-season forages grown on acid, sandy, low-Mg soils receiving moderate to high rates of N. Plant genetic variability in tolerance to soil Al and to variability in ion uptake should be investigated.

Effects of Al on growth and nutrient relationships in plants are poorly understood. At present, Al-tolerant plant cultivars seem to be those that are capable of increasing the soil solution pH. How is this ability related to Mg uptake, and can it be genetically transferred to other plants?

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