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Fertilizing for High Yield and Quality

Maize

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1 Introduction

1.1 Planted area, productivity and tendencies/trends

Maize is one of the most important crops worldwide, both from an economic and social point of view, and stands out as the second most produced grain in the world.

The possibility of growing maize in two seasons of the year (spring/summer and summer/autumn) without the need of irrigation has contributed to increased Brazilian maize production over the years (Fig. 1) and ensured the country's position as the world's third largest producer.

Brazilian maize production has also increased due to a larger area seeded in the second crop. For the 2017/2018 crop year, 5.08 million ha were seeded for the first maize (summer) harvest (CONAB, 2018), whereas for the second crop 11.5 million ha were seeded. However, growing maize as a second crop is a high-risk activity because when maize is seeded in late summer, after the summer crop, temperature and solar radiation can be limited at the end of the cycle. Additionally, in some regions there is a significant risk of hoar frost and drought that severely reduces maize production (Sans and Guimarães, 2009; Duarte and Kappes, 2015).

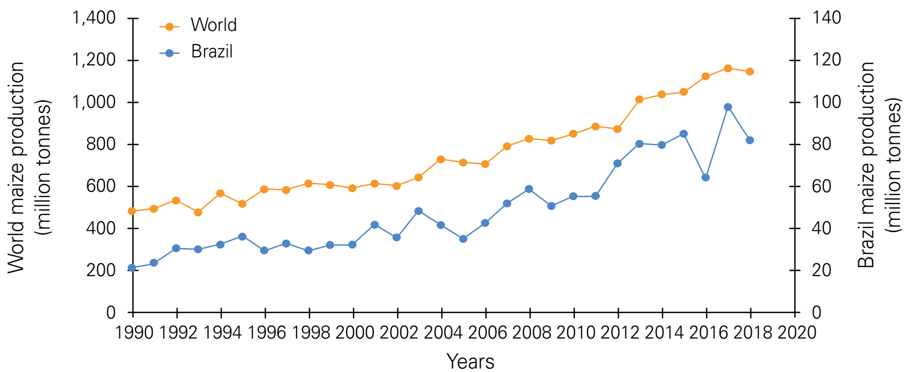

Fig. 1. Evolution of maize production in the world and in Brazil 1990 to 2018
Source: FAO, 2020.

Since 2012, the state of Mato Grosso produces 99% of the maize in the second crop, making it the largest maize producer in Brazil, followed by the states of Paraná, Goiás, Mato Grosso do Sul and Minas Gerais. Together, these five states represented

68% of total Brazilian production in the 2017/18 harvest (CONAB, 2018). The relative participation of each of the major producing states in Brazilian maize production is shown in Fig. 2.

Maize productivity levels have considerably increased, compared to the overall evolution of Brazilian agriculture over the past 40 years. In the 1976/1977 harvest, average productivity was approximately 1.5 t ha^{-1}, while the expectation is between 5.5 and 6 t ha^{-1} for the 2018/2019 harvest.

Although the climate exerts considerable influence and can limit productivity levels, there is still plenty of room for advance by using technological packages to raise current productivity levels.

Maize	**Crop year 2017/2018 (million kg)**	**%**
National production	90,018	100.0
Major maize producing states		
Mato Grosso	27,742	30.1
Paraná	14,574	16.2
Goiás	9,770	10.8
Mato Grosso du Sul	8,956	9.9
Minas Gerais	7,169	7.9
Rio Grande du Sul	5,093	5.7
São Paulo	4,653	5.2
Total	**77,957**	**85.8**

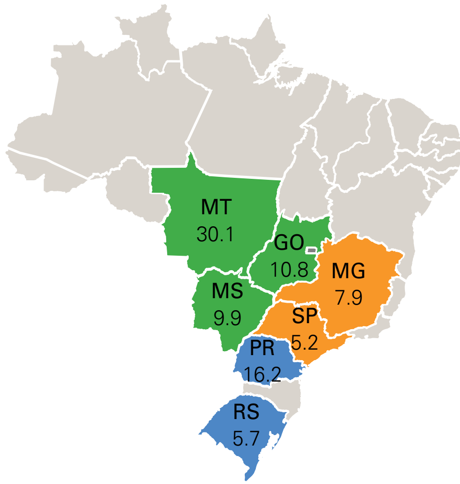

Fig. 2. Maize harvested in 2017/2018 in the largest maize-producing states (in million kilograms)
Source: CONAB, 2018.

The use of varieties with high productive potential in addition to fertilizers have been the determining factors in obtaining high productivity levels for maize in Brazil. As such, fertilizer expenses comprise the major portion of the cost of maize production in Brazil, corresponding to about 25% of total production costs (CONAB, 2017).

1.2 Botany and physiology

Maize belongs to the Poaceae grass family (former Gramineae family). It is an annual species that produces in summer, with a caespitose, erect form with low tillering, monoecious-monoclinic and classified as a C4 plant (which cycles carbon dioxide into four-carbon sugar compounds), with ample adaptation to different environmental conditions. The male spikelets are gathered in terminal vertical spikes. The maize grain is a fruit, called caryopsis, in which the pericarp is fused to the tegument of the seed. The female spikelets are joined on a common axis on which several rachides are gathered (cob), protected by bracts (maize cob). The female flower presents a single stigma.

To meet its maximum productive potential the crop requires high temperatures, of around 24-30°C, high solar radiation and adequate water availability in the soil. Due to its productive potential and strong environmental interaction, maize crops need to be rigorously planned and carefully managed, to attain their full productive capacity.

Among other factors that influence maize productivity, Fancelli (1994) points to humidity, temperature and solar radiation as the most determinant factors. Maize is cultivated in regions with annual precipitation levels of 300-5,000 mm, with the quantity of water consumed during the crop's cycle being around 600 mm (Magalhães and Durães, 2006). The highest water demands occur during the emergence, flowering and grain formation phases. This is especially true around the period 15 days before and 15 days after the appearance of the masculine inflorescence, when satisfactory water supply and adequate temperatures are critical to plant development. Soil temperatures below 10°C and above 42°C significantly affect the germination process. Temperatures between 25°C and 30°C provide the best conditions. During periods of flowering and maturation, mean daily temperatures above 26°C can accelerate germination processes, whereas temperatures below 15.5°C can decelerate them. With respect to light, maize responds to increasing luminous intensities with high yields, being a member of the C4 group of plants.

For a long time, the beginning of the rainy season has conditioned the start of seeding in many maize growing regions of Brazil; the period between August and November. However, a new growing season is now being used for a second maize crop, which has been termed *safrinha* (literally translated as "little crop" or "little harvest" due to the lower productivity attained when compared to summer maize). In this model, seeding occurs between January and March, after the spring/summer harvest of soybean, cotton or beans. Due to the occurrence of droughts and unfavorable temperatures, which are normal in this period, maize performs poorly compared to a crop produced during the recommended period; however, this second crop has contributed to an increase in producer incomes. This has led to the diffusion of the maize *safrinha* throughout the country, to such an extent that it is now larger than the total area of summer maize harvested (Fig. 1) and is now being called the 'second maize crop'.

In the majority of Brazil's regions, seeding of the second crop can be carried out until the end of February. Generally, the later the seeding the lower the productive potential, due to reduced water availability and lower temperatures and solar radiation in winter (Duarte, 2015). South of latitude 22° it is necessary to anticipate frosts when sowing in the higher areas. In the north, the availability of water drastically reduces with the arrival of winter, but it is possible to sow until February in the higher areas. However, in low altitude regions, between latitudes 22° and 23°, climates transition between dry winters and wet winters so it is possible to plant until the 20th of March.

As the temperatures are lower during the second cropping period, the cycle is longer than the summer cycle, with the majority of the crop being harvested 150 days after seeding. This exposes the second crop to adverse winter conditions for a longer time, increasing the risk of productivity losses. Therefore, varieties with early or super early cycles are often used, especially in regions with a high incidence of frosts (Duarte, 2015).

Maize is a plant with a varied vegetative cycle, ranging from 'early' where pollination occurs 30 days after emergence, to varieties with a long cycle of up to 300 days (Fancelli, 1994). However, depending on the genotype used (super early, early or late), under Brazilian conditions the maize cycle is between 110 and 180 days, covering the period between seeding and the point of physiological maturity.

Maize is a thermo-sensitive plant; to complete its cycle it needs to accumulate distinct amounts of thermal energy at each stage of development. Therefore rather than use the date to guide the seeding and management of the maize crop it is more suitable to use a system based on the degree days method (DD). DD is defined as the difference between the mean daily temperature and the basal temperature demanded by the species, as described by the equation (1).

(1)
$$DD_n = \sum_{i=1}^{n} \frac{T_{max_i} + t_{min_i}}{2} - Tb$$

Where: DD = number of degree days accumulated in n days
T_{max} = Maximum temp. (< 40°C) on the i^{th} day after emergence;
T_{min} = Minimum temp. (> 10°C) on the i^{th} day after emergence;
Tb = Basal temp. demanded by the species (10°C for maize)

In general, the thermal requirements of the available hybrids in Brazil are 890-1,200 DD for normal and late cycle varieties, 831-889 DD for early varieties (or medium), and 780-830 DD for super early varieties. The choice of hybrid should be based on its thermal requirements and on the climatic conditions of the region during the seeding period, as will be discussed.

As the duration of each stage of the maize cycle may vary according to genetic and environmental factors, most of the existing recommendations for adequate management of fertilizer application are based on phenological states (Table 1) rather than time after seeding. The mean duration and the phenological stages are briefly illustrated in Fig. 3.

Table 1. Vegetative and reproductive stages of maize.

Vegetative stages	Reproductive stages
Ve - Emergence	R1 - Silking
V1 - First leaf collar	R2 - Blister
V2 - Second leaf collar	R3 - Milk
V3 - Third leaf collar	R4 - Dough
V4 - Fourth leaf collar	R5 - Dent
Vn - n^{th} leaf collar	R6 - Maturity
VT - Tassel formation	

*When establishing the stage of development of a maize plantation, each specific vegetative or reproductive stage is defined as when 50% or more of the plants in the field are in that stage or beyond.
Source: Ritchie *et al.*, 2003.

The system of phenological identification is divided into two phases: vegetative and reproductive. These phases are subdivided, based on phenotypic characteristics that reflect the physiological processes that occur along the development of the crop. Thus, with the division into stages based on morphological changes of the plant, it is possible to make recommendations that increase the efficiency of management practices such as irrigation, fertilization and other treatments (Magalhães and Durães, 2006).

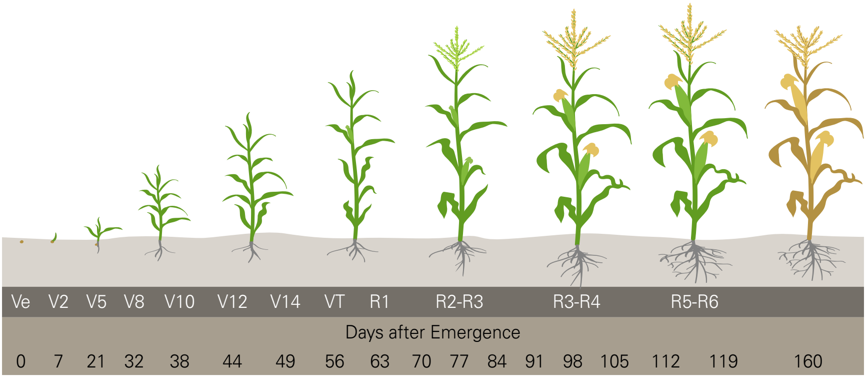

Fig. 3. Phenological states of maize.
Source: Adapted from PANNAR, 2016.

The accumulation of dry matter (DM) by maize along the crop cycle is described by a sigmoid curve, which generally occurs in crop species. The production of DM is low shortly after emergence, increases rapidly until 40-50 days, becomes uniform in the following 50-60 days and diminishes close to maturity. Between 30 and 100 days after emergence, the accumulation of DM is practically linear, reaching rates of 75 to 200 kg ha^{-1} day^{-1} of DM, as a function of soil fertility. However, caution should be exercised in the use of DM or nutrient accumulation data as a function of days after seeding or days after emergence, since different varieties show variation in the amount of time necessary for the physiological changes to occur due to genetic and environmental influences. Fig. 4 shows the curve representing the accumulation and partitioning of the maize DM as a function of the growing degree days and phenological state.

