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Boron: Dynamics and sources for soil application

Introduction

Brazilian agriculture is experiencing a time where the profitability associated with sustainability, efficiency in the use of fertilizers and productivity are the main components of the production process (Abreu et al., 2007).

In this context, micronutrients, especially boron (B), have gained great prominence in agriculture to obtain high yields. Nevertheless, B is considered by several researchers as the micronutrient with the most limited productivity gains in national agriculture. About 60% of Brazilian savannah soils are believed to be deficient in B (Lopes et al., 2012).

B is found in the solution of the soil, mainly in the form of boric acid (H3BO3), which is the predominant form in the pH range suitable for crops and in which it is absorbed by plant roots. However, the availability of this micronutrient can be influenced by factors such as pH, organic matter, texture, humidity, among others (Yamada, 2000; Fageria et al., 2009). In Brazilian soils, especially those with a sandy texture and low levels of organic matter, the lack of this element is even more pronounced (Malavolta, 2006; Embrapa, 1999).

In addition to the low availability of B, it is worth mentioning that the range of contents of this element between deficiency and toxicity is narrow ($0.3\text{-}0.6 mg.dm^{-3}$). In most Brazilian soils, organic matter is the main source of B for plants (Faquin, 2005). Fertilization recommendations in soils deficient in B suggest higher doses of this element in soils that were limed or with high clay and organic matter contents. This is due to the adsorption processes of B that occur with soil colloids (Alleoni, 1996).

The ionic absorption is influenced by the characteristics of the soil-plant system, for example, there is a selectivity in the absorption of nutrients where some have a greater preference in the absorption; the accumulation of nutrients are more concentrated in the cell sulcus than in the external environment and the genotype of the plants respond differently to the absorptions and concentrations of the elements (Malavolta, 2006; Taiz & Zeiger, 2014).

In order for the nutrient to be absorbed, there must be contact between the ion and the root, for B, this mechanism is carried out by the mass flow (97%) which is characterized by transport over long distances. Briefly, mass flow is the movement of the ion in a mobile aqueous phase (soil solution) respecting a water tension gradient. In other words, nutrients are dissolved and carried by the water until they reach the surface of the roots. A practical implication of this mechanism is the application of B to be carried out by casting, away from the roots or in coverage (Malavolta, 1997; Faquin, 2005; Malavolta 2006).

Transport by xylem is unidirectional, through a transpiration current from roots to shoots and in phloem B, it is practically immobile. Therefore, the deficiency of this element often appears in newer organs (Broadley et al., 2012).

Currently, Brazil is seen as the breadbasket of the world, not only because it has a high production potential of the most diverse crops, but also because it still has a large area to be exploited in a sustainable way. However, to support the constant growth, nutrient inputs will be necessary and attention should be paid to micronutrients, especially B.

Boron dynamics in the soil-plant system

B is an element found in the anionic form in soil in association with oxygen. Although it is found in some insoluble silicate minerals such as tourmaline, the main forms of boron present in the soil are sodium borate and calcium borate. Among these minerals are borax ($Na_2B_4O_7.10H_2O$), colemanite ($Ca_2B_6O_{11}.5H_2O$), ulexite ($NaCaB_5O_9.8H_2O$) and kernite ($Na_2B_4O_6.3H_2O$). The distribution of B in the earth's crust is different from that of other micronutrients due to its predominance in sedimentary rocks, and B contents in the soil are, on average, between 7 and 80 $mg.dm^{-3}$. In the form of boric acid, the average content of B is close to 10$mg.dm^{-3}$ (Abreu et al., 2007; Kabata-Pendias, 2011).

In soil, adsorption can occur through five mechanisms:

a) borate ion absorption in clays;
b) boric acid adsorption;
c) formation of organic complexes;
d) precipitation of insoluble borates with aluminum and silica;
e) entry of B into the crystalline structure of clay minerals
(Hatcher et al., 1967; Yamada, 2000; Kabata-Pendias, 2011).

