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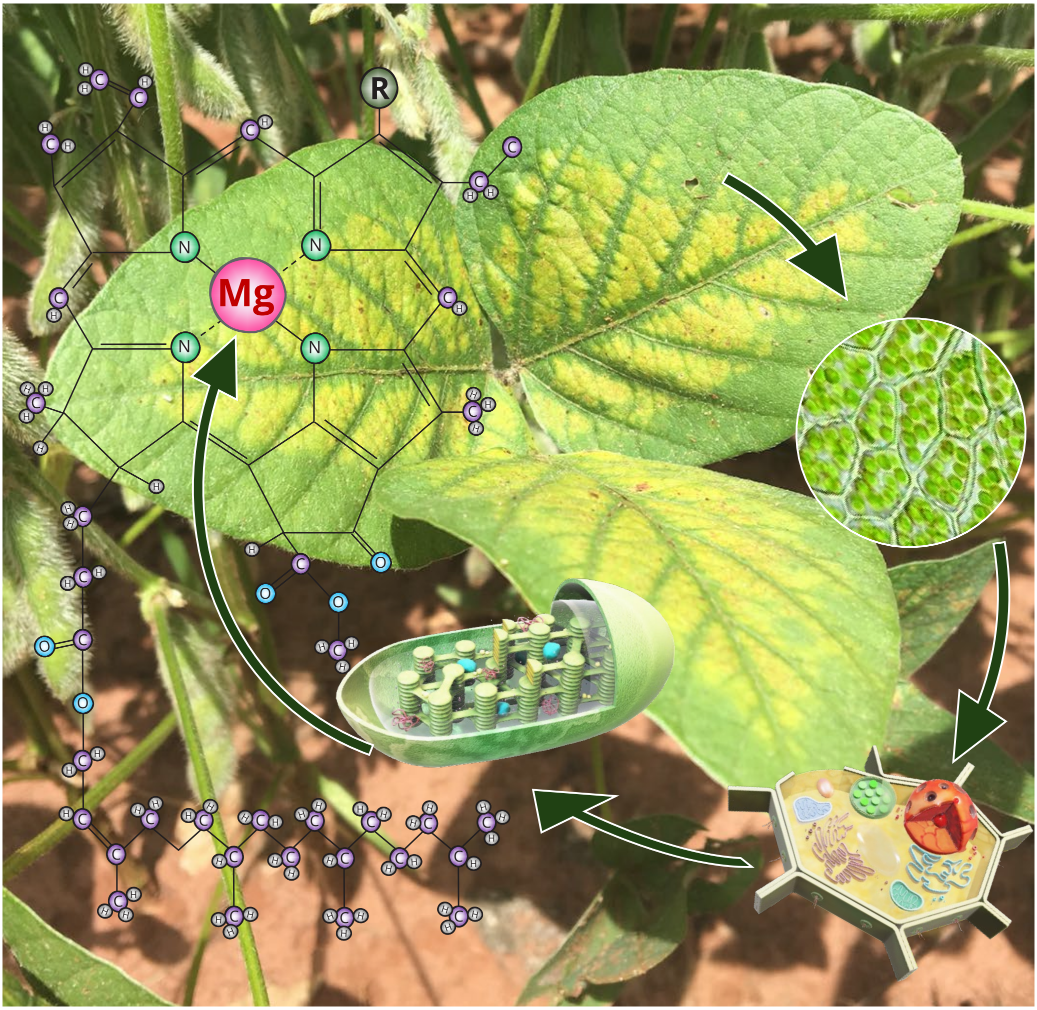

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Foreword

This publication is the result of the joint effort of years of research carried out at Embrapa (Soja, Cocais, Gado de Leite, and Solos) and Fundação MT. Over time and through experiments and field observations, these institutions have accumulated a great deal of technical information on a nutrient that is little discussed in the nutritional management of agroecosystems of production, i.e. magnesium (Mg).

In 2020, a year in which one of the few certainties is the sustainability of Brazilian agribusiness, and the empathy and intelligence need to be the extension of reason, we deliver this robust publication that, starting with the title "**Magnesium: management for the nutritional balance of soybean**", points out the importance of the relationships between nutrients, as well as their content. Furthermore, it emphasizes an undisputed truth, the **Law of the Minimum**, formulated by Justus von Liebig, to achieve high yields.

The main goal of this work was to promote a broad discussion about the importance of Mg in the nutritional management of crops, as well as in human and animal nutrition, by means of biofortification of grains, due to the greater supply of this nutrient, forgotten in the food chain. Thus, in the search for a better understanding of all aspects of the agricultural production, once again Embrapa Soja fulfills its mission of offering accurate, useful, and easy-to-use information, offering viable solutions for the improvement of the sustainable management of soybean.

Alvadi Antonio Balbinot Junior
Deputy Head of Research and Development
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Introduction

Despite all the technological advances in agriculture, including fertilizer formulations containing several technological innovations such as controlled-release mechanisms, nanotechnology, among others, symptoms of nutritional deficiency or toxicity have been common in several crops. Moreover, other barely visible symptoms, in addition to hidden hunger and nutritional imbalances, many of them related to magnesium (Mg), also occur.

Although the new technologies promote an increase in the efficiency of fertilizers, the lack of a correct diagnosis aggravates nutritional imbalances associated with the decrease in the crop yield potential. This is due to the inefficient use of soil analysis, the almost total neglect of adopting and appropriately interpreting the analysis of plant tissues, and the incorrect application of concepts of soil fertility management. In the case of Mg, little attention has been given to the nutrient, not only in agricultural production, but also in the production of pastures for animal feed and even in human health (Cakmak, 2013, 2015).

Before making a diagnosis of the nutritional status of plants, it is essential to have information to distinguish nutritional symptoms from other possible causes, associated with biotic stresses such as the incidence of pests or diseases, or abiotic stresses such as the occurrence of extreme weather events and phytotoxicity due to mistakes in fertilizer application. All relevant information should be collected to make the diagnosis more accurate, including past fertilizer application history, possible use of biostimulants, distribution of plants with symptoms in the crop, gradient of symptom development in the parts of the plants, and symmetry of symptoms in leaves of the same physiological age.

Given that the leaf is normally the organ with the highest metabolic activity and expresses symptoms of nutritional deficiency or toxicity more intensely and quickly, in general, it is the organ indicated to assess the nutritional status of plants. Nutrient mobility is an important detail that must be observed when seeking to identify a possible symptom of nutritional disorder in plants. Higher or lower mobility of nutrients in the phloem has a great practical importance in the visual identification of typical symptoms of some abnormalities (deficiency or toxicity). Symptoms in the leaves occur due to the redistribution of nutrients to the points of growth or accumulation, depending on several factors such as plant growth stage, among others. Thus, the position/age of leaves with symptoms (low/old or top/new leaves) allows the classification of nutrients according to mobility groups and, therefore, increases the chances of predicting the nutrient that is causing a specific symptom.

Following the same logic of attempting to identify symptoms, it should be noted that the symptoms of nutrients with high mobility (redistribution) appear first in the older leaves. Conversely, the symptoms of deficiency of nutrients with low redistribution appear in the new leaves. In all cases, it is possible to identify a gradient of intensity of typical symptoms. It is worth mentioning that this classification has a much more didactic than physiological function, since the temporal variation in the availability of nutrients in the soil and the plant growth stage can affect the characteristic absorption and distribution of the nutrient.

Despite the possibility of visual identification of nutritional symptoms, the correct identification and quantification of the degree of deficiency or toxicity, as well as the recommendation of fertilization and the monitoring of the nutritional status of the soybean (*Glycine max* L.) crop require two indispensable tools: soil analysis and leaf tissue analysis, together with a careful interpretation of the results.

The objective of this document was to gather information from soil fertility research carried out by Embrapa and partners, in addition to field observations, aiming to promote a broad discussion about the importance of Mg in the nutritional management of soybean, due to the wide distribution of symptoms of nutritional imbalances observed in crops in Brazil.

Magnesium in the soil

Approximately 2% of the Earth's crust is composed of Mg. In the soil, this nutrient originates from primary silicate minerals such as hornblende, augite, olivine, talc, serpentine, chlorite, and biotite. However, the main source of Mg for soil fertility management purposes is dolomite ($CaCO_3.MgCO_3$) (Slater, 1952; Tisdale et al., 1985 ; Sousa et al., 2007; Raij, 2011).

Brazilian tropical soils are generally poor in Mg because of the parent material with low contents of the nutrient and the intense pedogenetic processes that take place throughout the formation of the soils, which leach weathering products such as Mg. Soil acidification is a process that also negatively influences the content of Mg due to the low stability of Mg carbonates, sulfates, silicates, and aluminosilicates in acidic media.

In the soil, total Mg can be divided into three fractions: (1) non-exchangeable, present in the mineral structure; (2) exchangeable, which is electrostatically adsorbed by soil mineral and organic colloids; (3) free ion in the soil solution, in contents ranging from 5 to 50 mg/L (Tisdale; Nelson, 1993). These three fractions remain in thermodynamic equilibrium. The non-exchangeable fraction contains the largest proportion of total Mg and is composed of Mg originated from primary minerals and part of the Mg originated from secondary clay minerals (Mengel; Kirkby, 1978; Melo et al., 2000).

Figure 1 shows the biogeochemical cycle of Mg in an agricultural system. It depicts the mineral origin of rocks caused by weathering, nutrient "inputs" via crop residues and fertilizer application, and, mainly, soil amendments, as well as "outputs" represented by nutrient removal at harvest, in addition to losses due to leaching and erosion processes.

Similar to other nutrients, Mg can be exported via crop harvest or removed from the soil by leaching and erosion. Losses because of erosion depend on the texture and topography of the soil, volume of rainfall, crop cultivation system, and content of nutrients in the soil.