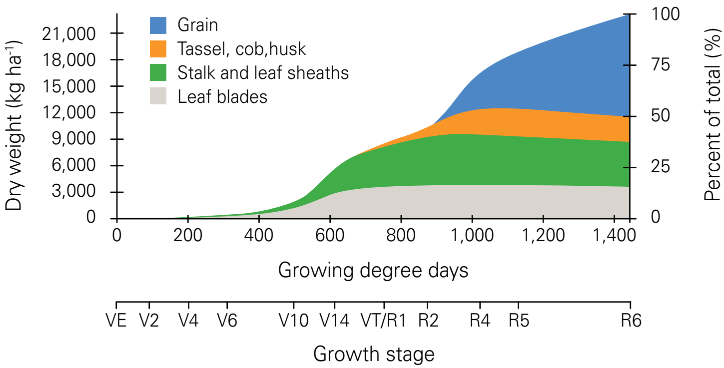

Fig. 4. Average accumulation and partitioning of DM for six maize hybrids cultivated at two locations.
Source: Adapted from Bender *et al.*, 2013.

2 Maize nutritional requirements

2.1 Uptake, accumulation and offtake of nutrients

Besides the organic macronutrients (carbon [C], hydrogen [H], oxygen [O]) supplied by the atmosphere (CO_2, H_2O, O_2), maize needs mineral nutrients from the soil and/or fertilizers: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), manganese (Mn), zinc (Zn), molybdenum (Mo), iron (Fe) and nickel (Ni).

With the development of increasingly productive maize cultivars, the necessity to supply nutrients to attain the nutritional requirement of the crop has become a key issue in high productive maize farms. As presented in Table 2, N and K are the most necessary nutrients to maize production and, along with P, the most removed from the crop field by grain harvest.

Table 2 . Uptake and offtake of macronutrients for a maize crop.

Source	Nutrient (kg t^{-1} of grain)					
	N	P_2O_5	K_2O	Ca	Mg	S
	Uptake (grain and aboveground part)					
(1)	20.0	9.0	17.0	4.0	4.0	2.5
(2)	28.4	6.3	18.0	5.0	3.8	2.0
(3)	23.8	9.5	16.8	-	4.9	2.2
	Offtake (grain)					
(1)	15.0	6.5	7.0	1.0	2.0	1.3
(2)	14.3	4.2	3.7	0.0	0.8	0.9
(3)	13.8	7.5	5.5	-	1.4	1.3

Source: (1) Fancelli, 2007: data not published – adapted from various authors; (2) Bender *et al.*, 2013: mean of six hybrid crops at two locations with a mean productivity of 12 t ha^{-1} of grain and 23 t ha^{-1} of biomass; (3) Resende *et al.*, 2016: mean of six hybrids under three management/culture systems with a mean productivity of 10.3 t ha^{-1} of grain and 25 t ha^{-1} of biomass.

Table 3. Uptake and offtake of micronutrients for a maize crop.

Source	Nutrient (g t^{-1} of grain)					
	B	Cu	Mn	Fe	Zn	Mo
	Uptake (grain and aerial part)					
(1)	8.0	12.0	45.0	230.0	50.0	1.0
(2)	-	9.0	63.0	220.0	45.0	-
(3)	6.9	11.8	45.2	114.7	41.5	-
	Offtake (grain)					
(1)	4.5	2.2	10.0	20.0	23.0	0.7
(2)	-	2.0	4.0	11.0	16.0	-
(3)	1.6	3.4	6.0	20.7	25.7	-

Source: (1) Fancelli, 2007: data not published – adapted from various authors; (2) Bender *et al.*, 2013: mean of six hybrid crops at two locations with a mean productivity of 12 t ha^{-1} of grain and 23 t ha^{-1} of biomass; (3) Resende *et al.*, 2016: mean of six hybrids under three management/culture systems with a mean productivity of 10.3 t ha^{-1} of grain and 25 t ha^{-1} of biomass.

The quantities of micronutrients required by maize are very small (Table 3). However, a deficiency in any of them could disorganize the metabolic processes and have an effect that is just as severe as a deficiency in a macronutrient (Vitti and Favarin, 1997).

When maize is harvested for silage production, the aerial part of the plant is completely removed, resulting in high uptake and offtake of nutrients. Thus, fertility problems will manifest themselves earlier in silage production than in grain production, especially if the area has been used for silage production for many years and an adequate soil management and fertilization program has not been implemented.

As important as the total nutrient uptake, the absorption rate at which the elements are demanded by maize along the crop cycle is a key factor that has to be taken into account by successful fertilization programs. As shown in Table 4, during the first 30 days the elements most in demand are K and Ca. At 90 days, the total demand for nutrients has practically been met. The highest demand for nutrients occurs between 60 and 90 days; the period of flowering and grain filling.

Table 4. Nutrient uptake during the maize vegetative stage.

Elements	Period (days)			
	0-30	30-60	60-90	90-120
	Nutrient uptake (% of the total uptake)			
N	2.5	38.0	47.0	12.5
P	1.0	26.5	46.5	26.0
K	4.4	66.0	29.6	-13.3*
Ca	4.6	49.2	46.2	-
Mg	1.5	46.5	42.0	10.0

* Negative values represent losses.
Source: Malavolta and Dantas, 1987.

Recently, Bender *et al.* (2013) investigated the accumulation and partitioning of nutrients in highly productive modern hybrids (Fig. 5). Despite the low production of DM over the first 20 days, the concern with the supply of N in the seeding furrow is coherent, since its availability depends on the rate of mineralization of plant residues and soil humus. Micronutrients tended to show a peak of demand later than that of the macronutrients, showing higher concentrations in the cob. Higher absorption and demand for K by the maize plants occurs during the vegetative period, presenting the highest rate of accumulation between stages V8 and V14, with a rate similar to that of N. This indicates that an adequate supply and availability of K should be present as early as the initial development stage of maize, which is the starting point for the development and production of biomass. This is evident when Figures 4 and 5 are compared. These show that when the plant has accumulated 50% of its DM at the end of the vegetative period, it has accumulated about 80% of the K needed for the whole cycle.

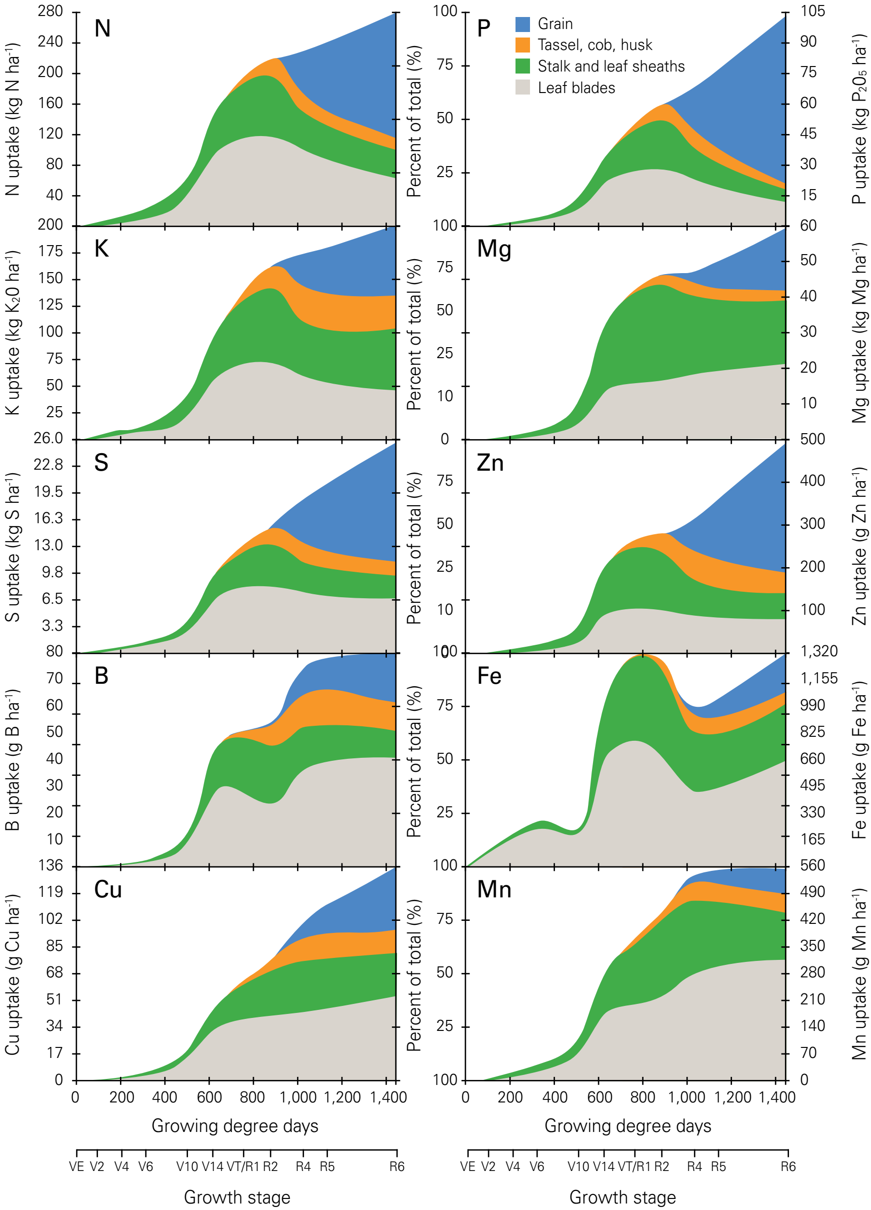

Fig. 5. Average accumulation and partitioning of macro and micronutrients of six maize hybrids cultivated at two locations.
Source: Adapted from Bender *et al.*, 2013.

2.2 Macronutrients: absorption, function and symptoms of deficiency

2.2.1 Nitrogen

Plant species differ in their preference for sources of N, but absorb the nutrient principally in inorganic forms such as nitrate (NO_3^-) or ammonium ion (NH_4^+) (Williams and Miller, 2001).

Nitrogen absorbed as NH_4^+ or from the reduction of NO_3^- is immediately incorporated into a carbon skeleton, to form organic compounds like amino acids. Of these, about 20 are used to synthesize proteins that participate, as enzymes, in plant metabolic processes, having a functional rather than a structural role. When N is incorporated into amino acids in the roots, they are transported to the leaves via the transpirational flux through the xylem (Marschner, 2012). Besides this, N participates in the composition of chlorophyll that is essential for plant metabolism (Raij, 2011).

Plants that have an N deficiency are yellow in color and show a reduction in growth. Chlorosis mainly develops in older leaves, from the leaf tip to the base in an inverted 'V' format (Appendix- Photograph 1) while the young leaves remain green. In cases of severe deficiency, the leaves turn brown and eventually die.

The fact that young leaves remain green under N deficient conditions is an indication of the mobility of this nutrient in plants. Proteins are broken down into simpler components, translocated from older deficient leaves and reutilized in younger leaves. Nitrogen-deficient plants have a shorter crop cycle and consequently mature sooner.

2.2.2 Phosphorus

Phosphorus is absorbed by the leaves preferentially as $H_2PO_4^-$ anion. After absorption, P is almost immediately incorporated into plant organic compounds (Raij, 2011). Phosphorus is particularly involved in the transfer of energy; ATP (adenosine triphosphate) is necessary for photosynthesis, translocation and many other relevant metabolic processes (Shuman, 1994).This nutrient is also part of plant compounds such as carbohydrate esters, nucleotides and nucleic acids, coenzymes and phospholipids. In its inorganic form (Pi), P is the substrate or the final product of many important enzyme reactions, including photosynthesis and chloroplast metabolism, synthesis of starch and sucrose, transport of triose-phosphates, translocation of sucrose and the synthesis of hexoses (Marschner, 2012).

Plants that are deficient in P have an accentuated decrease in growth and a purple coloring of older leaves (Appendix – Photograph 2) because of anthocyanin accumulation. Other symptoms of P deficiency are delays in flowering and cobs with a distorted, twisted appearance and with poor grain set at the point as consequence of pollination problems (Malavolta *et al.*,1997).

