Magnesium Usage
By turfgrasses

By Richard J. Hull, University of Rhode Island

Turf is maintained for its uniform presentation of green relaxing hues. Whether intended for athletic competition, recreation or aesthetics, the rich green color of turfgrasses is a prominent feature of its appeal and impact on the landscape. The green color of grass leaves is imparted by the presence in them of a fat-soluble pigment, chlorophyll. This green pigment brings us to the subject of the role of magnesium in turf management. Each chlorophyll molecule is constructed around a magnesium atom. Also, several steps in the biosynthesis of chlorophyll are catalyzed by magnesium requiring ions. In addition, the genetic material, which chlorophyll synthesizing enzymes depend on for expression, is held together by magnesium. In short, magnesium is an essential macronutrient upon which not only chlorophyll synthesis but all plant life depends.

The essential roles played by magnesium in plant growth and function are well recognized. Nevertheless, little research has been reported on its importance for turfgrass culture or on how best to make it available to turf. In their review of turfgrass nutrition, Turner and Hummel (1992) cite

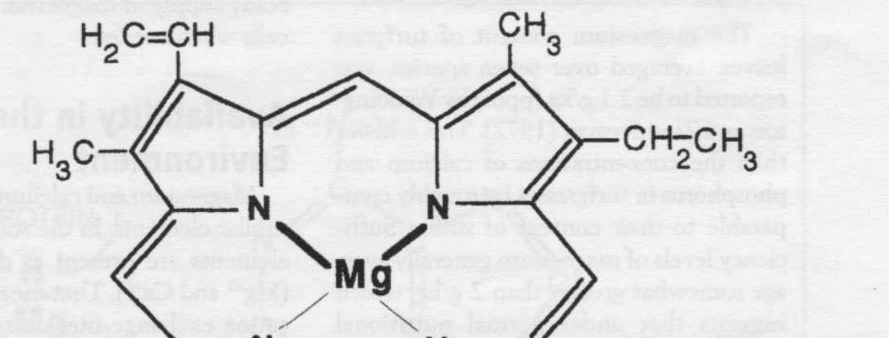

Figure 1. Structure of chlorophyll a showing the bonds formed between four nitrogens covalently binding with a single magnesium atom.

only seven reports on magnesium in turfgrass culture since the middle 1960s. Even the professional turf journals rarely consider the requirements for and management of magnesium in turf. One exception to this trend is an article in Golf Course Management by Rodney Garrett (1996) which described the contributions made by magnesium toward solving some long-standing problems on two golf courses. He mentions several important considerations in managing magnesium on turf, but not in any depth. I will try to provide an overview of magnesium's essential functions and discuss its contributions in the context of turf management for TurfGrass TRENDS readers.

Magnesium and calcium are chemically similar. Both bind to cation exchange sites on soil colloids and are retained within the soil against leaching when rain or irrigation water percolates through the soil profile.

Magnesium in turfgrasses

The magnesium content of turfgrass leaves, averaged over seven species, was reported to be 2.1 g/kg (ppm) by Waddington and Zimmerman (1972). This is lower than the concentrations of calcium and phosphorus in turfgrasses by roughly comparable to their content of sulfur. Sufficiency levels of magnesium generally average somewhat greater than 2 g/kg, which suggests that under normal nutritional management, turfgrasses may be chronically deficient in magnesium. This could be a serious matter as we shall discover later.

Unlike calcium, magnesium is present in plant tissues in a metabolic pool of between 2-10 mM (Leigh and Wyn Jones 1986) while that of free Ca^{+2} is closer to 0.1-0.2 uM (Hull 1997b) or 10,000 times less than Mg^{+2}. This is because Mg^{+2} is intimately involved in many metabolic processes and its concentration within the cytoplasm must be maintained within a fairly tight range. The presence of Ca^{+2} in the cytosol would effectively compete with Mg^{+2} for enzyme binding sites and this would be disastrous to metabolic function. This cytosolic magnesium concentration is stabilized by a large pool of reserve Mg^{+2} maintained within the vacuole where it can reach concentrations of over 100 uM. Considering that the vacuole can constitute 85% of the volume of a mature cell, this represents an enormous reserve supply of magnesium for the cell. This probably explains why magnesium deficiencies do not occur immediately following the withdrawal of available Mg^{+2} from the roots. This also indicates that Mg^{+2} plays an important role in balancing the ionic charge between vacuole and cytosol and in maintaining favorable water relations between the root and soil.