Illustration: Ruan Francisco Firmano

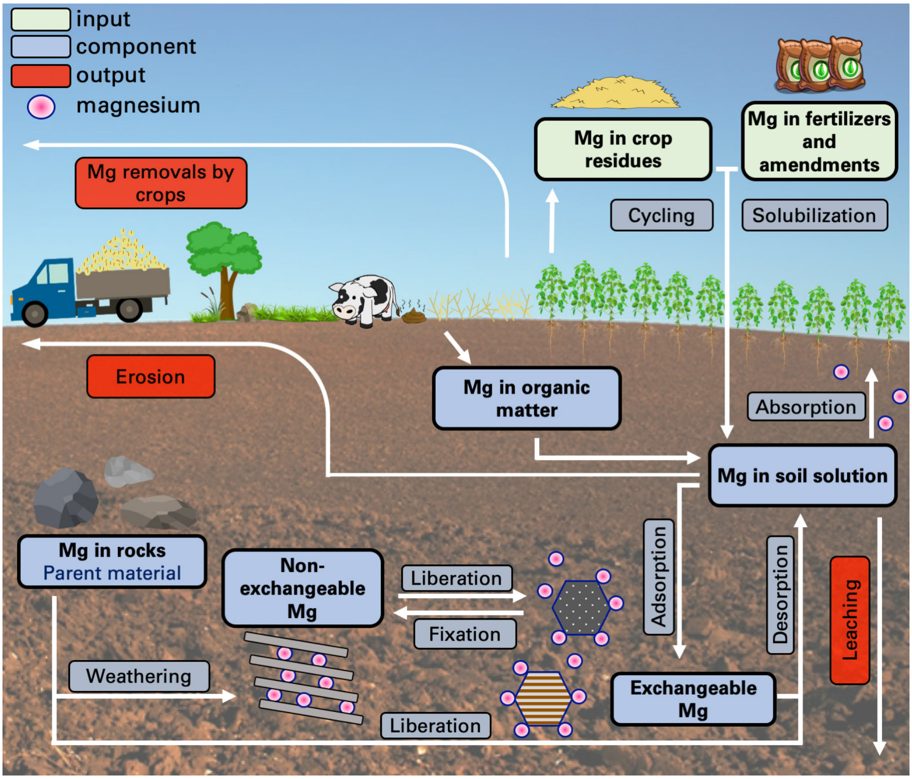


Figure 1. Schematic representation of the biogeochemical cycle of magnesium in an agricultural production system.

Due to the release dynamics, the non-exchangeable fraction is not considered an important source of Mg supply for annual crops. However, depending on the soil parent material and weathering conditions, this fraction can significantly contribute to the maintenance of Mg availability in the soil (Mengel; Kirkby, 1978). Similar behavior has been observed for potassium (K) in soils with very low soluble contents of the nutrient, with sufficient supply of K to plants (Oliveira Junior et al., 2013; Firmano et al., 2020).

Oliveira Junior et al. (2013) and Firmano et al. (2020) observed that the contribution of the non-exchangeable K fraction occurs under conditions of low K availability (~ 0.1 $cmol_c/dm^3$). Even under these conditions, soybean yields above 3000 kg/ha are feasible. This is possible on account of the “reserve” of non-exchangeable K, which is not accessed by the Mehlich-1 extraction procedure when evaluating the available content. However, as the non-exchangeable reserve of K or Mg is depleted by the natural processes of loss or removal by crops, it is impossible to achieve high soybean yields, even without the occurrence of apparent symptoms of nutrient deficiency (hidden hunger).

The Mg available in the soil is in the cationic form (Mg^{2+}), distributed in the base-cation exchange complex and in the soil solution (Figure 1). The main factors that affect its availability to plants are the total contents of exchangeable Mg and its concentration in relation to the degree of saturation of the exchange complex and, also, in relation to the other cations that prevail in this complex.

The absorption rate of Mg can be greatly reduced by other nutrients in the soil, as well as because of the imbalance in relation to calcium (Ca^{2+}), manganese (Mn^{2+}, Mn^{4+}) (Mengel; Kirkby, 1978; Heenan; Campbell, 1981; Bergmann, 1992), ammonium (NH^{4+}), and K^+ (Kurvits; Kirkby, 1980). High H^+ activity in soils with low pH (H_2O) (~ 4.5 or less) also decreases the availability of Mg (Marschner, 2012). Therefore, Mg deficiency induced by competing cations is a phenomenon that can be quite common under inappropriate liming and fertilizer management practices.

In the specific case of the K/Mg ratio, the imbalance decreases the availability of Mg due to the intensification of competitive inhibition. For this reason, it is recommended to evaluate the Mg content in the soil and its balance in relation to the other nutrients. Thus, it is observed that Mg deficiency due to competition with other soil cations may be common due to imbalances caused by other ions from liming and fertilization.

Originally, Mg deficiency occurs in acidic and sandy soils, whose parent material has low contents of Mg. Consequently, these soils have low natural contents of Mg (Arnold, 1967; Havlin et al., 2005) and high contents of K. In Brazil, the major processes that have led to Mg deficiency in the soil are the inappropriate lime, gypsum (Caires, 2011), and fertilizer management practices.

Leaching losses depend on soil texture and mineralogy, directly related to the soil cation exchange capacity (CEC) and that, in tropical soils, is predominantly pH dependent (Catani; Gallo, 1955; Raij, 2011). Therefore, this phenomenon can be strongly associated with the amount, type, and form of application of soil amendments. However, long-term experiments conducted in Londrina, PR, on a heavy clay soil (~ 800 g/kg clay), from 2010 to the present day, with soybean/wheat, wheat/sunflower, soybean/sunflower, and soybean/corn rotations, and combinations of doses and methods of application of dolomitic limestone and gypsum, showed different Mg movements to the 100-cm soil depth (Figure 2).

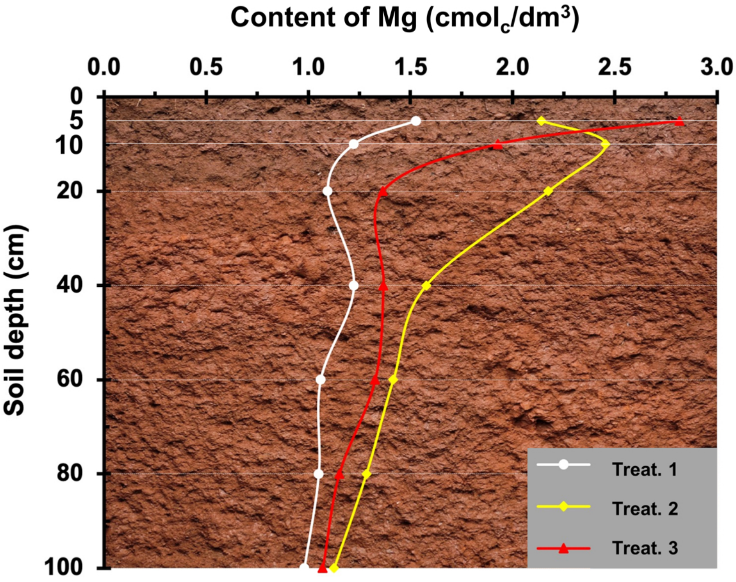


Figure 2. Effect of application of dolomitic limestone and gypsum on the magnesium movement in the soil (0–5, 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100-cm depth), in the 2015/2016 season. Treat. 1: control; Treat. 2: 8 t of lime and 8 t of gypsum (2 t/ha of lime and 2 t/ha of gypsum applied in 2010 and 6 t/ha of lime and 6 t/ha of gypsum applied in 2013 - broadcasted and incorporated); Treat. 3: Identical to Treat. 2, but without amendments incorporation after application..

In Figure 2, the main difference between treatments 2 and 3 lies in the form of application of the soil amendments. In treatment 2, the application was incorporated, while in treatment 3 it was superficial. As shown in Figure 2, Mg contents in the first 5-cm layer of soil were 1.53

$\text{cmol}_c/\text{dm}^3$ in treatment 1 (control), 2.1 $\text{cmol}_c/\text{dm}^3$ in treatment 2, and 2.82 $\text{cmol}_c/\text{dm}^3$ in treatment 3. In treatment 2, with the incorporation of limestone and gypsum, the highest Mg accumulation occurred in the 5 to 10-cm depth, with a more pronounced decline to the 40-cm soil depth. In treatment 3, with the superficial application of soil amendments, the highest Mg accumulation occurred in the first 5-cm layer of soil, significantly decreasing to the 10 to 20-cm soil depth, and maintaining lower content of the nutrient to the 100-cm soil depth compared to treatment 2 (with incorporation).

Plant roots absorb nutrients from the soil solution, which is kept in balance by the release of nutrients retained in the solid phase of the soil. However, the addition of nutrients to production systems and/or their cycling resulting from the incorporation of different crops also influence the chemical balance of Mg in the soil, which reinforces the importance of adopting more diversified production systems.

The mechanism of contact and the subsequent absorption of nutrients by plant roots can occur through three processes: root interception, mass flow, and diffusion. In the case of Mg, mass flow is of fundamental importance (Malavolta et al., 1997; Fageria et al., 2011) and is highly dependent on water availability in the soil and plant transpiration.

Another process that also significantly contributes to the absorption of Mg is root interception, which indicates that the nutrient should preferably be broadcast and incorporated to the soil. However, the amendments to acidic soils, the main source of Mg, are usually broadcast on the soil surface. Therefore, due to the positioning of Mg^{2+}, more reaction time is required for limestone solubilization and eventual contact of the ion with the roots.

The distribution of nutrients in the soil profile, within the area of root growth, has been increasingly important, not only for plant nutrition and water supply, but also for the reduction of the deleterious effects of toxic aluminum (Al), which can be mitigated by Mg (Cakmak, 2013). The beneficial effect occurs in the presence of Ca, a nutrient that plays a fundamental role in the protection of root growth against the effects of low pH (Kinraide, 1998; Marschner, 2012). Nonetheless, working with soybean roots in the presence or absence of Al under controlled conditions (phytotron), Silva et al. (2005) highlighted, above all, the importance of Mg for root elongation. According to these authors, Mg in low contents is more efficient than Ca to reduce Al rhizotoxicity. Furthermore, the physiological mechanisms involved in the protective effect of Mg against Al toxicity to the roots are not yet known.

Considering only the nutrients in the soil, the exchangeable cations are not held by colloids with the same strength. The preferential order of retention is: Ca^{2+}> Mg^{2+}> K^+ (Hoffmeister's lyotropic series). In general, this preferential series takes into account the binding energy and the hydrated ionic radius of the cation. Due to the law of mass action and the ionic activity, the variation in cation concentration in the soil solution can saturate the exchange complex with a cation, displacing the other exchangeable cations to the soil solution (Mengel; Kirkby, 1978; White; Greenwood, 2013). Thus, soil management programs that favor constant and high applications of calcitic limestone, gypsum, or potassium fertilizer and imbalance Mg in the soil can lead to the deficiency of this nutrient in the soil.