2.2.3 Potassium

Potassium is essential for the growth, development and maturation of grains (Meurer, 2006). The level of K in plants is inferior only to that of N (Raij, 2011) and the levels are generally higher in leaves than in grains. This could infer that K is not exported in large quantities during grain harvest.

Potassium is absorbed by plants as K^+ cation and principally during the vegetative growth phase (Raij, 2011). This nutrient is not part of any specific compound therefore its function is not structural. However, K is involved in numerous functions such as sugar translocation, stomata opening and closing, osmotic regulation, and is an activator of a large number of enzymes (Marschner, 2012). Plants deficient in K initially present yellow stripes, which evolve into necrosis at the edges of older leaves (Appendix – Photograph 3). At harvesting, cobs will be thinned at their apex and grains will be poorly filled. Potassium-deficient plants also present reduced turgidity, less resistance to drought and are more susceptible to fungi and lodging.

Potassium deficiency symptoms do not show immediately. Visible symptoms – chlorosis followed by necrosis of the tips and edges of older leaves, shorter internodes and a reduction in apical dominance – only occur in situations of extreme deficiency. Thus, maize productivity may be significantly compromised by poor K nutrition without the crop manifesting any visual symptoms. This reinforces the need for an adequate supply of this nutrient and nutritional monitoring during critical phases of K demand, in order to guarantee higher production quality and quantity.

2.2.4 Calcium

Roots absorb Ca as Ca^{2+}, but its absorption is diminished by high concentrations of K^+, Mg^{2+} or NH_4^+ in the soil. It is found firmly attached to the structure of the apoplast (cell wall) but is also present in an exchangeable form associated with pectates in the middle lamella and has an important role in stabilizing cellular membranes (Marschner, 2012). A large proportion of Ca is found in vacuoles. Low concentrations are found in the symplasm and in the phloem, indicating the plant's low redistribution capacity (Vitti *et al.*, 2006).

Many functions of Ca are associated with the composition of structural macromolecules or related to its coordination capacity, which gives more stable, more reversible intermolecular bonds, especially in the cell wall and plasma membrane. The largest proportion of plant Ca is in the cell wall, resulting from the presence of large numbers of binding sites for this element and the restricted transport of Ca in the cytoplasm (Vitti *et al.*, 2006).

Calcium has an important role in ionic absorption, particularly in correcting the unfavorable effects of excessive hydrogen ion concentration or the deleterious effects of aluminum (Al) in the soil, where the presence of Ca is essential for the absorption of other nutrients.

Ca is indispensable for germination of the pollen grain, elongation of the germ tube and root elongation, which can be attributed to its presence during cell wall synthesis and in the correct functioning of the plasma membrane (Malavolta *et al.*, 1997).

As Ca is a nutrient that has a direct role in the formation of the cell wall, calcium-deficient plants have a short stature, due to reduced cellular elongation and low root development. Young leaves grow stuck to each other with whitish spots and lesions (Appendix – Photograph 4).

2.2.5 Magnesium

Roots or leaves can absorb Mg as Mg^{+} cation (Malavolta, 2006). Among its various functions in the plant, Mg stands out as a component of the chlorophyll molecule (corresponding to 2.7% of the molecular weight), a structure that has great importance in the photosynthetic process. Magnesium is an important enzyme activator, activating more enzymes than any other element. The principal role of this nutrient is to be a cofactor in almost all of the phosphorylative enzymes, forming a bridge between the pyrophosphate of ATP or ADP (adenosine di-phosphate) and the enzyme. The transfer of energy from these two compounds is fundamental for photosynthetic processes, respiration, reactions for the synthesis of organic compounds, ionic absorption and mechanical work performed by the plant. Magnesium also has a role in the transport of photosynthates and, as a P carrier, contributes to the entry of P into the plant.

Magnesium deficiencies in plants are associated with soils that have a low cation exchange capacity (CEC), low levels of Mg in the mineralogical matrix and a low pH which, generally, cannot be corrected by the addition of lime. Deficiency can also be induced by the use of calcitic limestone over many years; a very high Ca:Mg ratio in soil can cause the plant to absorb less Mg. In addition, Mg deficiency can be observed in soils with adequate levels of Mg, induced by the excessive application of K or N fertilizers, since the cations K^+ and NH_4^+ compete with Mg^{2+} during their absorption by plants.

As it is part of the chlorophyll molecule, Mg can be redistributed by the plant in case of an insufficient supply from the soil. This leads to the appearance of deficiency symptoms in older leaves, starting with chlorosis, followed by necrotic spots between leaf veins, while the veins remain green (Appendix – Photograph 5).

2.2.6 Sulfur

Sulfur is absorbed via the roots in the form of a sulphate anion (SO_4^{2-}), entering the plant by symport transport. The transport of SO_4^{2-} to the root is mainly by mass flow. The absorption of SO_4^{2-} is reduced in the presence of Cl^- in the soil and stimulated by the presence of ions such as Ca^{2+} and Mg^{2+} (Malavolta, 1979). Within the plant, S is transported by the xylem, with only small quantities found in the phloem vessels, indicating a low capacity for translocation of this nutrient by the plant.

Sulfur is associated with various structural and metabolic functions in plants. It is a constituent of the amino acids cysteine and methionine, and is present in enzymes that are made from proteins containing the previously mentioned amino acids. It is a component of sulfhydryl groups (-SH) that appear to increase the resistance of plants to drought and cold (Vitti *et al.*, 2006).

As S deficiency results in the inhibition of protein synthesis, deficient plants present a reduction in the intensity of the green color (chlorosis) due to lower chlorophyll production. In consequence, S deficiency results in the reduction of photosynthesis that reduces maize growth and productivity. The symptoms are similar to those observed with N deficiency but occur in younger parts of the plant (Appendix Photograph 6), since S has limited remobilization within the plant (Marschner, 2012).

2.3 Micronutrients: uptake, function and symptoms of deficiency

2.3.1 Manganese

Manganese can be absorbed by plants as Mn^{2+} cation and there is evidence that Mn absorption is controlled metabolically, as in the case of Ca and Mg. However, passive absorption can also occur, principally when high levels are found in the soil.

The low mobility of Mn in phloem is responsible for the low concentrations of this element found in fruits, seeds and storage organs. Usually the ionic form of Mn is highly soluble and easily absorbed by plants. However, in soils with high pH values the precipitation of lower solubility forms of Mn can reduce uptake of this nutrient by plants.

Manganese is essential for the synthesis of chlorophyll and its principal function is related to enzyme activation. It participates in photosystem II, being responsible for the photolysis of water. Manganese can also act as a counter ion of many anionic groups and activates large numbers of enzymes, especially those involved in intermediary metabolism.

Manganese deficiency has a direct effect on the content of non-structural carbohydrates and is particularly evident in the roots. This is probably why root growth is reduced in plants with Mn deficiency. In severely affected plants, the leaf color is pale and shows flaccid growth. New leaves become chlorotic with white streaks between the leaf veins (Appendix – Photograph 7). However, the visual differentiation of the symptoms of Mn, Zn, S and Fe deficiency are difficult to identify accurately because deficiency of any of these elements can produce chlorotic streaks in the new leaves of maize.

2.3.2 Zinc

Zinc is absorbed in the form of Zn^{2+} cation by both the roots and leaves. Some researchers consider Zn to be highly mobile in phloem while others think that it has an intermediate mobility. Fig. 5 shows that most absorbed Zn is exported to the grain, therefore the replacement of this nutrient is fundamental for the maintenance of good yields. Zinc also acts as a cofactor for enzymes and is essential for the activity, regulation and structural stability of them. It is a constituent (structural) of dehydrogenases; participates in the activity of triphosphate-dehydrogenase; and affects the synthesis and conservation of auxins, phytohormones involved in plant growth.

When Zn is deficient, the plant suffers drastic alterations in enzymatic activity, chloroplast development, protein and nucleic acid content. Deficiency manifests as low activity of the terminal bud, which translates into a rosette format in herbaceous crops, while in other crops the internodes become short (Deschen and Nachtigall, 2006). The symptoms start in younger leaves, which present chlorotic streaks with necrotic edges, affecting the leaf parenchyma and veins. The leaves are generally smaller but remain attached to the plant (Appendix – Photograph 8).

The interaction between Zn and P in vegetable crops has been intensely studied, concluding that high levels of P induce Zn deficiency. In cultivated soils where acidity has been corrected, no problems with Zn toxicity are observed, since under these conditions Zn is intensely immobilized.

2.3.3 Boron

Boron is absorbed by the plant as boric acid $B(OH)_3$ and probably as the borate anion $B(OH)_4^-$ at elevated pH levels, by both leaves and roots.

Boron is transported principally through the xylem, having limited mobility in the phloem (Raven, 1980) so that fertilization with this nutrient should be preferentially carried out via soil at seeding time rather than through later foliar fertilization. This nutrient accumulates in old leaves, where the concentration is greatest at the tips and margins (Jones, 1970). In general, the aerial part presents a higher concentration of B than the roots.

Young plants absorb B with greater efficiency and B has roles in important biological processes, acting in some enzymatic systems as a constituent or in others as an active component.

Boron has an important function in the translocation of sugars and the metabolism of carbohydrates, with experimental evidence proving that B deficiency leads to the accumulation of sugars in plant tissues. It has an important role in flowering, growth of the pollen germ tube, fruiting processes, N metabolism and hormone activity. With regard to nucleic acid metabolism, B deficiency has been shown to disrupt cell maturation.

Boron interferes with the absorption and metabolism of cations, principally Ca^{2+}; in the formation of pectins from cellular membranes; in the absorption of water; and in carbohydrate metabolism. Plants with B deficiency have less resistant cell walls, presenting as salient folds in younger leaves.

2.3.4 Copper

Copper is absorbed as Cu^{2+} and chelated Cu^{-}. Root absorption of Cu is by an active process and there is evidence that this element strongly inhibits the uptake of Zn and vice-versa (Bowen, 1969). This element is considered immobile within the plant and is a constituent of ascorbic acid oxidase, cytochrome oxidase and plastocyanin, which are found in chloroplasts. Copper also participates in reactions of oxy-reductive enzymes, influences the fixation of N_2 by legumes, and is essential in the nutrient balance that regulates plant transpiration. It is rare to observe plants with Cu deficiency, as there is an adequate supply of this nutrient in the majority of Brazilian soils. Deficiency symptoms, when they occur, are difficult to recognize due to the interference of other elements such as P, Fe, Mo, Zn and S.

2.3.5 Cobalt

The absorption of Co by the plant is very slow, principally as Co^{2+} ion, and its translocation occurs only after the formation of chelates with organic acids (Malavolta *et al.*, 1997). Cobalt can also be absorbed when chelated and complexed with organic compounds.

Cobalt is reasonably well translocated from the leaves to other parts of the plant, and maize plants have yielded positive responses to Co associated with Mo fertilization via foliar application (Campo and Hungria, 2000).

The fertilization with Co in plants in deficient soils not only increases the biological fixation of N, but also contributes to improved nutritional quality of forage crops. Cobalt is essential for ruminants because its presence in an animal's diet allows the microflora to synthesize vitamin B12 in amounts sufficient to meet the needs of the animal (Asher, 1991).

2.3.6 Molybdenum

Molybdenum is absorbed as the anion molybdate (MoO_4^{2-}) in a way that its absorption can be reduced by the competitive effect of SO_4^{2-} anion. Although Mo is considered moderated mobile within the plant, the form in which this element is translocated is still not entirely known. It's believed that Mo moves in the xylem as MoO_4^{2-}, as a Mo-S amino acid complex or as a molybdate-sugar complex.

Molybdenum is a component of five distinct enzymes that perform reactions in electron transfer processes: nitrogenase, nitrate reductase, xanthine oxidase, aldehyde oxidase and sulphate oxidase.

Molybdenum deficiency has a negative effect on the formation of ascorbic acid, chlorophyll content and respiratory activity. Lack of Mo induces the accumulation of an abnormal concentration of NO_3^- in leaves and, therefore, influences N metabolism. Pollen grain viability is also affected by Mo deficiency, which consequently affects plant productivity.