Magnesium shares with calcium the cation exchange sites within the cell walls provided by pectate chains (Hull 1997b). Again because of its stronger ionic bonding, Ca^{+2} dominates the exchange sites within cell walls but Mg^{+2} is present to a significant extent (5-10 percent of the total cell magnesium). This also helps maintain a ready supply of magnesium for use within cells when needed.

Availability in the Soil Environment

Magnesium and calcium are chemically similar elements. In the soil solution, both elements are present as divalent cations (Mg^{+2} and Ca^{+2}). That means they bind to cation exchange sites on soil colloids and are thereby retained within the soil against leaching when rain or irrigation water percolates through the soil profile. The binding strength of cations to exchange sites depends upon the charge strength of the cation and its degree of hydration. Calcium and magnesium have essentially the same charge (+2) but magnesium is more highly hydrated than calcium: diameter of the hydrated ion is 0.64 nm for magnesium and 0.56 nm for calcium (Mengel and Kirkby 1982). The non-hydrated calcium is slightly larger than the non-hydrated magnesium (0.21 vs. 0.16 nm diameter respectively). This larger amount of water surrounding the magnesium ion tends to insulate its charge making it less effective in binding to cation exchange sites. Consequently, Mg^{+2} tends to be displaced from exchange sites by Ca^{+2} when the two ions are present in equivalent amounts.

If pH adjustment is achieved by using ground limestone (calcium carbonate = $CaCO_3$), Mg^{+2} will be displaced from exchange sites and lost during clipping removal if the Mg^{+2} is absorbed by the turf or leached from the root zone if it is not absorbed by roots. In any event, the amount of Mg^{+2} available to turf may become compromised if large quantities of calcium are applied with little regard for the magnesium supply.

A favorable magnesium status in turf is even more at risk because of the unfavorable competition between Mg^{+2} absorption by grass roots and other commonly applied cations. The rate of Mg^{+2} uptake can be strongly depressed by soil cations such as potassium (K+), ammonium (NH_4+), Ca^{+2} and low pH (H+). Consequently, magnesium deficiency induced by competing cations is a fairly common occurrence (Marschner 1995).

In turf management, there is a long tradition of applying adequate potassium to improve the texture of grass blades and increase disease resistance. Because most turfgrasses grow best at a soil pH range of 6.5-7.0, liming materials rich in calcium are often applied in the more humid regions. In areas where rainfall is limited, the soil pH is often near neutral because the soils are naturally enriched with calcium and potassium. In either case, the soil's ionic environment may not favor the uptake of adequate magnesium by turf even when its presence in the soil is reasonably high. This is an important consideration in turf management which will be discussed later.

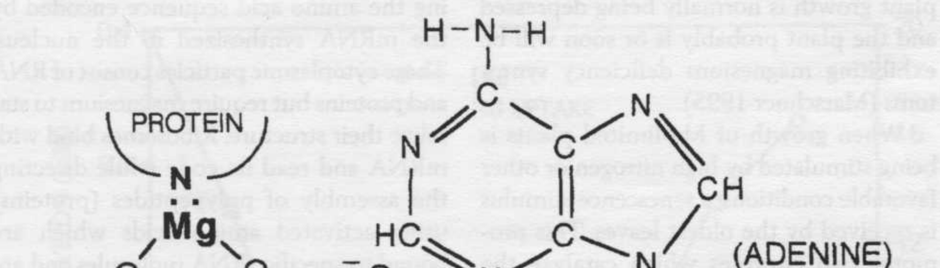

Figure 2. Chemical structure of Mg-Adenosine TriPhosphate (Mg-ATP) binding via a magnesium ion to an enzyme protein in the process of transferring the terminal phosphate of ATP to a metabolite.

Magnesium Functions

Magnesium performs at least four major functions in plant metabolism which will be considered briefly.