It is worth noting that this adsorption of B limits the availability of this nutrient (Figure 1).

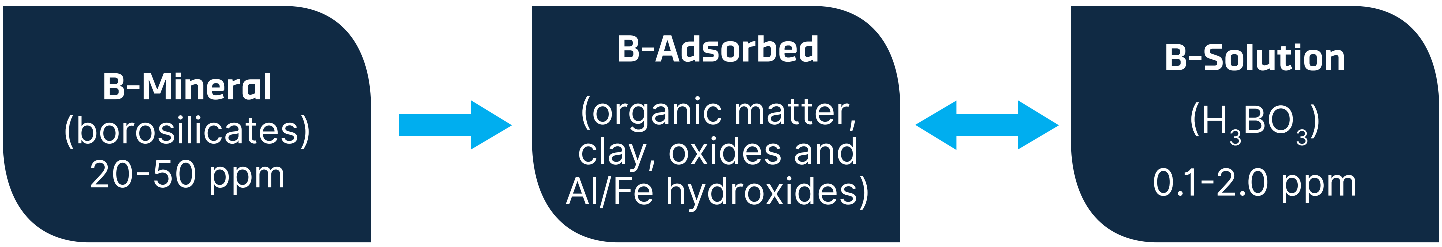

Figure 1. Forms and availability of B in soils (Adapted: Goldberg, 1997).

The B availability curve in the soil is variable and is in the ideal range for crops between pH 5 and 7, decreasing above and below these values (Abreu et al., 2007). Under these conditions, B remains in the undissociated form (H_3BO_3), which is the form in which the plant absorbs this nutrient (Hu & Brown 1997; Power & Woods 1997).

$$B(OH)_3 + H_2O \rightleftharpoons B(OH)_4^- + H^+ \text{ (pKa 9.25)}$$

On the other hand, the adsorption of B by iron and aluminum oxides is higher between pH 6 to 9 (Saltali et al., 2005; Abreu et al., 2007). Additionally, in soils that have been limed or where soils have a higher pH, B can bind to carbonate, precipitate in the form of calcium borate, or be adsorbed into calcium carbonate, becoming momentarily unavailable to plants (Alleoni & Camargo, 2000; Rosolem & Biscaro, 2007). According to the authors, during the liming year this deficit is more relevant and stabilizes again in the following years. This fact is extremely important for managing B in Brazilian soils, since they are rich in kaolinite (aluminum hydroxides) and iron oxides, have low base saturation and high doses of limestone are required for correction. In this context, it is worth mentioning that in areas under a no-tillage system, it is common to find a high pH in the upper layers between 0-10cm, another fact that may contribute to this low availability of B.

Organic soil matter concentrates most of the B that will supply the plant's demand. However, B will only be released into the soil solution after the mineralization of this organic matter and can follow several paths, as shown in figure 2. It is worth remembering that soil conditions that favor the decomposition of organic matter, such as: high temperatures, soil moisture, high microbial activity and soil aeration are essential for the increments of B available to plants (Abreu et al., 2007).