2.4 Diagnosis using the visual symptoms of deficiency

Visual diagnosis is based on the principle that all plants need the same nutrients, and if there are deficiencies in the soil, they will cause similar symptoms (morphological changes) due to the resulting physiological changes (Malavolta *et al.*, 1997). A visual diagnosis can therefore be used to indicate the availability of nutrients in the soil. In Table 5 the major visual symptoms of nutrient deficiency in maize are described. Photos of macro and micronutrient deficiency symptoms are displayed in the Appendix.

Table 5. A succinct description of the visual symptoms of nutrient deficiency in maize.

Element	Deficiency symptom
N	Yellowing of the oldest leaves (Inverted "V" format)
	Premature death of leaves and/or plants
	Small cobs
	Thin stalks
	Light grains
	Plant tumbling
P	Purple or purplish color of new leaves
	Thin, brittle stalks
	Small cobs with twisted tips
K	Edges of the older inferior leaves have a yellow, orange or bronze coloring
	Brown patches in the interior of the stalks
	Cobs without grain at the extremity and a tapered tip
Ca	Chlorosis of the new leaves
	Reduction in root growth
	Death of the root tips
	Failures in grain formation
Mg	Older inferior leaves with chlorotic areas parallel to the veins
	Plant growth reduced

S	Yellowing of the new leaves
	Plant growth reduced
B	Reddening of the leaves at the end of the crop cycle
	Formation of salient folds in new leaves
	Small cobs and failures in grain formation
	Tips of the cobs with a cork like appearance
Zn	Leaves with a whitish coloration in the husk region
	Reduction in plant growth
	Shortening of the internodes
Mn	Interveinal chlorosis in new leaves (similar to Mg deficiency)
	Thin stalks
	Lower plant growth

Source: Adapted from Fancelli and Dourado-Neto, 2000 and Fancelli, 2010.

3 Nutrition status assessment for fertilization purposes

3.1 Evaluation of soil fertility

The agricultural history of an area should be known so that the potential impacts of supplying nutrients can be estimated. It is important to obtain information such as which management systems were implemented and for how long, what crops have been grown, the type of fertilization used, and the level of productivity achieved.

Soil sampling is the first step in soil analysis, before a program for the correction and fertilization area is created. Therefore it is extremely important that the soil samples are representative of the area.

For the culture of maize, it is recommended that the soil should be sampled annually at two depths, 0-20 cm and 20-40 cm. For each plot (a similar plot, soil type or other factors), a composite sample, composed of 10 sub-samples – of which seven should be taken from between the crop rows and three in the crop row – should be analyzed. When the availability of S is to be evaluated, soil samples should be collected at greater depths.

A chemical analysis of the soil is based on the levels of nutrients available in the soil for plants. In order to establish if a range of soil nutrient availability is insufficient or adequate to obtain optimum levels of productivity, calibration and correlation studies need to be performed between the values obtained by a given extraction method and the response of the crops to the indicated fertilization level. In Brazil, different concentrations are used depending on the extractor used, and the crop and the type of technology adopted. Table 6 shows the level of K and P, extracted by resin, and the recommended levels for the state of São Paulo. Tables 7 and 8 present the interpretation of the chemical analysis of soil K and P from the Cerrado region, utilizing the Melich-1 extractor solution. The clay content was considered for the P analysis, and for the interpretation of the K content the soil CEC was analyzed. In Table 9, the limits of exchangeable Mg and S contents are listed for most crops. The interpretation of the levels of the micronutrients is shown in Table 10.

Table 6. Limits of the classes of P and K content for the soils in the state of São Paulo.

Content class	Relative production	K[(1)]	K[(1)]	P[(1)]	P[(2)]
	%	$mmol_c\ dm^{-3}$	$(mg\ dm^{-3})$		
Very low	<70	<0.7	<30	<6	<7
Low	71-90	0.8-1.5	30-60	7-15	7-15
Medium	91-100	1.6-3	61-120	16-40	16-25
High	>100	3.1-6	121-240	41-80	26-40
Very high	>100	>6	>240	>80	> 40

Extractor – resin.
Source: [(1)]Adapted from Raij *et al.,* 1996; [(2)]Suggested by Vitti, 2016: data not published.

Table 7. Interpretation of the soil analysis for P according to the clay content, for the recommendation of phosphate fertilization in non-irrigated systems with annual crops.

Clay content (%)	Soil P* content				
	Very low	Low	Medium	Adequate	High
	$mg\ dm^{-3}$				
≤15	<6	6.1-12	12.1-18	18.1-25	>25
16 to 35	<5	5.1-10	10.1-15	15.1-20	>20
36 to 60	<3	3.1-5	5.1-8	8.1-12	>12
>60	<2	2.1-3	3.1-4	4.1-6	>6.0

* Extractor – Mehlich-1.
Source: Sousa and Lobato, 2004.

Table 8. Limits of the classes of K content in soils under annual crops in the Cerrado.

CEC	Soil K* content			
	Low	Medium	Adequate	High
$(mmol_c\ dm^{-3})$	$mg\ dm^{-3}$			
<40	≤15	16-30	31-40	> 40
≥40	≤25	26-50	51-80	> 80

*Extractor – Mehlich-1.
Source: Vilela *et al.*, 2004.

Table 9. Limits of the classes of Ca, Mg and S content.

Content class	Ca[(1)]*	Mg[(2)]*	S[(3)]**
	$mmol_c\ dm^{-3}$		$mg\ dm^{-3}$
Low	<12	<4	<10
Medium	12-24	5-8	10-15
High	24-40	>8	>15

* Extractor – KCl 1 mol L^{-1}; ** NH_4OAc0,5N. HOAc0,25N.
Source: [(1)] Alvarez *et al.*, 1999; [(2)] Raij *et al.*, 1996; [(3)] Vitti, 1989.

Table 10. Interpretation of the limits for micronutrient content in soil

Content class	B*	Cu**	Fe**	Mn**	Zn**
	$mg\ dm^{-3}$				
Low	0-0.2	0-0.2	0-4	0-1.2	0-0.5
Medium	0.21-0.6	0.3-0.8	5.0-12.0	1.3-5	0.6-1.2
High	>0.6	>0.8	>12	>5	>1.2

* Extractor – hot water; ** Extractor – diethylenetriaminepentaacetic acid (DTPA).
Source: Raij *et al.*,1996.

3.2 Foliar diagnosis

The use of foliar diagnosis to evaluate the soil supply capacity is justified by the fact that leaves are organs that reflect the nutritional state of the plant; that is, they respond directly to the nutrient supply from the soil or fertilizer (Malavolta *et al.*, 1997).

In order to evaluate the nutritional status by foliar diagnosis in maize, foliar analysis protocols recommend that the central 20 cm of the leaf, opposite and below the cob (Fig. 6), should be sampled (with removal of the central vein) at a density of 30 plants ha^{-1} shortly after the appearance of the female inflorescence (Malavolta *et al.*, 1997). Some interpretation tables recommend the collection of the basal third of the same leaf (Martinez *et al.*, 1999). It is important to adapt the collection methodology to the interpretation table to be used, since different elements have distinct mobility within the plant and can vary in concentration throughout the plant and crop cycle, leading to incorrect interpretations if parts other than the recommended parts of the plant are collected at sampling.

In the literature, various ranges of nutrient levels considered adequate for maize can be found. When analyzing the recommendations, farmers should pay attention to those that most closely fit the soil type and climate found in their region and the level of technology that is being used. Table 11 shows the foliar levels considered adequate for the macro and micronutrients for the maize crop, according to several authors.

Fig. 6. Maize leaf sampling
Source: courtesy of Bruna Giacon.

Table 11. Foliar levels of macro and micronutrients adequate for maize.

Source	N	P	K	S	Mg	Ca
	g kg^{-1}					
(1)	27.5-32.5	1.9-3.5	17.5-29.7	1.5-2.1	1.5-4.0	2.3-4.0
(2)	27.0-35.0	1.9-4.0	17.0-35.0	1.5-3.0	1.5-5.0	3.0-10
(3)	27.5-32.5	2.5-3.5	17.5-22.5	1.0-2.0	2.5-4.0	2.5-4.0
(4)	35.0-40.3	3.3-3.8	22.7-28.9	2.1-3.0	1.6-2.2	4.4-6.2
Source	B	Cu	Fe	Mn	Mo	Zn
	mg kg^{-1}					
(1)	15-20	6-20	50-250	42-150	0.15-0.20	15-50
(2)	7-25	6-20	21-250	20-200	0.15-0.20	15-100
(3)	4-20	6-20	20-250	20-150	0.20	20-70
(4)	8.9-17.7	9.1-14.1	122-219	17.5-49.1	-	18-34.1

Source: (1) Bull, 1993; (2) Raij *et al.*, 1996; (3) Martinez *et al.*, 1999; (4) Gott *et al.*, 2014.

There is a disadvantage in interpreting nutrients levels individually using this technique, because the tables do not take into account various factors such as the interactions between nutrients, variation in concentration with age and degree of development of the plant and differences between varieties.

The classical method makes an interpretation based on the comparison of the analytical results with the previously tabulated parameters (standard index). One of the problems with this method is the fact that it does not indicate whether a determined nutrient is at a deficient or toxic concentration; only that it is outside the standard index.

For the interpretation and comparison of data from foliar analyses, there is the Diagnosis and Recommendation Integrated System (DRIS index), which is a tool that expresses the equilibrium among nutrients. Therefore, this system can be used to identify and correct nutritional deficiencies for future crop cycles, as well as discover possible causes of low productivity related to plant nutrition. In the interpretation of the DRIS index, the level of nutrient imbalance can be observed as a function of the amplitude of the negative or positive indices. The greater the distance the value of the index is from the standard (zero), both negative (deficiency) and positive (toxicity), the greater the negative effect of this nutrient on the plant's capacity to achieve high productivity.

Nutrient balance indices, such as DRIS, are increasingly used to investigate the nutritional state of plants in order to establish a correction priority and/or adequacy of limiting nutrients under given conditions. However, these indices should be used with caution, since the computer programs are using increasingly complex algorithms. Many professionals are therefore using the indices without knowing the implications of each variable and the specific local conditions. In order to use these indices properly, it is advisable that the user has a solid knowledge of plant mineral nutrition and the dynamics of these nutrients in the plant and in the environment.

In the case of K nutrition, the balance between nutrients is very important, since both its absorption and the participation of this nutrient in plant physiological functions is influenced by its interaction with other elements such as Ca, Mg and N, especially NH_4^+. Therefore, even in the presence of adequate nutrient levels in the soil or plant tissue, there could be a reduction in productivity or the manifestation of deficiency symptoms if there is nutritional imbalance.

4 Soil chemical management

4.1 Corrective practices

4.1.1 Liming

With the aim of maximizing efficiency in the use of the nutrients by the plants, the soil needs to have its acidity corrected according to the demands of the crop. Liming is a practice employed to correct soil acidity. The acidity of the soil can be divided into two types, active acidity and potential acidity which can be divided further into exchangeable and non-exchangeable acidity.

Active acidity is when H is dissociated, as H^+ ion, in the soil solution and is expressed as pH. However, it is important to note that, in soils, most of the H (as with weak acids) is not dissociated.

Exchangeable acidity refers to the ions H^+ and Al^{3+} that are retained on the surface of colloids by electrostatic forces. After liberation into the soil solution, the Al^{3+} ions are hydrolyzed, releasing H^+ ions. The quantity of exchangeable H, under natural conditions, appears to be small. Non-exchangeable acidity is represented by covalently linked H, associated with colloids with a variable negative charge and Al compounds (including hydroxyaluminium). These ions are not removed by saline solution, but as the H^+ ions are removed and/or neutralized in the soil solution, these compounds dissociate more H^+ ions, effectively buffering the pH of the soil solution; an effect that is even more evident in highly weathered tropical soils. Fig. 7 shows the simplified reactions that occur during the correction of soil acidity by the application of lime.

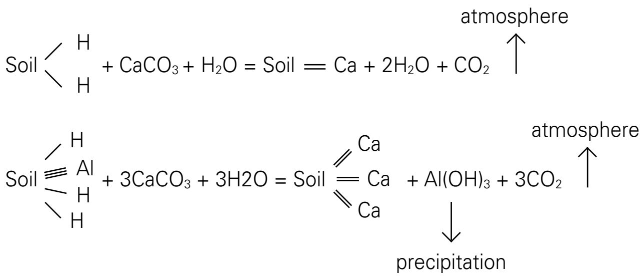

Fig. 7. Reactions in the neutralization of soil acidity
Source: Longanathan, 1987.