Component of chlorophyll. The chlorophyll molecule is coordinated around a magnesium atom to which it is covalently (nonionically) bound (Figure 1). Depending on the nutritional level, between 6 and 25 percent of plant magnesium is bound to chlorophyll (Marshner 1995). Because the incorporation of Mg^{+2} into Mg-protoporphyrin IX (the step in which Mg^{+2} is introduced into chlorophyll synthesis and is catalyzed by magnesium chelatase) has a strong affinity for free Mg^{+2}, it enjoys a high priority in the use of this nutrient (Held 1997). Consequently, other metabolic functions which depend on Mg^{+2} may suffer while chlorophyll synthesis utilizes available magnesium. When the amount of leaf magnesium contained in chlorophyll exceeds 20 percent of the total, plant growth is normally being depressed and the plant probably is or soon will be exhibiting magnesium deficiency symptoms (Marschner 1995).

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When growth of Mg-limited plants is being stimulated by high nitrogen or other favorable conditions, a senescence stimulus is received by the oldest leaves. This promotes two enzymes which catalyze the breakdown of chlorophyll, in particular a Mg-dechelatase which liberates magnesium from the porphyrin rings of chlorophyll. The Mg^{+2} freed from chlorophyll can be translocated to shoot growing points where it will be utilized to synthesize chlorophyll in new leaves.

This accelerated senescence of mature leaves by low magnesium not only produces the classical symptoms of magnesium deficiency (interveinal chlorosis) of the lower leaves but also reduces the photosynthetically active leaf surface thereby limiting plant growth.

Protein synthesis. One of the most devastating effects of low magnesium on plant growth is its inhibition of protein synthesis. Inability to synthesize new proteins (enzymes) limits the plant's capacity to respond to environmental stresses such as drought, heat and attack by disease organisms. While a connection between low magnesium and increased disease or stress injury has not been reported on turfgrasses, I am not aware that anyone has conductd research in this area.

Two essential processes in protein synthesis depend on the availability of Mg^{+2}. The nuclear enzyme RNA polymerase, which catalyses the synthesis of RNA from DNA that comprises the genes on which all plant genetic information is encoded, requires free Mg^{+2}. Upon withholding magnesium from a culture of plant cells, the synthesis of RNA immediately stops but resumes as soon as magnesium is restored. This is one of the most rapid plant responses to magnesium deficiency and may initiate many of the subsequent symptoms that are observed.

Ribosomes are the subcellular structures on which proteins are synthesized following the amino acid sequence encoded by the mRNA synthesized in the nucleus. These cytoplasmic particles consist of RNA and proteins but require magnesium to stabilize their structure. Ribosomes bind with mRNA and read its code while directing the assembly of polypeptides (proteins) using activated amino acids which are bound to specific tRNA molecules and are free within the cytoplasm.

If magnesium is withdrawn from a preparation of ribosomes, they disassemble into smaller units which are incapable of protein synthesis.

Only when ribosome structure is stabilized via Mg^{+2}, which bridges negative charges on the ribosome subunits, does proteins synthesis occur. Thus Mg^{+2} is required both for the synthesis of messenger RNA (mRNA) transcribed from genetic DNA in the nucleus and for stabilizing the protein synthesizing units (ribosomes) on which the genetic code is translated into proteins.

Phosphorylation. In plant and animal metabolism, one of magnesium's most critical functions is its capacity to bind ATP (adenosine triphosphate) to the enzyme proteins which catalyze the formation of phosthate esters (Figure 2). These phosphorylated metabolites are much more reactive and will enter into chemical reactions much more readily than their nonphosphorylated form (Hull 1997a). The phosphorylation of enzyme proteins also is now recognized as an important way by which the activity of such enzymes can be regulated; either activated or inhibited. In most cases, the source of phosphorus utilized in forming phosphate esters is ATP, more specifically Mg-ATP where a Mg^{+2} is ionically bound to the ATP's terminal two phosphates. It is through this Mg-bridge that Mg-ATP binds with the enzyme protein before a phosphate ester is formed (Figure 2). Thus, wherever a phosphorylated metabolite enters a biochemical reaction, its synthesis probably required the binding of Mg^{+2} with an ATP molecule.