Calcium, magnesium, and potassium relationships and the occupation of the soil cation exchange capacity

The content of exchangeable Mg is used as the major indicator of nutrient availability in the soil. However, this information alone may not guarantee the correct diagnosis of nutrient sufficiency for plants. Hence it is necessary to consider the close relationship of this nutrient with the other cations in the soil, its mobility, retention by colloids, and the processes inherent in the absorption of this cation by plants.

The availability of Mg^{2+} in the exchange complex and its absorption by plants is dependent on the availability of Ca^{2+}, a dominant cation in the soil exchange complex, as well as on that of K^+, a cation preferentially absorbed by plants and the second most removed nutrient in soybean seeds. Thus, in addition to the available content of the nutrient in the soil, measured in $cmol_c/dm^3$, in a secondary way, the percentage of the nutrient in the CEC and the Mg^{2+} ion to other cations ratio in the exchange complex, mainly Ca^{2+} and K^+, is also important in the evaluation of the balance among exchangeable basic cations, considering that these three nutrients make up the majority of exchangeable cations in the electronegative soil exchange complex.

Before thinking about the relationships between nutrients, it is essential to raise their contents to levels considered adequate, depending on the soil CEC and, only then, seek the desired balance.

Working with alfalfa in soils different from our conditions, in the state of New Jersey, United States, Bear and Prince (1945) and Bear and Toth (1948) established the concept of ideal soil considering the relationship between exchangeable soil cations. The existence of an ideal relationship of CEC saturation by basic cations is also the foundation of Albrecht's theory (Albrecht, 1996). Nonetheless, these theories that consider the balance of available bases in the soil the main reason for ensuring adequate plant nutrition are quite controversial and less accepted than the interpretation based on levels of sufficiency (Schulte; Kelling, 1985).

After a thorough review of studies concerning the Ca/Mg ratio carried out in Brazil, Quaggio (2000) concluded that it is not important to plant growth or yield. The author also affirmed that the effects of the extreme relationships between these two nutrients on plants are not due to the direct action of the Ca/Mg ratio, but rather of Ca or Mg deficiency. Barber (1984) pointed out that a wide range of relationships between Ca and Mg in the soil can exist without compromising crop yields, as long as the content of Mg in the soil is sufficient for that crop.

These ratios or balance of exchangeable cations in the soil do not frequently have significant correlations with the improvement in chemical, physical, and biological properties of the soil, since adequate contents of nutrients in the soil are more important (Kopittke; Menzies, 2007). Moreover, the relationships between nutrients are not conditions for achieving high soybean yields, because the highest yields not always have a close association with these balances. Despite this fact, the relationship between Ca and Mg can be useful for choosing the source of limestone (either calcitic or dolomitic) to be used in the management of soil acidity and in general as a complementary reference for interpreting chemical analysis of the soil (Oliveira Junior et al., 2020). But even considering that the relationships between Ca, Mg, and K in soil analysis reports do not represent what really happens in the rhizosphere, it is common for agronomists to determine a range of values for them.

An important aspect, sometimes not properly taken into consideration, is that crop yield depends on environmental conditions such as climate and altitude (Gonçalves et al., 2020), water distribution during the main plant growth stages, soil properties such as CEC, nutrient availability, soil structure, profile, and compaction, among other variables. Therefore, an important concept to bear in mind is that, in a broader view, soil fertility is not restricted to the chemical properties of the soil and the contents of nutrients, but the interaction and conditioning promoted by the physical properties of the soil and the biological activity of the soil are equally fundamental.

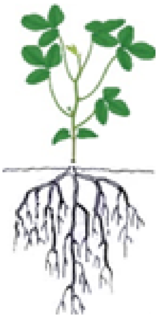
Another important fact that should be noted is how soil fertility management is being conducted in some areas. Currently, the application of amendments to acidic soils such as limestone and gypsum has been carried out superficially for the maintenance of no-till systems. In addition to limestone and/or gypsum application, principally aiming to increase the operational performance of sowing, fertilization with phosphorus (P) and K have been broadcast on the soil surface in many crops.

Because of the continuous use of these practices, and due to the solubility of these minerals and the characteristic mobility of each nutrient/source [Ca, Mg, sulfur (S), P, and K], associated with the distribution of rainfall, relief, vegetation, organic matter content, aggregate structure, soil porosity, and soil compaction, there is a gradient in the contents of nutrients and level of acidity in the soils. A nutrient considered a special case is P, because of its high contents in the first centimeters of the soil and a marked decrease in availability in deeper layers of the soil (Bataglia et al., 2009).

Other nutrients are also found in high contents in the first layer of soil, but to a lesser extent. Therefore, from the germination of the seed on, the same plant finds different contents and relationships between nutrients as the roots grow through different layers of the soil profile. Table 1 shows an example of the distribution of soil nutrients with depth and the relationships between soil nutrients in the soil under field conditions in a farmer's area.

Table 1. Contents of nutrients and relationships between calcium, magnesium, and potassium in the soil, in the state of Paraná, in the 2016/2017 season.

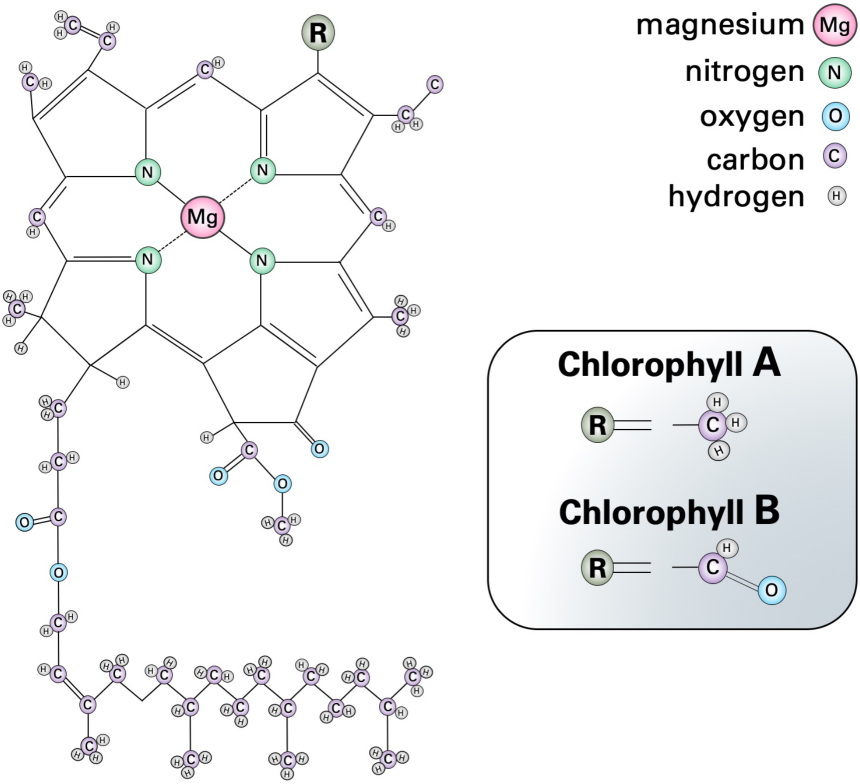
Soil depth (cm)	P	Ca	Mg	K	Relationship			
					Ca/Mg	Ca/K	Mg/K	(Ca+Mg)/K
	mg/dm^3	cmolc/dm3						
0–10	17.62	6.75	3.58	0.06	1.9	112	60	172
10–20	1.15	5.10	2.18	0.04	2.3	128	55	182
20–40	0.75	2.65	1.31	0.03	2.0	88	44	132



Magnesium in the plant

Plants absorb Mg as Mg^{2+} ions, and in this form the nutrient is transported to several parts of developing plants, via the xylem, and incorporated by the cells, where it plays important roles in plant metabolism such as photosynthesis and carbon (C) incorporation (Marschner, 2012). A fundamental role is also played by Mg in plant defense mechanisms under abiotic stress conditions (Senbayram et al., 2015), a process highly influenced by light intensity. Therefore, plants grown under high light intensity conditions seem to have a greater need for Mg than those grown in environments with lower light intensity (Cakmak; Yazici, 2010).

Unlike Ca, Mg is rapidly redistributed via the phloem from the mature to the youngest regions of the plant, with active growth ((Malavolta, 1976; Epstein; Bloom, 2005), i.e., from the older leaves at the bottom of the plants to the younger leaves at the top of the plants, and also towards the reproductive organs. Part of the Mg absorbed by plants is a structural constituent of chlorophyll (Figure 3), an organic molecule fundamental to the physical-chemical process of photosynthesis and to life. The central atom of the chlorophyll molecule is Mg, corresponding to approximately 2.7% of its molecular weight, and depending on the nutritional status, between 6% and 25% of the total Mg in the plants is linked to chlorophyll (Marschner, 2012). In general, another 5% to 10% of the total Mg is present in the leaves, tightly associated with pectin in the cell walls or precipitated as slightly soluble salts in the vacuole, involved in osmoregulation. However, between 60% and 90% of the Mg accumulated in the plants is extractable with water (Marschner, 2012) and, therefore, remains soluble, conferring the nutrient a mobile character.



Source: Adapted from Taiz and Zeiger (1998)

Figure 3. Chemical structure of the chlorophyll molecule (A and B), consisting of four pyrrolic rings and a central magnesium atom attached to the four nitrogen atoms.

In addition to its structural role in chlorophyll, Mg performs a large number of functions. Together with K, it is one of the main enzyme activators in vegetables, directly participating in the synthesis of carbohydrates and nucleic acids as well as in the energy transfer metabolism via adenosine triphosphate (ATP) (Epstein; Bloom, 2005; Cakmak; Yazici, 2010). About 75% of leaf Mg is involved in protein synthesis (White; Broadley, 2009), acting as an enzyme activator in the metabolism and incorporation of photosynthetic carbon (Cakmak; Kirkby, 2008). For this reason, an adequate supply of Mg is important for soybean, a plant that accumulates circa 40% protein in the seeds, ranging from 31.7% to 57.9%, in the dry matter (Pipolo et al., 2015).

The average protein content found in the seeds of 2,581 soybean samples collected in Brazil ranged from 28.7% to 42.0% (Mandarino et al. 2016, 2017, 2018). Even though the protein content of the seeds is a feature with a strong genetic component, the efficiency of protein synthesis is directly related to the adequate supply of Mg to the plants.