Lime reduces soil acidity (increasing the pH) by converting H ions into water. Above pH 5.5, Al^{3+} precipitates as $Al(OH)_3$, removing Al^{3+} ion, which has a phytotoxic effect and is also a source of H^+ ions after undergoing a hydrolysis process in soil solution. The reaction works like this: while the Ca ions (Ca^{2+}) from the lime substitute the Al (Al^{3+}) on the exchange points, the carbonate ion (CO_3^{2-}) reacts with the soil solution creating an excess of hydroxyl ions (OH^-) that react with the H^+ ions (excess acidity), forming water. Magnesium carbonate can react in the same way as described above. Carbonates (from Ca or Mg) react with the soil's H releasing water and carbon dioxide. With the rise in pH, Al is insolubilized in the form of a hydroxide. In the case of other correctives other than lime, such as CaO virgin lime, $Ca(OH)_2$ hydrated lime, calcined limestone etc., which are chemically strong bases, the mechanism of neutralization of soil acidity is based on the reaction of the hydroxyl (OH^-) with the (H^+) in the soil solution.

The opposite of this process can also occur, with the soil becoming more acid if a program of liming is not followed. As the basic ions (Ca^{2+}, Mg^{2+} and K^+) are removed, generally absorbed by the crops, they can be substituted by H^+ and, because of the alteration in pH, by Al^{3+} in soil CEC. These basic ions can also be lost by leaching, again being substituted by H^+ and Al^{3+}. The activity of the H^+ ion increases, lowering the pH of the soil, if adequate liming is not carried out.

The practice of liming is considered essential in soils with pH value below 5.6. Low pH implies very low base saturation (V%) in the soil (Catani and Gallo, 1955). If the V% of the soil is low, instead of elements essential for maize metabolism being adsorbed to the colloids, the adsorption sites are occupied by other cations such as H^+ and Al^{3+}, which are detrimental to root growth and plant metabolism.

Once the toxic levels of H^+ and Al^{3+} have been corrected by liming, the chemical environment in the soil is more favorable to root system development, which implies greater resistance to drought, greater absorption of nutrients and consequently greater productivity. The reduction of factors that negatively influence the development of the root system is fundamental for the success of the agricultural system, especially in tropical countries with warm temperatures and in regions where "Indian summers" are common.

Another motive for the use of liming is the supply of Ca and Mg to the soil. Lime is a product that is obtained by grinding limestone, whose constituents are calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$).

Besides being a source of Ca and Mg, liming increases the availability of nutrients, principally P, K, S and Mo, and reduces the absorption of Al^{3+}, Fe^{2+} and Mn^{2+}, increases microbial activity, leading to higher mineralization of organic material (OM) and increases the biological fixation of N_2, as well as improving the soil structure.

Diverse studies have demonstrated variable results about the effect of liming on maize productivity. In a few cases, no positive response was observed (Moreira *et al.*, 2001), however the majority of studies showed that the application of lime leads to an increase in productivity (Zandoná *et al.*, 2015; Caires *et al.*, 2004; Dalla Nora *et al.*, 2014). Caires *et al.* (2004), for example, demonstrated that superficial liming, whether in a single dose or in split application, increased maize yield in the order of 13% in a red Oxisol with a clayey texture.

Maize productivity is positively influenced by the application of a phosphogypsum-lime combination, with the increment in Ca in subsurface soil being a determinant factor. This is confirmed by experiments where no yield response was achieved with single lime application, even when lime corrected soil pH and promoted adequate levels of Ca and Mg in the topsoil layer.

In Brazil, the recommendations for the correction of acidity for maize growing aims to raise the V% by up to 70% (Raij *et al.*, 1996), which correlated to a pH ($CaCl_2$,) close to 6. According to Raij *et al.* (1996), in soils with levels of OM higher than 50 g dm^{-3} the elevation of V% to 50 is sufficient. There are various criteria for liming; the main ones are those that consider the soil buffering capacity (given by soil CEC), V% and the levels of Ca and Mg. In areas cropped for the first time, it is necessary to correct the base content to a greater depth, recommending the use of the equation (2). In consolidated areas, the use of the equation (3) is recommended:

(2)
$$NL = \frac{\left[\left(V2 - V1_{0-20}\right) \times CEC_{0-20}\right] + \left[\left(V2 - V1_{20-40}\right) \times CEC_{20-40}\right]}{10 \times TRNP}$$

(3)
$$NL = \frac{\left[\left(V2 - V1_{0-20}\right) \times CEC_{0-20}\right]}{10 \times TRNP}$$

Where: NL = Necessity for the application of lime (t ha^{-1});
V2 = V% recommended for maize culture, 70%;
V_{0-20} = Current V% of the soil in the 0-20 cm layer;
V_{20-40} = Current V% of the soil in the 20-40 cm layer;
CEC_{0-20} = CEC of the soil in the 0-20 cm layer ($mmol_c$ dm^{-3});
CEC_{20-40} = CEC of the soil in the 20-40 cm layer ($mmol_c$ dm^{-3});
TRNP = Total Relative Neutralization Power of the lime (%).

Another criterion for liming recommends the lime application to elevate the levels of soil Ca and Mg to 30 $mmol_c\ dm^{-3}$. This method is particularly used for soil with low CEC aimed at guaranteeing adequate levels of Ca and Mg for maize. The recommendation for this criterion is based on the equation (4). As a rule, it is recommended to opt for the criterion that demands the application of the highest dose of lime.

(4)

$$NL = \frac{\left[30 - \left(Ca + Mg\right) \times 10\right]}{10 \times TRNP}$$

Where: NL = Necessity for the application of lime ($t\ ha^{-1}$);
Ca = Level of Ca in the soil layer 0-20 cm ($mmol_c\ dm^{-3}$);
Mg = Level of Mg in the soil layer 0-20 cm ($mmol_c\ dm^{-3}$);
TRNP = Total Relative Neutralization Power of lime (%).

Lime should be applied about three months before seeding to guarantee the reactivity of carbonate with soil. In addition, as shown in Fig. 7, soil moisture is fundamental to guarantee the effectiveness of liming. Incorporating surface-applied lime with a lightweight harrow is also recommended, since poor distribution and/or very shallow incorporation of lime can cause or aggravate the deficiency of metallic micronutrients, resulting in a decrease in productivity.

In areas cropped for the first time, the incorporation of lime into the arable layer (0-20 cm) is fundamental, because of the application of high doses of lime that are recommended. If the lime is not adequately incorporated, there could be high concentrations of the corrective in the superficial layer, which could lead to the precipitation of other nutrients such as P, Zn, Fe, Cu, Mn. For this same reason, the recommendations for areas under no-tillage have some restrictions.

In areas with a clay content above 30% and/or a CEC >70 $mmol_c\ dm^{-3}$, and the levels of the cationic micronutrients (Mn, Zn and Cu) are considered adequate, liming can be broadcast without incorporation, providing the dose does not exceed 3 $t\ ha^{-1}$. If the necessity for liming exceeds 3 $t\ ha^{-1}$, the lime should be incorporated into the arable layer of the soil (0 to 20 cm). However, in areas with a clay content below 30% and/or a CEC <70 $mmol_c\ dm^{-3}$, and the levels of the cationic micronutrients (Mn, Zn and Cu) are at levels considered adequate, lime can be broadcast without incorporation providing the dose does not exceed 2 $t\ ha^{-1}$. If the necessity for liming exceeds 2 $t\ ha^{-1}$, the lime should be incorporated into the arable layer of the soil (0 to 20 cm).

In areas under consolidated no-tillage, for both clayey and sandy soils, which present micronutrient contents below the critical level, it is fundamental to correct the content of these elements when using surface lime applications to correct soil acidity.

4.1.2 Phosphogypsum

The application of calcium sulphate (phosphogypsum) is an important corrective practice to reduce Al saturation and elevate the levels of Ca and S, improving the chemical qualities of the subsoil, which is generally an unfavorable environment for root development (Vitti *et al.*, 2008). Calcium sulphate exists in three forms: anhydride ($CaSO_4$), gypsum (natural gypsum $CaSO_4 \cdot 2H_2O$), and agricultural gypsum (phosphogypsum) which is obtained as a by-product of the production of phosphoric acid.

According to Raij *et al.* (1998) the response to phosphogypsum application depends on the varieties' degree of tolerance to Al stress. The authors state that in acid soils, with V% values below 36% and high Al content, the maize yield was lower for varieties sensitive to Al toxicity in areas where only limestone was applied; the use of phosphogypsum reduced Al saturation in the subsurface and increased grain yield in these varieties.

Studies by Zandoná *et al.* (2015) showed that the application of agricultural gypsum helps to raise Ca^{2+} levels, redistribute Mg^{2+} to the 10-20 cm and 20-40 cm soil layers, and decrease the Al content of the subsurface layer. When gypsum was applied, an increase of up to 2 t ha^{-1} in maize grain was observed.

With the application of only phosphogypsum (9 t ha^{-1}) as the Ca source, Caires *et al.* (2004) demonstrated a 5% increase in maize production. Applying lime with phosphogypsum increased maize production by 17% compared to when only phosphogypsum was applied. According to the authors, the increase in maize grain production with the application of phosphogypsum and lime was not due to alterations in the growth of the root system, but to the increase in Ca saturation in the superficial soil layers. Additionally, the authors suggested that gypsum may have increased the leaching of the Mg, thus reducing Mg availability in topsoil layer. Lime application provided to be useful to provide Mg and compensate for the increased Mg leaching, and the application of phosphogypsum in combination showed to be an efficient strategy to maximize grain production.

Thus, the application of phosphogypsum should be carried out after liming, aiming at conditioning the subsoil (20-40 cm), when any of the following conditions are met:

(i) Level of exchangeable Ca is lower than 5 $mmol_c\ dm^{-3}$;
(ii) Level of exchangeable Al is higher than 5 $mmol_c\ dm^{-3}$;
(iii) Saturation of the effective CEC (Ca+Mg+K+Na+Al) by Al is higher than 30%;
(iv) V% is lower than 30% (V%<30).

To determine the dose of gypsum to be applied, various criteria can be used. The main ones that have produced better results are listed below:

(i) Recommendation based on the clay content (Sousa and Lobato, 2004).

(5) $$NG_{(t\ ha^{-1})} = 5.0 \times Clay_{(g\ kg^{-1})}$$

(ii) Recommendation based on the clay content (Raij *et al.*, 1996).

(6) $$NG_{(t\ ha^{-1})} = 6.0 \times Clay_{(g\ kg^{-1})}$$

(iii) Recommendation based on the elevation of the V% of subsurface to 50 (Vitti *et al.*, 2008).

(7) $$NG = \frac{\left[\left(50 - V1_{20-40}\right) \times CEC_{20-40}\right]}{500}$$

Where: NG = Need for phosphogypsum ($t\ ha^{-1}$).
V1 = V% in the 20-40 cm soil layer.
CEC_{20-40} = CEC in the 20-40 cm soil layer ($mmol_c\ dm^{-3}$), for a maximum CEC of 100 $mmol_c\ dm^{-3}$.

(iv) Recommendation based on supply of sufficient S for three crop cycles, in areas with low Al and sufficient Ca in subsurface (criteria of the authors).

If $V1_{(20-40\ cm)}$ > 40: verify $S_{(20-40\ cm)}$ content:
If $S_{(20-40\ cm)}$ < 15 mg dm^{-3}, NG = 300 kg ha^{-1},
If $S_{(20-40\ cm)}$ > 15 mg dm^{-3}, do not apply gypsum.

The phosphogypsum should be broadcast on the whole area, after liming, and about three months before mineral fertilization at seeding, with no need for incorporation.

4.1.3 Phosphate

In the soil, P is available to plants as the anions PO_4^{3-}, HPO_4^{2-} and $H_2PO_4^-$. The clay fraction of most tropical soils has a large quantity of Fe and Al oxides that, in the natural range of pH for these soils, have positive charges on their surface. These positive charges attract and strongly bind the phosphate anions making them unavailable for root growth and development. It is then said that the P is fixed in the soil or has undergone soil fixation.