Enzyme activation. As mentioned above, Mg-ATP can sometimes activate an enzyme by binding a phosphate from the ATP directly to the enzyme protein through the action of a separate protein kinase enzyme. Sometimes, however, an enzyme can be activated by ionically binding directly with a Mg^{+2}. A good example of Mg^{+2} activation of an enzyme is RubisCo (ribulose bisphosphate carboxylase/oxygenase). This enzyme catalyzes the primary reaction whereby atmospheric CO_2 is photosynthetically fixed into an organic molecule. Pretty much all carbon enters the biosphere via the action of this one enzyme.

However, before this enzyme can function to assimilate CO_2, it must be activated by binding with a Mg^{+2}. This Mg-RubisCo complex requires a couple additional activation steps but only when fully activated can it catalyze the fixation of CO_2.

The binding of a Mg^{+2} to the enzyme increases its affinity (ability to bind) for CO_2 and also increases the rate of its catalytic action. Because the action of this enzyme is so important to all of biology, the involvement of magnesium in its activation stands out as an important chemical role of this nutrient. There are other enzymes, some even involved in photosynthesis, that also require activation by Mg^{+2} binding before they can function at high efficiency.

Root:shoot partitioning. For the turf manager, one of magnesium's most important functions is its involvement in the transport

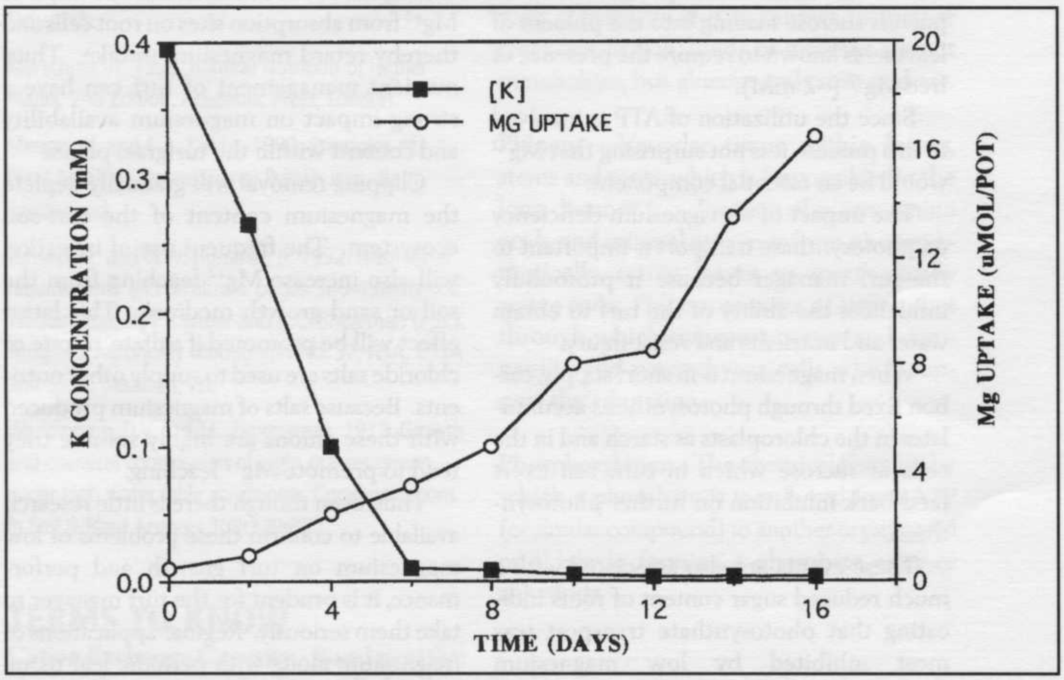

Figure 3. Magnesium uptake by ryegrass as affected by soil pH and potassium concentration (Based on Marschner 1995).

of soluble carbohydrates from leaves to sites of utilization in roots, rhizomes and growing points. One common observation associated with a magnesium deficiency is a sharp decline in the root:shoot ratio (weight of roots/weight of shoots).

When magnesium is inadequate, the root:shoot ratio will often decline to less than half that of a magnesium sufficient plant. This means that when turfgrasses are experiencing inadequate magnesium, they will produce less than half the root mass and depth that normally would be present.

When magnesium is in short supply, carbon fixed through photosynthesis accumulates in the chloroplasts as starch and in the cells as sucrose, which in turn can exert feed-back inhibition on further photosynthesis.