Tanaka et al. (1995) reported an increase in the protein content of soybean after the application of different rates of dolomitic limestone. In addition to the effects on the protein metabolism, according to White and Greenwood (2013), the supply of Mg is also important for the formation of oil, and the oilseeds are richer in Mg than the seeds that accumulate starch in greater proportions.

Another important aspect of Mg^{2+} is its positive influence on the absorption of the orthophosphate ion (H_2PO^-), the main form of P absorbed by plants (Malavolta, 1976). Positive interactions between P and Mg are expected, since the latter is an activator of kinases as well as of many reactions involving phosphate transfer (Fageria, 2001).

Similar to its roles in plants, Mg performs important metabolic functions in animals, and its deficiency in animal feeds also causes problems. Grass tetany, also called hypomagnesemia, is the most apparent or known Mg deficiency, and is caused by low contents of this nutrient (Santos, 2011). This problem occurs worldwide in cattle, sheep, and goats. The affected animals show an abrupt decrease in serum Mg contents and consequent clinical symptoms of increased neuromuscular excitability. The occurrence of grass tetany is higher in beef cattle and in pastures with Mg deficiency and fertilized with high contents of nitrogen (N) and K. Nonetheless, it is also a metabolic disease commonly found in dairy cows and small ruminants that consume forage with high contents of K and crude protein. This disorder generally occurs in subtropical or temperate regions due to the use of forage crops that accumulate more K and N and little Mg. It is worth mentioning that high K content in the forage crop inhibits the absorption of Mg. Grass tetany affects both males and females, but lactating females are more susceptible to it because of the increased use of Mg in milk synthesis, which contains about 150 mg/kg Mg. Untreated grass tetany usually causes animal death due to cardiac and respiratory arrest.

A point that should be evaluated is the Ca/Mg ratio in non-ruminant diets, because of the feed composition, basically restricted to soybean and corn meals, the contents of both nutrients in these seeds, and the high feed conversion ratio in pigs and poultry, for example. Given the high demand for Ca in a close relationship with P (Bikker; Blok, 2017) in the formulation of feeds and the consequent need for mineral supplementation, the Ca/Mg ratio may have been neglected, as in the fertilization of crops, causing a slightly noticeable deficiency in animals, similar to the hidden hunger in soybean.

The body of an adult human contains around 25 g of magnesium, of which 60% is in the bones, where it plays a major role in the development of the skeleton (Joy et al., 2013). Similar to plant production, it has been quite common to find Mg deficiency in human diet in some countries (Karley; White, 2009; White; Broadley, 2009; Rosanoff et al., 2012; Cakmak, 2013). In Brazil, an estimated 70% of the population consumes inadequate amounts of Mg, especially in urban areas (Araujo et al., 2013).

Grain biofortification for direct use in human diet or in animal feed, aiming to prevent diseases caused by mineral deficiencies or nutritional deficiencies, basically focuses on the supply of iron, zinc, selenium, and vitamins. However, almost never this process takes into consideration offering adequate levels of Mg (Gerendás; Führs, 2013).

Symptoms of magnesium deficiency in plants

The symptoms of Mg deficiency can appear from the early soybean growth stages until the end of seed filling, depending on the content of this nutrient in the soil, the nutritional management adopted, and the soil texture. Nevertheless, they are most often observed at the reproductive stage, during the seed filling phase.

In addition to the low content of Mg in the soil, nutritional deficiency is usually associated with high soil acidity. In sandy soils, however, symptoms of Mg deficiency are often related to inadequate management of acidity and varying levels of Mg in the soil, indicating that the deficiency in nutrient absorption may be initially caused by another factor than the primary lack of Mg in the system.

Similar to N, P, and K, Mg is mobile in the phloem (Marschner, 2012). In environments with low contents of Mg in the soil, or with imbalanced contents of this nutrient in relation to other ions, Mg can be redistributed from the oldest leaves to the youngest ones or to the fruits. In general, the most peculiar deficiency symptom is interveinal chlorosis (light yellow) in old leaves, with green or pale green veins (thick reticulate), as in Figure 4, showing soybean plants containing 19.8 g/kg K, 9.4 g/kg Ca, 0.9 g/kg Mg, and 211 mg/kg Mn.

Photograph: Cesar de Castro

Figure 4. Soybean plants with symptoms of magnesium deficiency in older leaves at the base of the plants.

Figure 5 depicts the accumulation and remobilization dynamics of Ca, Mg, and K in the upper third leaves of soybean plants with Mg deficiency, sampled at the R6 stage, in commercial soybean crops. The deficiency of Mg is observed in all the leaves analyzed, but significantly decreases from 2.34 g/kg in +1 leaves (younger) to 0.81 g/kg in +3 leaves, reaching the minimum 0.66 g/kg in +7 leaves (older). This gradient indicates the remobilization of this nutrient to younger leaves and, possibly, higher physiological activity. The accumulation of Ca is higher in younger leaves due to the low demand for this nutrient to accumulate in the seeds, demonstrated by its lower removal rate. In contrast to Ca and Mg, K contents decrease from +7 leaf to +1 leaf, indicating its remobilization from the leaves to the seeds, the main drain for the accumulation of this nutrient.

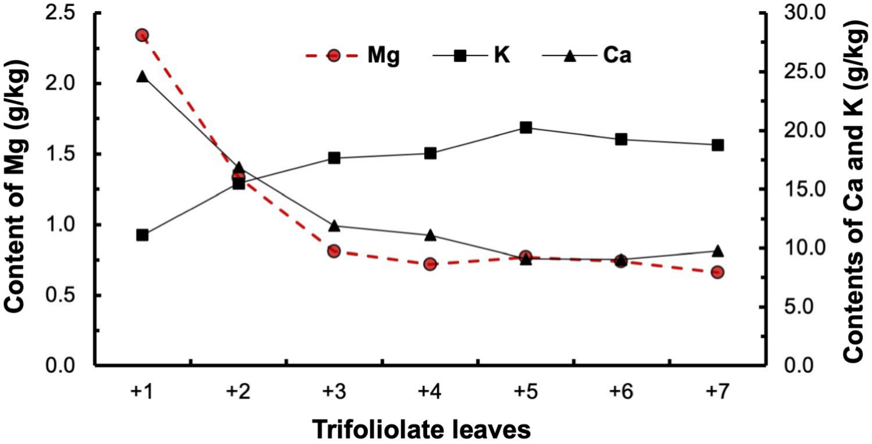


Figure 5. Nutrient contents in soybean leaves with symptoms of magnesium deficiency, in Wenceslau Braz, PR, in the 2016/2017 season.

This pattern of symptoms, exhibited by several species, is related to the metabolism of nutrient remobilization triggered by the nutritional deficiency, a process that prioritizes the degradation and senescence of the interveinal region, preserving intact the chlorophyll in the cells of the vascular bundles for a longer time (Taiz; Zeiger, 1998). Studies developed by Cakmak and Marschner (1992) suggest that the photo-oxidation of thylakoid constituents is an important factor in the development of chlorosis in the leaves due to Mg deficiency. Therefore, since

Mg is strongly linked to the chlorophyll molecule, chlorosis appears to be the late response to Mg deficiency (Gransee; Führs, 2013). However, the initial stage of Mg deficiency is characterized as hidden hunger, when plant metabolism is affected and yield is reduced, even in the absence of visible symptoms.

Similar to other mobile nutrients in the phloem, in cases of deficiency, the typical symptoms occur primarily in the older leaves, in the lower parts of the plants. Because of this, their identification and subsequent correction are more difficult. As the deficiency progresses, the symptoms reach the leaves of the middle third, and in more severe cases, they also reach the leaves of the upper third and even affect pod filling (Figure 6), mainly in combination with great imbalance in the Ca/Mg ratio and high doses of K. In soils with severe Mg deficiency, these symptoms may develop to necrosis between the main veins, and consequently the leaves curve downwards.

Figure 6 shows the deficiency of Mg affecting the plant up to the upper leaves and the result of photo-oxidation of thylakoid constituents as mentioned by Cakmak and Marschner (1992), an important factor in the development of chlorosis in these leaves. This damage occurs due to light intensity, especially when the deficiency is severe, expanding to the upper leaves of the plants directly exposed to sunlight, increasing the intensity of typical chlorosis.

Photograph: Leandro Zancanaro

Figure 6. Soybean plants with symptoms of magnesium deficiency even in the upper third leaves, at the R6 stage, at Fundação MT, in the 2013/2014 season.

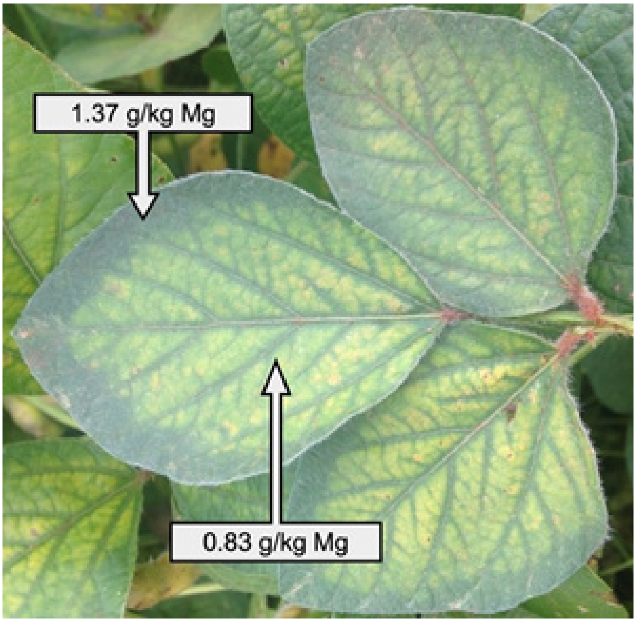
A less typical variation of the symptom has occurred in deficient crops recently, making diagnosis difficult for some farmers or technical assistance. In response to a lower availability of Mg in the soil, the old leaves exhibited interveinal chlorosis (light yellow) and change in the color of the veins to lighter shades of green or pale green. However, the leaf edges remained green (Figure 7). In that crop, the plants that had leaves presenting with these peculiar symptoms had 22.1 g/kg K, 8.12 g/kg Ca, and 0.67 g/kg Mg. In the same crop, in areas without these symptoms, the plants had 16.69 g/kg K, 7.39 g/kg Ca, and 1.36 g/kg Mg. Therefore, even without showing these symptoms of Mg deficiency, the contents of this nutrient found in the plants demonstrate that they had Mg contents below the appropriate level, characterizing hidden hunger.