As a way to improve the utilization of P in tropical systems, the application of P fertilizer as an amendment is usually carried out. This practice consists of the application of sources of P with low water solubility so as to release the P slowly into the soil. Its slow release corrects the demand for P fixation in the soil, while providing P for the plants. Phosphate application is characterized as being a practice aimed at increasing the efficiency of water-soluble phosphates applied in–furrow to increase P uptake by plants. This practice does not eliminate the necessity for P fertilization during seeding to enable maize growth.

In soils with less than 15 mg dm^{-3} of P (the low or very low class, resin extractor) and classified below the adequate level (Table 9) using the Melich-1 extractor, the application of low solubility phosphate to the whole area is recommended. For this purpose, it is possible to use reactive natural rock phosphate (taking into consideration the total P_2O_5 content), magnesium thermophosphate, partially acidulated rock phosphates, or even more soluble sources, depending on the cost of a unit of $P_2O_5^-$.

The two main recommendation criteria for P application using phosphate sources with correction purpose are:

(i) Application of 5 kg of P_2O_5 ha^{-1} for each percentage point of clay content, up to the maximum content of 30% (Vitti and Mazza, 2002).

(ii) Doses of P_2O_5 to increase the P content of the soil (mg dm^{-3}), to attain critical levels, are linked to the clay content and the type of extractor used in the soil analysis (Sousa *et al.*, 2006). In this case, the buffering capacity of the soil (Table 12) should be considered, with the quantity of P_2O_5 to be applied defined by the following formula:

(8) $$NP_{(kg\ ha^{-1})} = \left(P_{critical} - P_{soil}\right) \times CT$$

Where: NP = Quantity of P_2O_5 to be applied (kg ha^{-1}).
$P_{critical}$ = Critical level of P in the 0-20 cm layer.
P_{soil} = Level of P in the 0-20 cm layer (mg dm^{-3}).
BC = Buffering capacity of P in the soil (kg P_2O_5 ha^{-1}/mg dm^{-3} of P)

Table 12. The critical levels of P for non-irrigated systems and the buffering capacity of P in the soil to determine the dose of P fertilizer using corrective fertilization for annual crops (using the Mehlich-1 and resin extraction methods).

Clay content	Critical level of P for non-irrigated systems*		Phosphorus buffering capacity**	
	Mehlich-1	Resin	Mehlich-1	Resin
%	mg dm^{-3}		kg P_2O_5 ha^{-1} to increase 1 mg dm^{-3} of P in the soil	
10-15	20	15	5	6
16-25	17	15	7	8
26-35	15	15	10	10
36-45	12	15	16	12
46-55	9	15	26	15
56-65	6	15	42	17
66-70	4	15	70	19

*To obtain the critical level of P for irrigated systems (90% of the productive potential), multiply the values for the non-irrigated system by 1.4; ** Dose of P_2O_5 to elevate the level of P in the soil by 1 mg dm^{-3}, based on a sample taken from the 0-20 cm layer. *Source*: Sousa *et al.*, 2006.

The critical levels and the buffering capacity of P in the soil, as a function of clay content, are described in Table 12. For example, considering resin as the extractor, in a soil with a clay content of between 260 and 350 g kg^{-1} and a P content of 5 mg dm^{-3}, it is necessary to increase P content by 10 mg dm^{-3} to attain the critical level of 15 mg dm^{-3} of P in the soil. Based on the clay content of this soil, it would be necessary to apply 10 kg ha^{-1} of P_2O_5 to increase the P level by 1 mg dm^{-3}, therefore 100 kg ha^{-1} of P_2O_5 needs to be applied.

4.2 Mineral fertilization

4.2.1 Nitrogen

Nitrogen fertilization is of great importance in the culture of maize, as N is the mineral nutrient most absorbed by the crop. The recommendation for N fertilization of maize is based on factors that include an estimation of the N mineralization potential of the soil, the quantity of N mineralized or immobilized by the covering crop, the N requirement of the crop to achieve the projected yield, and the expected efficiency of N recovery from different sources (soil, crop residues, mineral fertilizer).

The recommended N dose to be applied in-furrow at maize seeding is between 30 and 45 kg ha^{-1} of N, varying in accordance with the previous crop. Using elevated doses of N (> 60 kg ha^{-1}) at seeding may led to salinization and/or alkalization of the rhizosphere and reduce the rate of absorption of some essential elements, principally of micronutrients, by maize root. Later in the maize cycle, approximately 70 to 150 kg ha^{-1} of N should be applied at the stage where four to six leaves have fully developed (V4 to V6); the period where the potential yield of the crop is defined.

To calculate the N required by the crop, various criteria have been adopted. The adapted formula of Stanford and Legg (1984) can be used:

(9)
$$Nf = \frac{(Ny - Ns)}{Ef}$$

Where: Nf = Quantity of N needed by the plant;
Ny = Quantity of N that can accumulate in the DM from the aerial part of the plant (straw + grain), for a determined grain production (approximately 1% of N in the straw and 1.4% of N in the grain);
Ns = N supplied by the soil (20 kg of N for each 1% of OM in the soil);
Ef = Efficiency factor or use of the fertilizer by the plant (calculated as a function of the increase in the N content of the aerial part of the plant per unit of fertilizer applied [between 0.5 and 0.7]).

An example of the estimation of a topdressing of N for an average maize yield of 7 t ha^{-1} is shown in Table 13.

Table 13. Estimation of the quantity of N fertilizer for production of 7 t ha^{-1} of maize grain.

Necessity for the crop to produce	
Grain, 7 t ha^{-1} × 1.4% of N	100 kg
Straw, 7 t ha^{-1} × 1% of N	70 kg
Total	170 kg
Supply from the soil	
20 kg of N per 1% of OM (soil with 3% of OM)	60 kg
N applied at seeding	30 kg
Need for fertilization	
N rate = (170-90)/0.6*	130 kg

*Efficiency of fertilization = 60%

When soybean is the previous crop, it is necessary to consider the N supplied by the crop from biological fixation. This is a Brazilian reality because almost all areas grown with maize as a second crop were previously cropped with soybean. In general, it is calculated that the contribution of soybean is about 15 kg of N t^{-1} of soybean produced. For the average production in the Cerrado, it is calculated that biological N fixation by soybean contributes 35 to 45 kg ha^{-1} of residual N in the soil that can be subtracted from the topdressing fertilization calculation.

Care must be taken when urea is applied in topdressing to maize since this fertilizer is susceptible to N losses in the order of 30 to 50% of the N applied through the volatilization of ammonia (NH_3) formed after urea is hydrolyzed in soil. To reduce ammonia volatilization loss is recommended that urea-based fertilizers should be incorporated into the soil to prevent the ammonia produced from being transported out of the soil. Another option is to use urea sources coated with urease inhibitors that delay the hydrolysis of urea in the soil and guarantee a longer window of time for the occurrence of rain that helps to incorporate the fertilizer into the soil, thus reducing N losses. It is also possible to use controlled release fertilizers, which consist of grains of urea coated with polymers that reduce the contact of the fertilizer with water in the soil, making it is solubilization slower. This allows a regular and continuous supply of N to the plants, while reducing losses due to leaching, immobilization and volatilization.

Although the mechanical incorporation of urea diminishes the losses by volatilization, elevated doses of urea applied in-furrow at seeding can lead to losses in production because of seed damage caused by salinization. Roscoe and Miranda (2013) tested doses of N fertilizer in second crop maize and demonstrated a linear response of maize grain production to urea broadcast. The positive response extended until 160 kg ha^{-1} of N with an estimated yield of 7,920 kg ha^{-1} (Fig. 8). The application in the seeding furrow gave a quadratic response in production in the second crop maize, presenting peak production of 7,380 kg ha^{-1} at a maximum dose of 75 kg ha^{-1} of N.

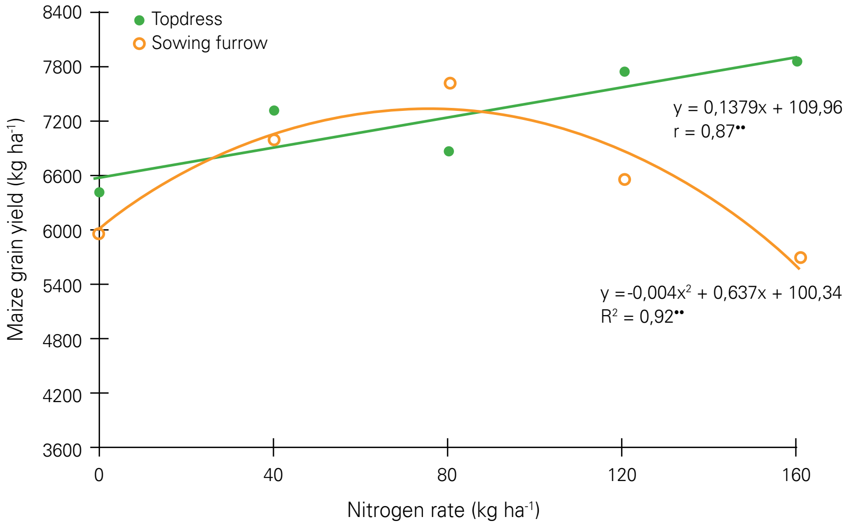

Fig. 8. Productivity of second crop maize as a function of the N applied to the seeding furrow or as a topdressing
Source: Roscoe and Miranda, 2013.

Ammoniacal and nitric fertilizers are not susceptible to ammonia losses when applied on the surface of non-alkaline soils and are an alternative for topdressing N to maize crops. Additionally, ammoniacal fertilizers dissociate in the soil releasing ammonium ions (NH_4^+) that oxidize in turn releasing H ions (H^+), reducing soil pH and increasing the availability of metallic micronutrients (Zn^{2+}, Mn^{2+}, Cu^{2+}, Fe^{2+}) in soils with high pH levels. However, the cost per unit of N is usually higher for these types of fertilizers.

4.2.2 Phosphorus

Although P uptake by maize is relatively small, in Brazil the low levels of P in the soil is one of the factors that limits high productivity. The management of P fertilization depends on the fixation capacity and P content of the soil.

In Cerrado soils, during the first years of maize cropping, lower yields are observed, with the main reason being the low P content of these soils. After several years of maize cropping, and constant applications of P fertilizers, the soil becomes enriched with P, making it more accessible to the roots and consequently increasing production. In soils with low P content, P application is recommended to increase the level of this element. After correction of the P content in the soil, maintenance of P fertilization in the seeding furrow is recommended.

Table 14. Criteria for the fertilization of maize crops with P_2O_5, according to the level of P in the soil.

P* in the soil	Recommended dose of P_2O_5
mg dm^{-3}	kg ha^{-1}
0- 7	200
7- 15	165
15- 25	130
25- 40	95
> 40	60

* Extractor resin

The quantity of fertilizer applied depends on the P soil content and the quantity of the nutrient exported by the crop. Higher P rates will be applied when there are lower levels of the nutrient in the soil, with the expectation of higher productivity.

When P levels have been corrected by fertilization, or the levels encountered are in the medium to high classes, a maintenance dose of 9 kg of P_2O_5 t^{-1} of grain applied to the seeding furrow is recommended. Thus, for an expected productivity of 10 t ha^{-1}, it is recommended that about 90 kg ha^{-1} of P_2O_5 should be applied. Where P content has not been corrected, it is suggested that fertilization should be based on the level of P extracted by resin, as described in Table 14.

For the application of P during seeding operations, acidulated sources with high water solubility should be used, such as single superphosphate, triple superphosphate, monoammonium phosphate or diammonium phosphate, preferentially in granulated form.

4.2.3 Potassium

4.2.3.1 Recommendations for potassium fertilization

The first fertilizer recommendation programs in Brazil presented simple recommendations of K fertilization for maize. This could be attributed to the weak response of maize to K fertilization, since soil K stocks and natural biogeochemical cycles were able to supply sufficient K for the maize to reach its potential productivity. However, the advent of more productive maize hybrids, especially when soybean is the previous crop (a legume that exports large quantities of K), has demanded the application of higher doses of K in order to compensate offtake in grain.

Table 15. Interpretation of the soil analysis and recommendations for corrective K fertilization for annual crops according to nutrient availability in the soils of the Cerrado.