It is not known at exactly what step in the transport of photosynthetic products out of leaves that magnesium is required, but the H+ pumping ATPase responsible for phloem loading is a likely candidate (Marshner 1995).

This enzyme—which creates the transmembrane pH gradient that powers sucrose loading into the phloem of leaves—is known to require the presence of free Mg^{+2} (~2 mM).

Since the utilization of ATP is involved in this process, it is not surprising that Mg^{+2} would be an essential component.

The impact of a magnesium deficiency on photosynthate transport is important to the turf manager because it profoundly influences the ability of the turf to obtain water and nutrients and resist injury.

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These events are also associated with a much reduced sugar content of roots indicating that photosynthate transport was most inhibited by low magnesium (Marschner 1995).

Magnesium and turfgrass management

In an earlier article, I argued that promoting root growth was among the most important tasks confronting the turf manager (Hull 1996). A strong root system will make a turfgrass stand better able to mine the soil for water and mineral nutrients, stabilize the plants against wear, tolerate insect feeding and be more resistant to disease. Thus any condition that does not favor root growth is not working with the turf manager. Inadequate magnesium may be just such a condition.

The likelihood of low magnesium having a depressing effect on turf root growth can be increased by turf management practices. If soil pH adjustment is achieved through the application of lime, the increased Ca^{+2} in the soil solution along with K+ displaced from cation exchange sites by Ca^{+2} may inhibit root absorption of Mg^{+2}. Magnesium uptake might be even further reduced if additional potassium fertilizer is applied (Figure 3) and an ammonium source of nitrogen is used. In acid soils, the high H+ concentration can also displace Mg^{+2} from absorption sites on root cells and thereby retard magnesium uptake. Thus, nutrient management of turf can have a strong impact on magnesium availability and content within the turfgrass plants.

Clipping removal will gradually deplete the magnesium content of the turf-soil ecosystem. The frequent use of irrigation will also increase Mg^{+2} leaching from the soil or sand growth medium. This latter effect will be promoted if sulfate, nitrate or chloride salts are used to supply other nutrients. Because salts of magnesium produced with these anions are highly soluble they tend to promote Mg^{+2} leaching.

Thus, even though there is little research available to confirm these problems of low magnesium on turf growth and performance, it is prudent for the turf manager to take them seriously. Regular applications of magnesium along with periodic leaf tissue analyses will help the manager keep on top of a turf's magnesium status. Such diligence might very well offset problems of turf decline and help turf to tolerate environmental stresses including disease infections.

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TERMS TO KNOW

Cation Exchange Capacity - Fixed negative charges that are capable of ionically binding positively charged cations. In soils, clay minerals and organic matter contain numerous cation exchange sites. In plant tissues, pectice substances in cell walls, proteins and nucleic acids all contain exchange sites.

Covalent bond - A chemical bond in which two atoms share one or more pairs of electrons. Sometimes referred to as an organic bond, it can occur between an organic molecule and a mineral element. Magnesium bonding within a chlorophyll molecule is covalent. Should not be confused with ionic or hydrogen bonding.

Cytoplasm - That portion of a cell protoplast exclusive of the vacuole. The part of the cell in which most metabolic reactions take place. The fluid matrix in which all cytoplasmic inclusions (chloroplasts, mitochondria, ribosomes, etc.) are suspended is called the cytosol.

Enzyme - A protein catalyst that alters the rate of a chemical reaction without being consumed in the process. An enzyme normally speeds a biochemical reaction rate but its effectiveness depends upon its degree of activation.

Metabolite - A biochemical that is part of a metabolic pathway or the end-product of such a pathway if it is subject to further reactions. Starch, lipids or proteins are not metabolites, but glucose and citric acid are.

Phloem - Vascular tissue within leaves, stems and roots, which is responsible for the long-distance translocation of sugars, amino acids, and mineral nutrients from photosynthetically active leaves to metabolically active sinks. Phloem consists of sieve tubes through which transport occurs and companion and parenchyma cells which support their function.

Phosphorylation - The chemical reaction by which a phosphate is transferred from ATP (or similar compound) to another organic acid or aldehyde forming a phosphate ester or anhydride.