Photograph: Cesar de Castro

Figure 7. Soybean plants with symptoms of magnesium deficiency in the center of the older leaves but with green edges at the base of the plants, in a sandy soil, in Bela Vista do Paraíso, PR, in the 2017/2018 season.

These symptoms have been observed in several crops, regions, and even in experimental areas. Over the last seasons, leaves with symptoms of interveinal chlorosis and green leaf edges have been analyzed in some areas of traditional regions in the states of Mato Grosso, Mato Grosso do Sul, Paraná, and Goiás, but also in areas of expansion of soybean culture such as northern Rio de Janeiro and Sergipe.

Chemical analyses of leaves with these atypical symptoms of interveinal chlorosis restricted to the leaf center, collected in a soybean crop at the R3 stage in the state of Mato Grosso do Sul (Figure 8), revealed that the asymptomatic edges had 1.37 g/kg Mg, whereas the central symptomatic area displayed 0.83 g/kg Mg, i.e. severe deficiency. Although the remobilization of Mg was more pronounced in the central region of the leaf, the general diagnosis is nutritional deficiency, because the leaf edges characterized hidden hunger, since the adequate content of Mg, considering the plant growth stage, should be around 3.0 g/kg.



Photograph: Cesar de Castro

Figure 8. Contents of magnesium on the edges and in the center of a soybean leaf exhibiting symptoms of magnesium deficiency.

In this area, in addition to the outstanding Mg deficiency in the leaves, other nutrients such as Ca and K were out of balance or in altered levels. The content of Ca in the leaves was low, around 8.45 g/kg, while the contents of K in the center (19.17 g/kg) and mainly at the edges of the leaves (26.26 g/kg) were high. The uniqueness of this symptom is not only due to Mg deficiency, but also because of a combination of factors involving Mg, Ca, and K.

Diagnosis under field conditions can be particularly difficult when plants exhibit multiple symptoms of nutritional imbalance. Simultaneous occurrences of deficiency and toxicity in the same plant can be found, for example, in acidic soils and in the presence of water accumulation (reduced environment), such as Fe or Mn toxicity and Mg deficiency (Marschner, 2012). This situation was observed in a soybean crop in the state of Paraná (Figure 9), in the 2016/2017 season, where plants simultaneously had old leaves with symptoms of Mg deficiency (0.67 g/kg) and upper leaves with toxicity of Mn (714 mg/kg). As described by Marschner (2012), these plants were grown in an acidic soil, with pH ($CaCl_2$) 4.05 and 0.6 $cmol_c/dm^3$ Al^{3+}, in an area with water accumulation.

Photograph: Cesar de Castro

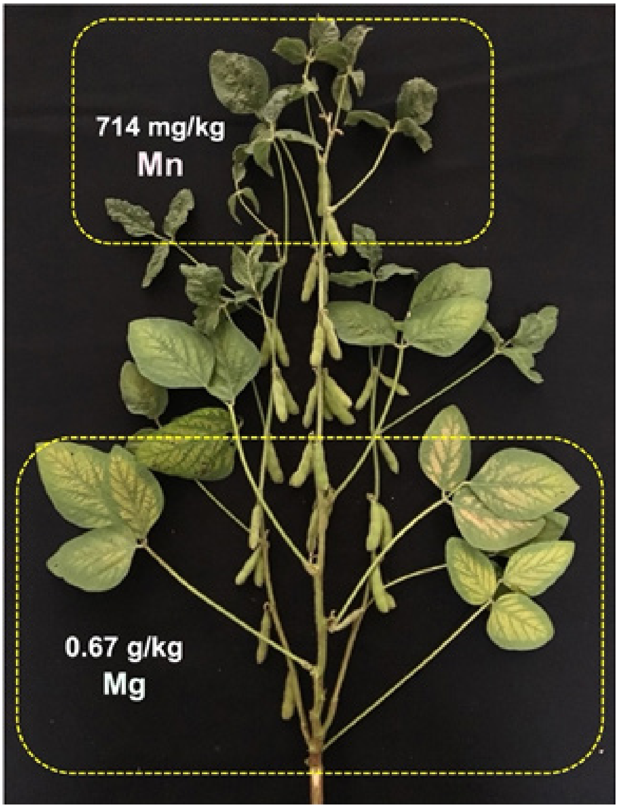


Figure 9. Soybean plants exhibiting symptoms of magnesium deficiency in the lower leaves and manganese toxicity in the upper leaves.

Sandy soils, common in areas of expansion of the grain production system, are classified as restricted in agricultural suitability, with productive potential highly dependent on the technology to manage the physical, chemical, and biological properties of the soil. Therefore, without the use of technology adapted to these production environments, the intensive use of these soils can be restricted, mainly due to the low water storage capacity and high susceptibility to erosion, among other aspects.

Long-term experiments carried out by MT Foundation on sandy soils (110 g/kg clay in the inorganic matrix), using combinations of doses of calcitic and dolomitic limestone, show the clear effect of the composition of these two limestones in the contents of Ca and Mg in the soil (Figure 10). The Ca/Mg ratio was 6.4 with the exclusive use of calcitic limestone, but it decreased to 1.6 when only dolomitic limestone was applied. The close relationship of the type of limestone with the contents of Ca and Mg in the soil and in their relationships reinforces the importance of choosing the type of limestone not only for soil correction, but also for the balance of nutrients in the soil.

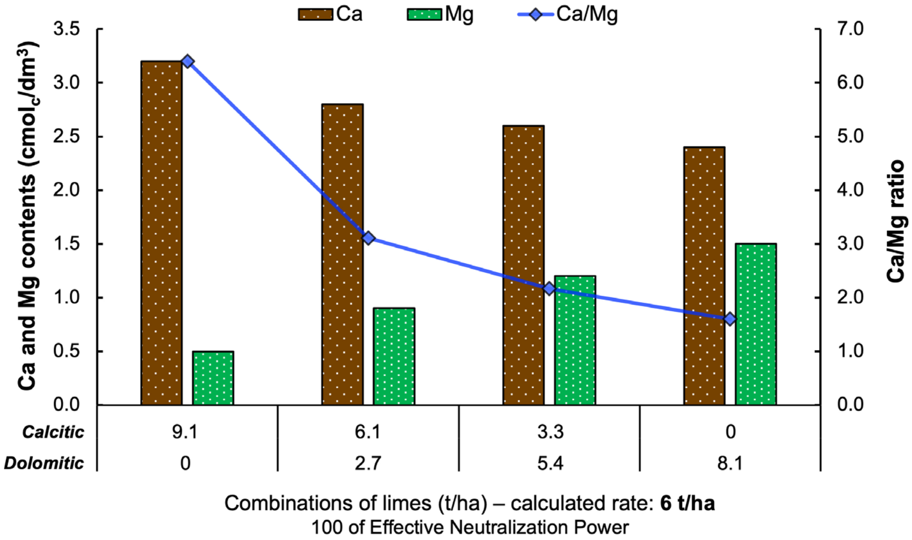


Figure 10. Contents of calcium and magnesium and Ca/Mg ratio in the soil in response to combinations of doses of calcitic and dolomitic limestone, at Fundação MT, in the 2014/2015 season.

Figure 11 shows that despite the low relationship between soybean yield and Ca/Mg ratio, the lowest soybean yield was achieved with the highest Ca/Mg ratio (6.4), while the highest yield was achieved with a Ca/Mg ratio of 3.1. The low yield obtained with the use of calcitic limestone can be explained by the low Mg content in the soil (0.5 $cmol_c/dm^3$), which was the limiting factor to yield. In the other limestone combinations, the contents of Mg were increased, ranging from 0.9 $cmol_c/dm^3$ to 1.5 $cmol_c/dm^3$, enough to meet the needs of the plants, depending on the soil CEC. The results shown in Figure 11 reinforce the fundamental concept that, before considering the relationships between nutrients, it is necessary to raise the contents of Ca and Mg to the levels considered adequate. The results obtained in sandy soils demonstrate that it is of paramount importance to pay close attention not only to the absolute amounts of nutrients in the soil, but also to a better adjustment of the dose of nutrients, especially K, and to the type of limestone, because of the lower electronegative exchange complex of these soils.

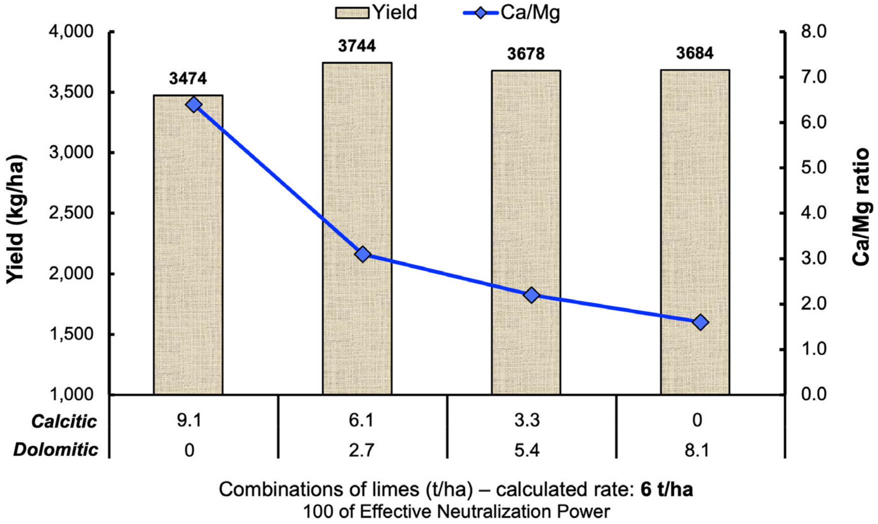


Figure 11. Soybean yield and Ca/Mg ratio in the soil in response to combinations of doses of calcitic and dolomitic limestone, at Fundação MT, in the 2014/2015 season.

In addition to the problems regarding yield and the symptoms of deficiency, an aspect that is little discussed is the interaction of Mg with diseases. The management of fertilization with Mg can help increase the yield and also reduce diseases, as long as it is in balance with the other nutrients. However, this is an underused tool (Huber; Jones, 2013) or little recognized in the control of diseases.