K content	Interpretation	Corrective fertilization
mg kg^{-1}		kg of K_2O ha^{-1}
	CEC < 40 $mmol_c$ kg^{-1}	
< 15	Low	50
16 to 30	Medium	25
	CEC > 40 $mmol_c$ kg^{-1}	
< 25	Low	100
26 to 50	Medium	50

Source: Vilela *et al.*, 2004.

The first step to elevate the concentration of K to reach adequate levels for maize seeding is through corrective fertilization. A study by Vilela *et al.* (2004) proposes corrective fertilization as a function of the level of nutrients and soil CEC, as shown in Table 15.

Another practical method that is used is to elevate the K content in the soil so that the element occupies 4% of the soil CEC. The calculation to perform this correction using KCl is described in equation 10.

(10) $$KCl_{(kg\ ha^{-1})} = \left(160 \times \left[0.04 \times CEC_{(0\text{-}20cm)}\right]\right) - K_{soil}$$

Where: $KCl_{(kg\ ha^{-1})}$ = Need for KCl application (kg ha^{-1});
$CEC_{0\text{-}20}$ = CEC in the 0-20 cm layer ($mmol_c$ dm^{-3});
K_{soil} = Exchangeable K in the 0-20 cm layer ($mmol_c$ dm^{-3});

After the K levels in the soil have been corrected, annual fertilization should only be carried out to replenish K offtake and possible losses by leaching. The interpretation of the soil analysis and the recommendations for K fertilization, for maize grains, based on the expected yield, are presented in Table 16, adapted from Coelho (2005).

Table 16. Recommendations for K fertilization of maize.

Productivity expected	Recommendation for fertilization (kg ha^{-1} of K_2O)			
	K content of the soil			
t ha^{-1}	Very low	Low	Medium	High
	State of Minas Gerais[1]			
4-6	-	50	40	20
6-8	-	70	60	40
>8	-	90	80	60
	State of São Paulo[2]			
4-6	70	50	40	20
6-8	110	70	50	30
8-10	140	110	70	40
>10	160	130	90	50
	Rio Grande do Sul and Santa Catarina[3]			
-	100-130	70	40	20

Source: [1] Alves *et al.*, 1999; [2] Raij and Cantarella, 1996; [3] Comissão de Fertilidade do Solo – RS/SC, 1994.

4.2.3.2 Management of potassium fertilization

For the corrective fertilization of K, pre-seeding is a recommended management practice for soils with low K levels by providing adequate K in the soil, consequently increasing the efficiency of maintenance fertilization.

The most commonly used material for K fertilization is potassium chloride (KCl), which presents a high salinity index (117). The application of high doses of this fertilizer in the seeding furrow can result in germination problems and reductions in productivity due to soil salinization. As a result, it is recommended to avoid K_2O doses greater than 50 to 60 kg ha^{-1} in the seeding furrow. Instead, the rest of the recommended dose should be broadcast on the soil surface. In soils with a clay content over 30 g kg^{-1} and/or soil CEC over 40 mmol$_c$ dm^{-3} the application can be made pre-seeding. However, if the clay content is less than 30 g kg^{-1} and/or soil CEC is less than 40 mmol$_c$ dm^{-3}, K should be applied on the soil surface, no later than 25 days after emergence, since the absorption of K by maize occurs principally in the initial growth phases (Table 4 and Fig. 4).

Natural fertilizers are now produced using a mineral called polyhalite, which has a low salinity index (12), contains 14% of K_2O and contains three important macronutrients: 19.2% S, 12% Ca, and 3.6% Mg. Polyhalite is a more complete and more recommended source of K to be applied in seeding furrow since along with K it provides Ca and Mg and S in balanced levels, while maintaining lower salinity levels in the root environment.

4.2.4 Sulfur

For production of up to 6 t ha^{-1} of maize grain, the application of 20 kg ha^{-1} of S is recommended. Maize yields greater than this require the application of 40 kg ha^{-1} of S.

The need for S is usually met by the application of agricultural gypsum (15% S) during the soil correction stage. However, other fertilizers that contain S in their composition can be used annually to replenish the soil. Fertilizers such as ammonium sulphate (24% S), single superphosphate (12% S), polyhalite (19.2% S) or magnesium thermophosphate (4-6% S) are good options.

Sulfur requirements are commonly met by the application of agricultural gypsum (15-16% S) when applied as a subsurface conditioner during corrective practices. New products are available, such as elemental S that can be applied together with P in the seeding furrow or with N, in which the S envelopes the fertilizer granule, increasing the fertilizer's efficiency.

4.2.5 Magnesium

Maize requirement for Mg is usually met by liming when dolomitic limestone is used. However, to achieve the highest levels of productivity, a foliar application of 0.9 kg ha^{-1} of Mg is necessary, divided into two applications of 0.45 kg ha^{-1}; with the first application before, and the second after, tassel formation.

The most common source of Mg is magnesium sulphate, which is soluble and also supplies sulfur. Other recommended sources are magnesium oxide (MgO), magnesium chloride ($MgCl_2 \cdot 6H_2O$), magnesium nitrate ($Mg(NO_3)_2 \cdot 6H_2O$) and Mg chelates (as Mg-EDTA, for example).

4.2.6 Micronutrients

Due to the low soil content, cultural practices such as liming and the use of increasingly purified fertilizers, which reduces the availability of micronutrients to plants (Vitti *et al.*, 2006), an adequate supply of micronutrients becomes essential for increasing maize yield and quality.

Among the metallic micronutrients (Cu, Mn, Fe and Zn), Zn is the most limiting for the production of maize in Brazil, however reports of deficiency of this element are common throughout the world. Low levels of Zn occur principally in the weathered soils of the Cerrado region or in soils formed over sedimentary rocks with low Zn content, such as sandstone and siltstone. The response to Zn application depends on the level of crop productivity and the nutrient content of the soil. Ritchey *et al.* (1986) observed that in an experiment with varying doses of Zn, plants fertilized with 3 kg ha^{-1} yielded similar amounts to those receiving 9-27 kg ha^{-1} of the micronutrient. In applications with high doses of Zn, reductions in production were normally observed. Due to the low mobility of metallic micronutrients in the soil, where the principal mechanism of ion-root contact is diffusion, the application of these elements in the seeding furrow is recommended, aiming at adequate plant nutrition. However, it is possible to make corrective applications of micronutrients, when necessary.

Of the anionic micronutrients (B and Mo), B has been shown to be the most limiting to productivity in highly weathered soils, therefore maize responds to the application of this micronutrient, principally in sandy soils. In soils with low levels of B, high maize productivity combined with high doses of N and K can cause deficiency of this micronutrient in the crop (Woodrdruff *et al.*, 1987). Due to the high mobility of B in the soil, the source of this element for the plant can be broadcast or applied in the seeding furrow. For the second option, lower doses of a less water-soluble source are recommended. During the reproductive phase of maize growth, B demand is high and coincides with the critical period for water supply, essential for the distribution of this micronutrient within the plant by the transpiration stream. In this case, foliar B application is recommended.

The sources of micronutrients are divided into inorganic (mineral) and organic. Among the inorganic sources are the acids, salts, silicates (fritted trace elements), carbonates, hydroxides, oxides, oxysulfates and phosphites. The principal organic sources are chelates, fulvic and humic acids. In general, these sources can be supplied in three forms to maize: soil or foliar applications and treated seeds. The application of micronutrients via the soil is most commonly performed during seeding and applied in the seeding furrow (Table 17).

Table 17. Suggestions for maize fertilization with micronutrients.

Nutrient	Dose (kg ha^{-1})	Source
Zn	3 to 5	Oxysulfate
B	1	Ulexite or Borax Pentahydrate

Source: Vitti, 2017: data not published.

For foliar application, the dose, period of application and type of micronutrient should be taken into consideration. The supply of micronutrients via foliar application allows for quick correction but is less durable and it does not correct these micronutrients levels in the soil. Micronutrients are mainly applied in the form of sulfates, chelated sources or phosphites.

For maize, Zn and Mn should be applied together with an insecticide for the control of fall armyworm between stages V4 and V6, at 100 g ha^{-1} for a chelated source and 400 g ha^{-1} of a salt. Besides this, 60 g ha^{-1} of Mo should be applied together with the first application of Zn and Mn. A summary of foliar applications for maize is shown in Table 18.

The application of Zn via seeds can be carried out together with phytosanitary products, at doses of about 90 to 100 g ha^{-1} of Zn. It is important to check compatibility with the phytosanitary product when application is via seed. The biggest problem for seed treatment is that the producing companies already shield/protect them in some way, hindering additional amendments.

Table 18. Suggestions for maize foliar fertilization.

Stage	Mn	Zn	Cu	Mo	Mg
	g ha^{-1}				
V4	50	60		30	-
V8	100	60	25	30	-
Pre-tassel formation	100	-	25	-	450
Post-tassel formation	-	-	25	-	450
Total	250	120	75	60	900

Source: Recommendation of authors.

5 Aspects of maize fertilization in succession systems

An increasingly common reality in tropical agriculture is the practice of growing more than one crop per agricultural year. This has increased productivity per cultivated area and promised greater returns and sustainability of the productive system. With this practice, a second maize crop is grown after the summer crop, with the soybean-maize system being the most common in Brazil. This has a direct impact on nutrient availability, making fertilization recommendations for the second maize crop slightly different from that of the summer maize crop.

A practice that is being carried out by some farmers is the anticipation of fertilizer application necessary for maize, by applying a quantity superior to the demand of the previous crop in order to generate a surplus to be used by the second maize harvest. This practice seeks to fit the concept of 'system fertilization' and aims to increase the operability and speed of seeding, since fertilizers occupy a reduced amount of space in the seeder. However, this type of fertilizer management requires some caution.

Farmers carry out P fertilization for soybean crops, however, this practice may not be so efficient because the P available for the maize is not the simple difference between what was applied and that extracted by the soybean. It is more complicated, as the phosphate anion can be fixed in the soil by Fe and Al oxides that reduce its availability to maize in the soil solution. In soils where fertility is already consolidated, and the fixation of P by the oxides is stabilized, the anticipation of P fertilization for maize has produced results similar to those using fertilization at seeding. However, in soils with low P content, it is recommended to maintain P fertilization at seeding. Where the P availability in the soil is very low, the necessity to apply high doses of P fertilizers almost always makes the maize crop uneconomical.

Nitrogen fertilization for maize varies depending of the previous crop (gramineae or leguminous), especially in the no-tillage system. Gramineae leave residues on the soil surface that have a high C:N ratio. To decompose these residues, the soil microorganisms demand N from the soil solution, reducing availability to the maize crop and demanding compensation through N fertilization. On the other hand, when leguminous crops are seeded before the maize crop, there is a possibility of a considerable reduction in the application of mineral N fertilization due to the rapid mineralization of the plant residues with high N content (Amado *et al.*, 2002). In the case of second crop maize, other important factors should be considered, such as the occurrence of periods without rainfall (lower latitude) and low temperatures (higher latitudes). Low humidity and low temperatures reduce the mineralization of OM in the soil, therefore reducing the availability of N from plant residues for the maize crop. These climatic conditions limit the potential productivity of the second maize harvest, reducing the demand for nutrients.

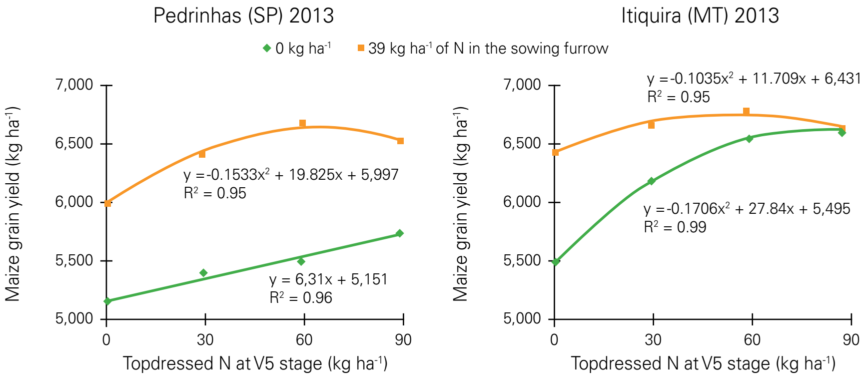

Fig. 9. Response of second crop maize 2B587Hx to topdressing N fertilization in fields with and without N application in the seeding furrow. Adapted from Duarte, 2015.