According to Cakmak and Kirkby (2008), Mg plays a fundamental role in photoassimilates removal in the phloem. Therefore, Mg deficiency restricts the dry matter partitioning between roots and shoots, resulting in excessive accumulation of sugar, starch, and amino acids in the leaves. This accumulation, which is a source of energy (sugars), promotes the development of diseases in Mg-deficient plants. Thus, for Huber and Jones (2013) balanced nutrition is fundamental for the expression of resistance to diseases, since nutrition is part of an interdependent and delicately balanced system influenced by plant genes (cultivar) and environment.

In addition to leaf symptoms and hidden hunger, Mg deficiency can have a much more insidious effect on plants, affecting root growth and the root/shoot ratio caused by the accumulation of photoassimilates in the shoot, at the expense of roots (Cakmak, 2013). This problem can be aggravated in acid soils with a poorly developed profile and in plants under water stress, intensifying yield losses.

Importance of soil and plant tissue analysis

The typical symptoms of a deficiency occur because the metabolic or structural mechanisms dependent on a certain nutrient are missing or in great imbalance with other elements. Even so, despite the possibility of identifying the typical symptoms of deficiency or toxicity, visual assessment should only be used as a support for a more scientific and judicious assessment, namely soil analysis, complemented by tissue analysis.

In an increasingly connected world with technological tools available to most farmers and consultancy companies, the anachronism of the correct use of soil analysis and the rarity of tissue analysis is at least strange. Misunderstandings in soil fertility management, coupled with lack of attention or little perception of cause and effect relationships, are responsible for the increased occurrence of nutritional imbalances that limit crop yields. It is worth mentioning the fact that soil analyses are neither carried out regularly or with representativeness, nor appropriately used as a tool to interpret the availability of nutrients in the soil and/or the need for fertilization. Another important fact is the lack of information on the history of agricultural practices, rainfall, and yields in each plot. Despite the set of spreadsheets and forms that can be used, this task is almost always entirely entrusted to the memory of the farmers or their production managers.

Undoubtedly, without adequate parameters for a better fertilization planning, fertilizer use efficiency is certainly reduced, causing a direct impact on variable production costs, which may result in decreased yield and loss of seed quality. Given that the critical contents of nutrients in the soil are well established, apparently there are no reasons for deviations in the fertilization model. These values should be used to interpret the contents of nutrients in the soil and to recommend liming or corrective fertilization.

Although the parameters of interpretation of leaf analysis are also established, their use is very restricted. This is a waste of a very efficient tool for assessing plant nutrition and nutritional balance and managing nutrients. Basically, leaf diagnosis consists of chemically analyzing the leaves and interpreting the results according to Table 2.

Table 2. Classes and contents of nutrients used in the interpretation of the results of leaf (without the petiole) analysis of soybean[1] cultivars with a determinate and undetermined growth habit.

Nutrient	Content		
	Low	Sufficient or medium	High
	g/kg		
N	< 45.0	45.0 to 65.0	> 65.0
P	< 2.8	2.8 to 4.5	> 4.5
K	< 18.0	18.0 to 25.0	> 25.0
Ca	< 6.0	6.0 to 10.0	> 10.0
Mg	< 2.8	2.8 to 5.0	> 5.0
S	< 2.4	2.4 to 4.0	> 4.0
mg/kg			
B	< 40	40 to 60	> 60
Cu	< 6	6 to 12	>12
Fe	< 90	90 to 180	> 180
Mn	< 70	70 to 150	> 150
Zn	< 30	30 to 45	> 45

[1] Third or fourth trifoliolate leaves without the petiole, from the apex of the main stem, collected at the R2/R3 stage, when the plant is at the V8/V10 stage.

Source: Oliveira Junior et al. (2020).

The collection of leaf samples should be careful and performed when 50% of the plants in the plot are at the correct sampling stage. For cultivars with a determinate growth habit, it is recommended to carry out sampling at the beginning of flowering (stage R1). For cultivars with an indeterminate growth habit, the recommended time is when 50% of the plants in the plot are in full bloom (stage R2, flowers open in one of the two upper nodes of the main stem with fully developed leaves), which can extend up to the beginning of the R3 stage (beginning of pod development), provided that the plants are also at the vegetative stage V8/V10 (7 to 9 fully developed first trifoliolate leaves). Around 30 freshly mature leaves should be harvested per plot, in general, corresponding to the third or fourth trifoliolate leaf from the apex of the main stem. Annex 1 shows soybean growth stages with a determined and indeterminate growth habit (Oliveira Junior et al., 2016).

It is important that soil analysis and leaf analysis, which can be interpreted according to sufficiency range tables or even by the regional Diagnosis and Recommendation Integrated System (DRIS) (Embrapa Soja, 2003), are used for the diagnoses and recommendations of liming and fertilizer management. Besides enabling crop monitoring over the seasons, this analysis is necessary, since visual identification is not always enough for a complete assessment of the nutritional status of plants, considering that the relationships between nutrients may be more important than the isolated identification of a single element that is causing problems.

As a practical use of the visual diagnosis, it is possible to identify the need to apply a certain nutrient that would be limiting production or, more broadly, to adjust the fertilization program. However, the final decision can only be efficiently made using leaf diagnosis obtained after the chemical analysis of the leaves of the plants with some visual symptoms and comparing them with the analyses of the leaves of the plants considered normal.

Magnesium in production systems

In soil fertility management, the technical criterion for the recommendation of fertilization is based on crop nutritional requirements and potential response to the nutrients. The application of primary macronutrients should be prioritized using NPK formulations or applying simple sources and inoculants to promote biological nitrogen fixation. In contrast, the other nutrients are indirectly provided because they are also contained in the applied sources, often without considering their contents or the crop requirements for calculating their recommendation. This is frequently observed in the case of limestones, with varying contents of Ca and Mg, or in the case of gypsum, source of Ca and sulfur (S), and even with organic fertilizers, organomineral fertilizers, and soil conditioners.

Liming is the main form of supplying Ca and Mg to plants. It raises the soil pH, decreases the content of toxic Al, and increases the availability of nutrients since it increases effective soil CEC. Nevertheless, the ratio between the contents of Ca + Mg, provided mainly by liming or in the specific case of Ca supplied by gypsum, and the content of K, supplied by KCl, should not be very high (Usherwood, 1982). Even so, the correlation between the ratio of exchangeable (Ca + Mg)/K in the soil and the production of dry matter by plants has not shown satisfactory results for different soils and crops (Usherwood, 1982) or for soybean (Rosolem et al., 1992).

Oliveira et al. (2001) affirmed that when the ratio of exchangeable (Ca + Mg)/K is less than 20, a higher availability of K in the soil promotes a stronger effect of competitive inhibition on Mg absorption than that of Ca. Kopittke and Menzies (2007) analyzed data from experiments conducted in the United States and concluded that in soils that have available contents of exchangeable cations above the critical levels, the saturation relationship between cations in the soil CEC does not influence crop yield and the application of this concept may lead to the inefficient use of inputs.

Regarding the ratios between Ca, Mg, and K, it is of fundamental importance that the contents of the nutrients are above the critical level of sufficiency, as highlighted by Barber (1984), Quaggio (2000), and Kopittke and Menzies (2007). For the primary macronutrients, the criterion for fertilizer management considers crop nutritional requirements and potential response to the nutrients, resulting in applications to all crops in the production systems in all the seasons. Therefore, nutritional replacement is carried out at the same frequency as the area is cultivated, even if the contents of nutrients are not adequate or balanced with removal. For Mg, however, the main criterion for fertilizer management is not the nutritional requirement of the plants. The main source of this nutrient is dolomitic limestone, used with the main objective of correcting acidity and that has a consequent secondary effect of increasing base saturation (V%) by supplying Ca^{2+} and Mg^{2+}.

The decision to use limestone is based on the expected Ca/Mg ratio, for example, 3:1, which may vary depending on the applied dose of the soil amendment. This ratio should be understood as a secondary criterion for interpretation, whereas reaching critical levels of Mg in the soil should be the priority to meet the crops needs. After all, a 3:1 ratio can be achieved with different levels of Ca and Mg, as shown in Table 3. Nevertheless, only the examples that consider the critical content of nutrients can be considered adequate, while the others evidence the risk of imbalance with the remaining nutrients in the exchange complex due to plant competitive absorption processes (Oliveira Junior et al., 2020).

Table 3. Calcium, magnesium, and potassium ratios as a function of hypothetical levels of nutrients in the soil.

Content in the soil (cmolc/dm3)			Ratio		
Ca	Mg	K	Ca/Mg	Mg/K	(Ca+Mg)/K
0.9	0.3	0.3	3.0	1.0	4.0
1.8	0.6	0.3	3.0	2.0	8.0
3.6	1.2	0.3	3.0	4.0	16.0
7.2	2.4	0.3	3.0	8.0	32.0
10.8	3.6	0.3	3.0	12.0	48.0

In areas with subsurface acidity and indication of gypsum recommendation, the final balance of exchangeable bases in the soil should be considered to avoid decreasing the availability of Mg^{2+}, given that the application of this input increases the contents of exchangeable Ca^{2+} and S_4O^{2-}, with a possible residual effect for some years, as well as the interaction with other ions in the balance of the exchange complex and in the interactions during the absorption process. Lime and gypsum management practices, amendments usually broadcast on the surface, cause a great concern due to their possible direct effects on soil acidity and neutralization of toxic Al in soil subsurface, but with possible indirect effects on nutritional relationships, more specifically Ca/Mg and K/Mg (Cakmak, 2015).

Therefore, the increase in the content of a nutrient due to improper fertilizer, lime, or gypsum management, causing imbalance of this nutrient in relation to the others, may imply a decrease in the absorption of other nutrients, mainly in the first layer of soil, the region of higher contents of nutrients and roots. As an example, some areas of soybean showing symptoms of Mg deficiency were found in plots that had received large amounts of gypsum or even calcitic limestone (Bergmann, 1992). Figure 12 shows a soybean plant with Mg deficiency due to the application of gypsum (~ 3 t/ha) in an area with low Mg content and a Ca/Mg ratio greater than 4.

Photograph: Cesar de Castro

Figure 12. Soybean plant exhibiting symptoms of magnesium deficiency in the lower leaves due to the application of a high dose of gypsum.

Another situation that affects the absorption of Mg and Ca in plants is the negative interaction between the increase in the contents of K in the soil and the decrease in the contents of the other nutrients in the leaves. Therefore, management programs that favor high doses of K, or soils with high contents of the nutrient, can lead to a lower absorption of Mg and even Ca, with consequences in the contents of nutrients in the leaves and possible decrease in yield.

An inverse relationship between the increase in the content of K in the soil and the decrease in the contents of Ca and Mg in soybean leaves is observed in Figure 13. In these experiments, although the contents of Ca and Mg in the leaves did not fall below the adequate levels (Table 2), in soils with lower-limit contents of these two nutrients, this management could reduce the contents of Ca and Mg in the leaves even more, reaching levels below the adequate, with negative consequences in yield.

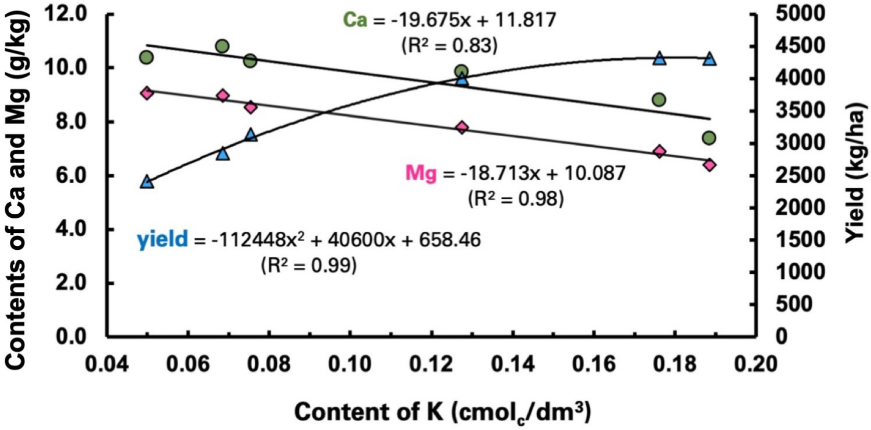


Figure 13. Contents of calcium and magnesium in the leaves (stage R2) and soybean yield as a function of the content of potassium in the soil, in Londrina, PR, in the 2017/2018 season.

Firmano et al. (2019) reported a decrease in the contents of Ca and Mg in diagnostic soybean leaves with the increase in the doses of K. According to the authors, excess K in the soil due to the high doses employed had more severe consequences for Mg, since the contents of the latter decreased in a nonlinear mode up to ~ 4 g/kg, while for Ca, the decrease was linear and reached up to ~ 8 g/kg.

The isolated increase in the contents of exchangeable Ca, Mg, or K resulting from lime, gypsum, and fertilizer management practices may not significantly inhibit the absorption of another nutrient. However, neglecting the use of criteria regarding nutritional balance and replacement of losses and removals for the calculation of fertilizers and corrective agents to improve soil fertility may result in an imbalance between nutrients over time. This may trigger the occurrence of symptoms in plants, evidencing nutritional deficiency and decreasing the crop yield potential.

Experiments carried out in the state of Paraná since the 1990s, applying different doses of K to the soil, have demonstrated the antagonistic effect between the increase in the contents of K in the leaves, due to the increase in the doses of K in the soil, and the decrease in the contents of Mg in the leaves at the R2 stage (Figure 14). The highest soybean yields were reached in the intervals between 18 to 25 g/kg K and 2.8 to 5 g/kg Mg in the leaves.

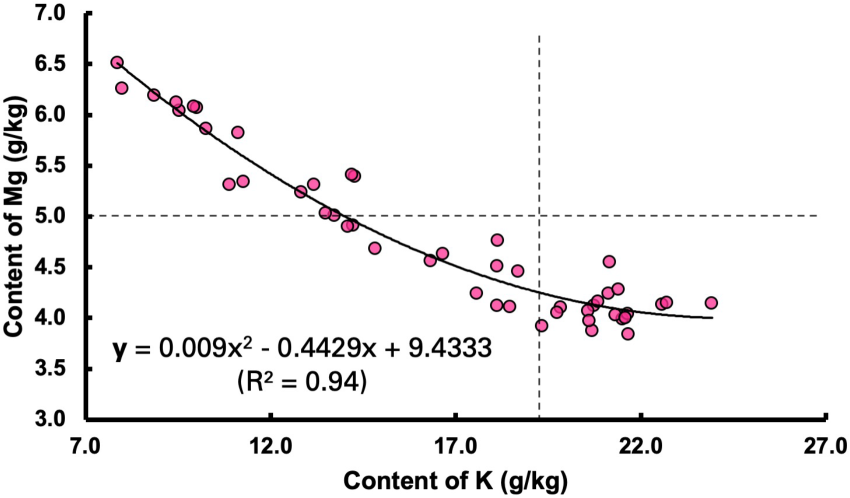


Figure 14. Interaction between the contents of potassium and magnesium in soybean leaves (stage R2) as a function of the contents of potassium in the soil, in Londrina, PR, in the 2015/2016 season.

Another important point to be considered is the processes of nutrient removal by crops and other forms of loss of Mg^{2+} from the exchange complex, mainly in the first layers of the soil, depending on the method of application of corrective agents, gypsum, and fertilizers, and the different erosion forces, principally in areas with steep slopes and little infiltration capacity, without the protection of surface crop residues or cover crops. Due to the aforementioned reasons, Mg can be considered a “forgotten element” in soil fertility management (Cakmak; Yazici, 2010). Therefore, Mg deficiency is becoming an increasingly important factor that can limit the obtention of high yields in intensive agricultural production systems, especially in soils fertilized only with N, P, and K.

Depletion of Mg in soils and “forgetting” the fundamental importance of this nutrient in plant metabolism is a growing concern among producers that adopt high yield farming.

Absorption and accumulation of magnesium in soybean plants

Nutrient absorption by plants is determined by genetic and edaphoclimatic factors related to the production of total dry matter [TDM = shoot dry matter (ShDM) + root dry matter] and the contents of nutrients in the plant. Table 4 shows the average amounts of nutrients accumulated by the aerial part of the plants of five soybean cultivars, belonging to groups of relative maturity ranging from 5.8 to 6.3 and average seed yield of 3.4 t/ha and 8.9 t/ha TDM.

Table 4. Content of nutrients accumulated and removed by soybean crops[1].

Part of the plant	Nutrient										
	N	P[4]	K[4]	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	kg/ha						g/ha				
Seeds[2]	187	16.6	61	10	9	9.5	106	39	223	135	142
Crop residues	83	6.8	104	66	28	4.9	177	29	1062	545	116
Total[3]	270	23.4	165	76	37	14.4	283	68	1285	680	258
Removed %	69	71	37	13	24	66	38	58	17	20	55
kg/t seeds							g/t seeds				
Seeds	54	4.8	18	2.8	2.5	2.8	31	11.5	65	39	41
Crop residues	24	2.0	30	19.3	8.2	1.4	51	8.3	310	159	34
Total	78	6.8	48	22.1	10.7	4.2	82	19.8	375	198	75

[1] Cultivar 1: BRS 360RR, 2011/2012 season, relative maturity group (RMG) 6.2, apparent harvest index (AHI) 0.445; Cultivar 2: BRS 1010IPRO, 2014/2015 season, RMG 6.1, AHI 0.408; Cultivar 3: BRS 360RR, 2010/2011 season, RMG 6.2, AHI 0.396; Cultivar 4: V-Top RR, 2013/2014 season, RMG 5.8, AHI 0.301; Cultivar 5: DM 6563IPRO, 2014/2015 season, RMG 6.3, AHI 0.407.

[2] Content of nutrients in the seeds at the final stage of development (R8, full maturity), basic moisture 14%.

[3] Content of nutrients in the plant tissue at the stage of maximum dry matter accumulation (R6).

[4] Conversion factors: P → P_2O_5 = multiply by 2.29; K → K_2O = multiply by 1.21.

Source: Oliveira Junior et al. (2020).

Nutrient absorption is generally proportional to TDM accumulation; however, due to the variation in the apparent harvest index [AHI = seed dry matter (SeDM)/ShDM] and the effect of dilution/concentration of nutrients, higher amounts of absorbed nutrients do not necessarily result in increases in grain yield, indirectly showing the higher or lower efficiency of plants. The removed quantities (Table 4) are directly proportional to the yield (SeDM) and the contents of nutrients in the seeds. Therefore, the replacement of removed nutrients, especially in soils with contents above the critical level, is also an essential criterion regarding fertilizer recommendation for soybean crops and maintenance of the availability of soil nutrients at adequate levels. Nonetheless, continuous soil fertility monitor is still necessary.

As it can be seen in Table 4, the extraction of nutrients by soybean plants follows this order of priority: N > K > Ca > Mg > P > S. In contrast, the order of nutrient removal (quantity contained in the seeds) is: N > K > P > Ca = Mg = S. Thus, each ton of soybean seeds taken from the field removes around 2.5 kg of Mg, similar to the quantities of Ca and S. Despite the need to replace these nutrients in fertilizer management, Mg is not given the same attention as other macronutrients. In contrast, it is possible to maintain the balance and critical cation contents in the soil by applying soil fertility monitor and soil acidity and fertilizer management practices.

In absolute terms, considering Mg accumulation curves evaluated in four soybean cultivars (Figure 15), the amount of absorbed nutrient is approximately 35 kg/ha, whereas the removal ranged from 7.5 to 10 kg/ha, depending on the yield. Based on the quantities absorbed and removed (Table 4) and on the dynamics of Mg accumulation (Figure 15), it is possible to infer that in soils with adequate levels of Mg, K, and Ca, even though the available quantities meet the needs of the crop, the absorption/demand of Mg^{2+} by soybean is much lower than that of K^+ and Ca^{2+}. Thus, Mg deficiencies can be more easily induced by a lower variation in the nutrient content in the soil as well as by excess Ca and K, reinforcing the need for greater attention to fertilizer management and soil acidity correction.