Irrespective of the climatic conditions or the previous crop, the need to apply N fertilizer for the second maize harvest is indisputable. As demonstrated by Duarte (2015), the withdrawal of the N fertilizer at seeding could mean up to double the levels of fertilizer are required to recover the productivity expected when N is applied during seeding, when this does not irreversibly jeopardize maize productivity (Fig. 9).

When the second maize harvest is cultivated in areas where soybean has been the previous crop (the vast majority of cases), the biological fixation of N by the soybean crop leaves between 35 to 45 kg ha^{-1} of N in the soil. Added to the 60 kg ha^{-1} of N available from the mineralization of the soil OM (see 4.2), this results in the supply of about 100 kg ha^{-1} of N for maize after soybean. Considering an average grain productivity of 4,500-6,000 kg ha^{-1} for the second maize harvest (Roscoe and Miranda, 2013), between 120 and 150 kg ha^{-1} of N will be extracted from the soil. Under these conditions, the recommendation would be to apply 20 to 50 kg ha^{-1} of N to the seeding furrow.

For yields above 6 t ha^{-1} in the second maize harvest, it is fundamental to complement fertilization during seeding with the application of N fertilizer to the soil surface in doses compatible with expected productivity. Suggestions for fertilization adapted from Duarte *et al.* (2013) are shown in Table 19. However, when approximately 30 kg ha^{-1} of N is applied to the seeding furrow, with soybean as the previous crop and clayey soils, the frequency of a positive response to surface N application is very low, resulting in productivity below 6 t ha^{-1}. Under these conditions, Duarte *et al.* (2013) reported that only 10% of the experiments, with productivity levels equal to or below 6 t ha^{-1}, showed a response and economic return with the surface application of N, while 60% of the experiments with higher productivity obtained profits when N fertilization of maize applied at sowing was complemented with a N topdressing at V4 stage (Fig. 10). Thus, N fertilization for the second maize grown in succession systems is indispensable, however, additional N topdressing should only be used when a productivity above 6 t ha^{-1} is expected.

In areas under cultivation for more than five years, K levels are probably the lowest levels due to the high demand for this nutrient by soybean (Duarte *et al.*, 2013). This makes K fertilization in seeding furrow a fundamental practice in systems where maize is grown after soybean. As K is the nutrient that accumulates in the highest quantities during the initial phases of maize development, and there is a low probability of rainfall events to move down the K applied during the second maize crop period, split K fertilizer application should be avoided.

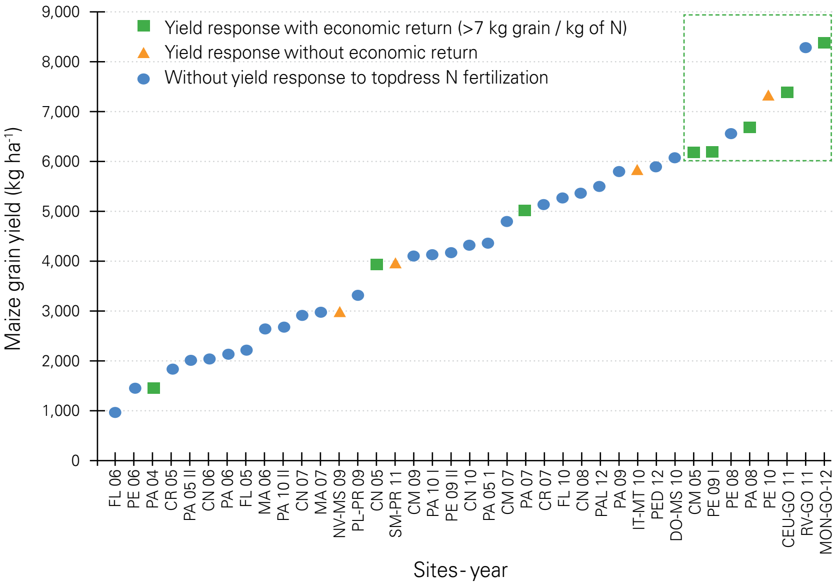

Fig. 10. Responses to topdressing N fertilization, using ammonium nitrate in 39 second crop maize experiments, in the main Brazilian maize-producing states during the period 2005 to 2012.
Source: Adapted from Duarte *et al.*, 2013.

Table 19. Fertilization recommendations for second crop maize.

Expected grain productivity (t ha^{-1})	N*			
	Response class			
	Low		Medium	
	Seeding	Topdress	Seeding	Topdress
	kg N ha^{-1}			
<4	30	0	30	0
4-6	40	0	30	20
6-8	30	20	30	40
	P			
	P-resin (mg dm^{-3})			
	0-6	7-15	16-40	>40
	kg P_2O_5 ha^{-1}			
<4	nr**	40	30	20
4-6	nr	50	40	30
6-8	nr	70	60	40
	K***			
	Exchangeable K- Melich-1 ($mmol_c$ dm^{-3})			
	0-0.7	0.8-1.5	1.6-3.0	>3.0
	kg K_2O ha^{-1}			
<4	50	40	20	0
4-6	60	50	30	20
6-8	nr	60	40	30

* Low response to N = maize after soybean or another legume in summer, in clayey soils; medium response to N = maize after soybean, in medium texture or sandy soils; ** nr = fertilization not recommended because it is unlikely to obtain high levels of productivity; *** Do not apply more than 40 kg K_2O ha^{-1} in the seeding furrow.
Source: Adapted from Duarte *et al.*, 2013.

As the quantities of K recommended for the second maize harvest are lower than for summer maize crops (Table 16), there is logically a lower productivity potential. However, lower levels of application reduce the risk of injury to the root system due to salinization by K and N applied to the seeding furrow (in general, a maximum of 50 kg K_2O ha^{-1}). With the aim of maximizing crop yield and/or avoiding damage caused by salinization, the K can be surface applied along with N as soon as possible after seeding using single-element sources or in NPK formulas such as 20-00-20. However, in late applications, when the soil humidity is inadequate to move the K from the surface into the soil and be absorbed by the plant roots, this type of fertilization will probably have a low or no effect on crop productivity (Duarte, 2015).

Table 19 contains the fertilization recommendations for the second maize harvest with primary macronutrients, which are those with peculiarities between the recommendations for summer maize and the second crop. The application of other macro and micronutrients can proceed according to the recommendations for summer maize, based on the expected productivity and the soil content of that element.

6 Inoculation of maize with *Azospirillum*

A practice that is gaining popularity in the maize production system is the inoculation of seed with N-fixing microorganisms. The use of plant growth-promoting bacteria and mycorrhizal fungi, among others, could have a strategic role in guaranteeing high productivity with lower costs and with increases in fertilizer use efficiency. The process of biological fixation of N in gramineae occurs through the action of diazotrophic bacteria. In the specific case of maize, *Azospirillum brasilense* is one of the organisms that is showing encouraging results (Hungria, 2011; Rosa, 2017).

Bacteria of the genus *Azospirillum* stimulate an increase in the density and length of root hairs and the rate of appearance of lateral roots. This increases the surface area of the roots and the utilization of nutrients, resulting in better plant development and greater crop productivity. Inoculation with *A. brasilense* promotes a greater accumulation of DM, higher uptake of nutrients and higher maize grain productivity (Rosa, 2017).

Long-term studies carried out by Okon and Labandera-Gonzalez (1994), showed that in 20 years of experiments, the use of *A. brasilense* and *A. lipoferum* on seeds resulted in a positive result in 60-70% of cases, leading to increases in grain production of 5-30%. Hungria (2011) reported increases of 24-30% in maize grain productivity when inoculated with *A. brasilense*, compared to a control that did not receive topdress N fertilization. However, under the same conditions, increases in maize grain production of 38-43% were observed with conventional N fertilization. Therefore, the inoculation of maize seeds with *Azospirillum* spp. is a good alternative N supply to improve crop productivity. Inoculation, however, is a practice best suited to low input systems and should not be used as the only source of N for maize.

Commercial products containing *Azospirillum* spp. can be found in the form of a powder (based on peat) or liquid, with cellular protectors that ensure that the bacteria remains viable for several months (Fancelli, 2010; Hungria, 2011).

7 Santa Fé intercropping system: maize and *Brachiaria*

The Santa Fé intercropping system is an intensive use of agricultural areas with a reduction in production costs. This system consists of intercropping tropical forages, principally of the genus *Brachiaria*, in agriculturally established areas after the maize harvest. This is because it provides year-round harvests, including annual grain crops in the summer, in addition to all of the benefits of crop rotation, maintenance of soil cover and improved structure, control of erosion, nutrient recycling, increase in soil organic C, and reduction of pests, diseases and weeds.

The principal objectives of the Santa Fé system are the production of forages between harvests and straw for no-tillage system. This system has advantages; it does not alter the chronogram of activities, it is low cost and it does not require special equipment for its implantation. The intercropping is established annually, at the time of maize seeding (Kluthcouski *et al.*, 2000).

Fig. 11. Santa Fé intercrop system of maize and *Brachiaria*
Source: courtesy of Rodrigo Estevam Munhoz de Almeida.

When the *Brachiaria* is seeded between maize rows, the efficiency of fertilizer uptake by maize is increased from 13% to 21%; this occurs because *Brachiaria* roots exude a substance called brachilactone (Crusciol, personal communication), which is capable of reducing the nitrification of ammonia, increasing its relation with the nitrate of the soil, which is an ion that requires greater energy expenditure by the plant for its absorption. With the increase of the ammonium:nitrate ratio in the soil, there is a beneficial acidification, especially near the rhizosphere, that favors the availability of metallic micronutrients. The increase in the quantity of OM by *Brachiaria* promotes higher microbiological activity that may favor the solubilization of less soluble forms of P, increasing the availability of this nutrient to the plants.

Another benefit of using the system is its ability to recycle K, which is very important for maize nutrition and avoids K losses by leaching. Garcia *et al.* (2008) studied the dynamics of K in a soil-straw-plant system where maize was cultivated on its own or intercropped with *Brachiaria brizantha* and verified that the intercrop was more effective in recycling K and increasing the levels of exchangeable K in the superficial soil layers. The authors concluded that *Brachiaria* was able to access and absorb non-exchangeable forms of K in the soil and that K was washed from the *Brachiaria* residue after drying, making it more available for the maize.

8 References

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9 Appendix

Visual symptoms of nutrient deficiency in maize

Photo 1. Nitrogen deficiency symptoms.

Photo by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.

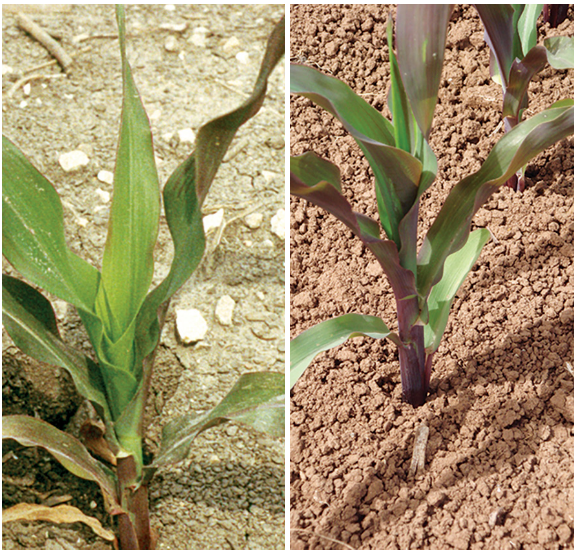

Photo 2. Phosphorus deficiency symptoms.

Photo (left) by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.
Photo (right) by Yaron Bar (Israel).

Photo 3. Potassium deficiency symptoms.

Photo by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.

Photo 4. Calcium deficiency symptoms.

Photo by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.

Photo 5. Magnesium deficiency symptoms.

Photo by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.

Photo 6. Sulphur deficiency symptoms.

Photo by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.

Photo 7. Manganese deficiency symptoms.

Photo by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.

Photo 8. Zinc deficiency symptoms.

Photo (left) by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.
Photo (middle) by Mateo Martinez Nicolas (Mexico).
Photo (right) by Patrick Gesualdi Haim (Brazil).

Photo 9. Iron deficiency symptoms.

Photo by Iowa State University Extension and Outreach Publication IPM42 (Reprinted February 2012), John Sawyer, Department of Agronomy, Iowa State University.