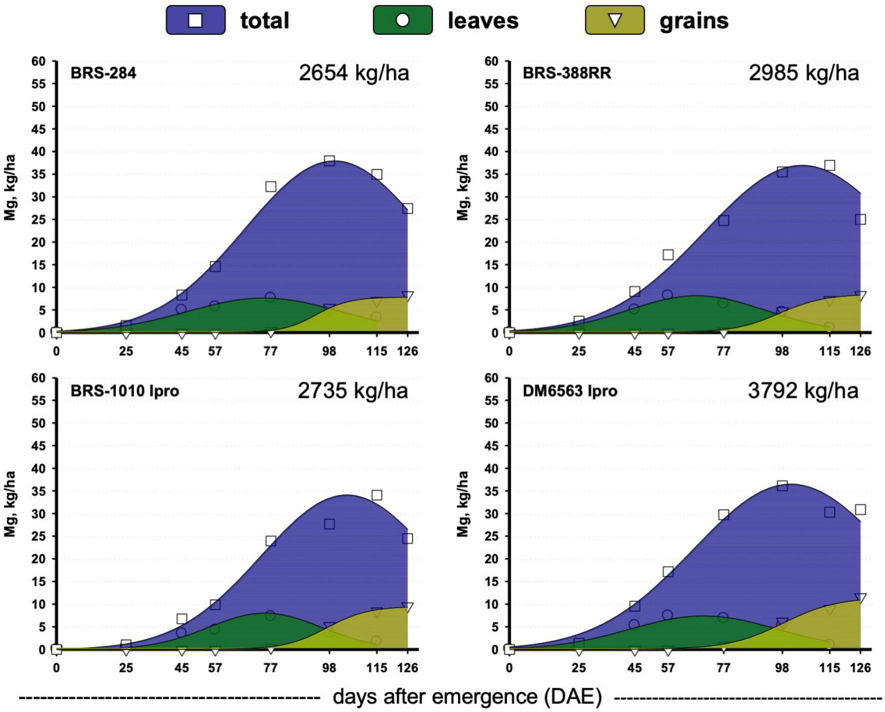


Figure 15. Magnesium accumulation curves in four soybean cultivars, in Londrina, PR, in the 2015/2016 season.

Strategies for correcting magnesium in the soil

Fertilization with Mg is not an agronomic practice carried out on a regular basis or in a conscious manner, as it is the case of N, P, and K, since Mg is generally considered a secondary nutrient. However, since Justus von Liebig's Law of the Minimum, of 1840, is an undisputed truth and is still in force, the content of Mg in the exchange complex suitable for plant metabolism is essential to achieve high yields. Because of the relationship between the nutrient content in the soil and crop yield, the details of soil fertility management will be increasingly responsible for sustaining higher yields and adequate seed composition.

As Mg is primarily applied to the soil by liming, a practice that, in addition to the other chemical transformations in the soil, also increases the levels of Ca and Mg, it is mainly through it that we should balance the ratio of these cations in the soil (Ca/Mg). Nevertheless, when the balance between cations is not possible or it does not exist, due to severe imbalances in the exchange complex, or even if the Mg deficiency in the soil is severe, some possibilities for total or partial correction still exist. These possibilities are strictly technical, and do not take into account economic aspects or logistics, factors that must be evaluated for each situation.

As shown in Table 5, some sources of Mg also contain Ca, a detail that must be taken into account for making fertilizer management decisions. This concern is due to the fact that, if the Ca/Mg ratio of the fertilizer source is not adequate to adjust the content of Mg in the soil, it will not be the best option and may cause an even higher imbalance. With regard to limestones, even if the current legislation does not classify them as calcitic, magnesian, and dolomitic, there are limestones with different contents of Ca and Mg, ranging from those consisting basically of Ca to others with a high content of Mg (Sousa et al., 2007).

Table 5. Commercial sources of magnesium used in Brazil.

Sources	Composition (%)	Observations
Corrective agent		
Dolomitic limestone	> 12 MgO (CaO + MgO > 38)	Acidity corrective agent $CaCO_3.MgCO_3$
Fertilizers and other sources		
Magnesium oxide	45 to 52 Mg	Characteristics of acidity correction, total magnesium as MgO (magnesite calcination)
Magnesium carbonate	25 Mg	Characteristics of acidity correction, total magnesium as $MgCO_3$ (magnesite grinding and sieving)
Kieserite	15 Mg 20 S	Water-soluble magnesium – $MgSO_4.H_2O$
Thermophosphate	3.50–10 Mg 14.5 to 18 Ca 16.5 to 18 P_2O_5 6 S	Characteristics of acidity correction (thermal treatment of phosphate rock containing calcium, magnesium, and silicon compounds)

To be continued...

Table 5. Continuation.

Sources	Composition (%)	Observations
Fertilizers and other sources		
Potassium and magnesium sulfate	10 Mg 20 K_2O 20 S	Water-soluble magnesium – K_2SO_4. $MgSO_4$
Polyhalite	3.6 Mg 14 K_2O 12 Ca 19 S	$K_2SO_4.MgSO_4.2CaSO_4.\ 2H_2O$
Magnesium silicate	21% Mg 24% Si	$MgSiO_3$

Source: Adapted from Brasil (2018).

In addition to the choice of dolomitic limestone or limestones with different contents of Mg for the management of acidity and Ca and Mg balance, other sources can be used to increase Mg saturation in the exchange complex, some of them with high contents of Mg. Another possibility may be the use of fertilizers with variable contents of the nutrient but that can participate in fertilizer management and correction of Mg deficiency.

It should be noted that some sources contain other nutrients that must be considered such as Ca, which can affect the Ca/Mg balance and have properties for soil acidity correction. Some sources contain other elements such as K, S, or micronutrients, for example, which must be considered in fertilizer management and are a positive differential. Castro (1991) studied thermophosphates produced from the rocks of the alkaline-ultramafic-carbonatitic complex of Maicuru, PA, and demonstrated that, in addition to raising the content of P in the soil, thermophosphates are important sources of Mg and Ca for the soil.

In general, soil correction and fertilization must be performed using technical criteria. To accomplish this, chemical analyses of soil and plant tissue are efficient tools to evaluate the effectiveness of these operations. Another possibility is the index for meeting nutrient removals, calculated based on fertilization balance, which indicates whether fertilizer management is balanced. For this purpose, Embrapa Soja developed the platform Avaliação da Fertilidade do Solo e Recomendação da Adubação (AFERE, Soil Fertility Assessment and Fertilization Recommendation), available at www.embrapa.br/soja/afere. At the first stage (module 1), it calculates fertilization balance using the correlation between crop yields and contents of nutrients removed and indicates the need for fertilization, aiming, at least, to replace the nutrients removed from the soil and removed by the seeds. With the adjustment in fertilization, the levels of nutrients in the soil can remain adequate; therefore, soil fertility, especially considering the chemical aspects, is not going to be a limiting factor for obtaining high yields.

Final considerations

Fertilizer management to achieve high soybean yields cannot be evaluated separately, since chemical, physical, and biological factors are interconnected. Nonetheless, soil pH and critical levels of nutrient are the main indicators that determine fertilizer recommendation. Furthermore, the relationships between Ca/Mg, Mg/K, (Ca + Mg)/K, in addition to other relationships and interactions between nutrients must be observed in a complementary way as a criterion for interpreting soil fertility and fertilizer management.

In the last few years, soybean yield in Brazil has increased, not only due to the increased yield potential of cultivars, but also because of the improvement in the productive environment, especially soil management. The increase in yield, which can exceed 6,000 kg/ha, demands, in addition to a higher amount of fertilizers, a more balanced fertilization that considers not only the adequate contents of P and K, but also their relationships with other nutrients such as Ca, Mg, and S, as well as micronutrients.

Another important point is that fertilizers significantly contribute to the variable costs of production, with a great impact on crop profitability, and nothing points to changes in the medium-term scenario. In order to develop a strategy for increasing soybean yield, it is necessary to choose the most suitable cultivars for each region, have knowledge of the soil fertility and the need for lime and gypsum application, apply the appropriate amounts of macro and micronutrients, and take into account the possible interactions with Mg. This is a big step towards the success of farming. Therefore, the careful soil sample collection, regardless of the occurrence of symptoms in plants, as well as the careful analysis and accurate interpretation of the results are the first steps for the possible solution of soil fertility problems. Leaf tissue analysis is complementary to the interpretation of soil analyses and helps identify nutrient deficiencies or excesses that could affect soybean high yields.

The use of leaf tissue analysis as a diagnostic criterion is based on the premises that there is a significant relationship between the supply of nutrients and their respective levels in the soil, and that increases or decreases in the contents of nutrients are related to higher or lower yields, respectively. Given that Justus von Liebig's Law of the Minimum, of the 19th century, remains true, there is no reason why it should not be applied to Mg.

A possible explanation for the increase in nutrient deficiency or toxicity problems in soybean crops, as well as in other agricultural crops, is the low importance given to nutritional balance in plant metabolism and, perhaps most importantly, to the position of symptoms on the plants. Since Mg is mobile in the phloem, typical symptoms of its deficiency occur primarily in older leaves, which makes it more difficult to visualize and identify them, even using image capture technologies.

Based on these considerations, it is necessary to improve technical assessments to enable the adequate fertilizing management, giving attention to all nutrients, to achieve high yields and more nutritious soybean seeds for human consumption and animal feed. The identification of symptoms of deficiency or nutritional toxicity in agricultural crops is the first and important step in the search for the solution of the problem; however, it is not enough to identify a nutritional symptom in plants, its causal agent, and biochemical and physiological explanations for its occurrence. It is mandatory to act to solve the problem. Therefore, the possible commercial sources of Mg are here shown to guide the choice of the amendment agent that can control or solve the problem.

It is interesting to note that even today, over 520 years after the discovery of Brazil, when the Portuguese nobleman Pero Vaz de Caminha predicted, before the splendor of the Atlantic Forest, the abundance of water, and the exuberant land, “EVERYTHING CAN GROW”, there are still those who believe that fertilization is not one of the most important factors controlling yield. Based on this fragment of the letter, the expression “EVERYTHING THAT IS PLANTED CAN BE SUCCESSFUL” was coined and is used until today, meaning that the land was fertile, a mistake that is thought to be true until now. In fact, Caminha, who was not an agronomist, did not understand the reasons for nature vigor in the region. In order to sustain the production of more than 251 million tons of seeds, Brazil is a major consumer of fertilizers, and nothing points to changes in the medium-term scenario. In fact, the country has a large area, freshwater, sunlight, and technology, factors that distinguish it from other countries.

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