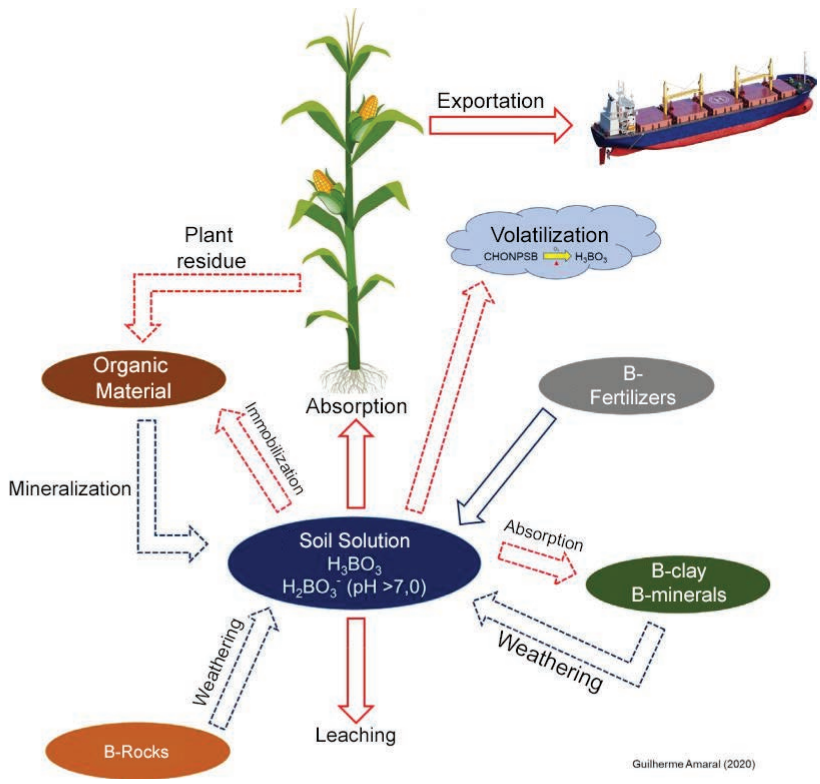

Figure 2. Boron dynamics in the soil-plant system.

B availability is directly affected by soil water content and becomes a limiting factor in dry conditions where mass flow to roots is reduced (Broadley et al., 2012). As mentioned before, under these conditions, there is a decrease in the mineralization of organic soil matter, reducing the availability of B (Abreu et al., 2007). As a consequence, there is a reduction in the root system of the plants, a smaller volume of explored soil and deficiency symptoms may appear, which often disappear with adequate soil moisture (Abreu et al., 2007; Broadley et al., 2012).

On the other hand, under conditions of high precipitation, B losses through leaching reduce availability, especially in sandy soils. The literature shows that B leaching is greater in soils without liming when compared to soils that received limestone (Communar & Keren, 2007) and that leaching has a greater relationship with the applied dose and with the levels of this nutrient in the soil (Rosolem & Biscaro, 2007).

In plants, B is probably taken up by plant roots in the form of undissociated boric acid (H_3BO_3), the main soluble form in soil. However, much is discussed about whether it is absorbed through a passive or active process. It is transported through the transpiration current, i.e., from roots to shoots, and in the phloem B, it is practically immobile. Therefore, deficiency symptoms appear in young tissues and growth points (Faquin, 2005; Malavolta, 2006; Broadley et al., 2012).

B is the only element that does not meet the essentiality criterion in plants, but satisfies the indirect criterion (Faquin, 2005). Among the main functions of B in plants includes:

plasma membrane stability, nucleic acid metabolism and sugars, auxin regulation and tissue differentiation, root elongation, phenolic compounds, biological nitrogen fixation, pollen tube growth, among others (Gupta, 2006; Malavolta, 2006; Jehangir et al., 2017).

Among the micronutrient deficiencies, B is best known worldwide, as plants grown in soils with low availability of this nutrient show significant reductions in soy (Gomes et al., 2017; Longkumer et al., 2017), corn (Lordkaew et al., 2011; Wasaya et al., 2017), rice (Rehman et al., 2014; Rehman et al., 2018), cotton (Ahmed et al., 2013; Wahid et al., 2020) and wheat yields (Nadeem et al., 2019).

Due to its low translocation in the phloem, deficiency symptoms appear in new tissues and apical meristems. There is a reduction in plant size, leaf deformation and even death of the terminal bud (figure 3) (Broadley et al., 2012; Gupta, 2006). Toxicity is more common in arid regions or where the source material of soils is marine. On the other hand, excess in the application of fertilizers, soil or foliar, can cause toxicity. Symptoms manifest as mottled chlorosis and, later, necrotic spots on the edges of older leaves, which coincide with regions of the leaf where there is greater transpiration (Faquin, 2005; Malavolta, 2006; Broadley et al., 2012).

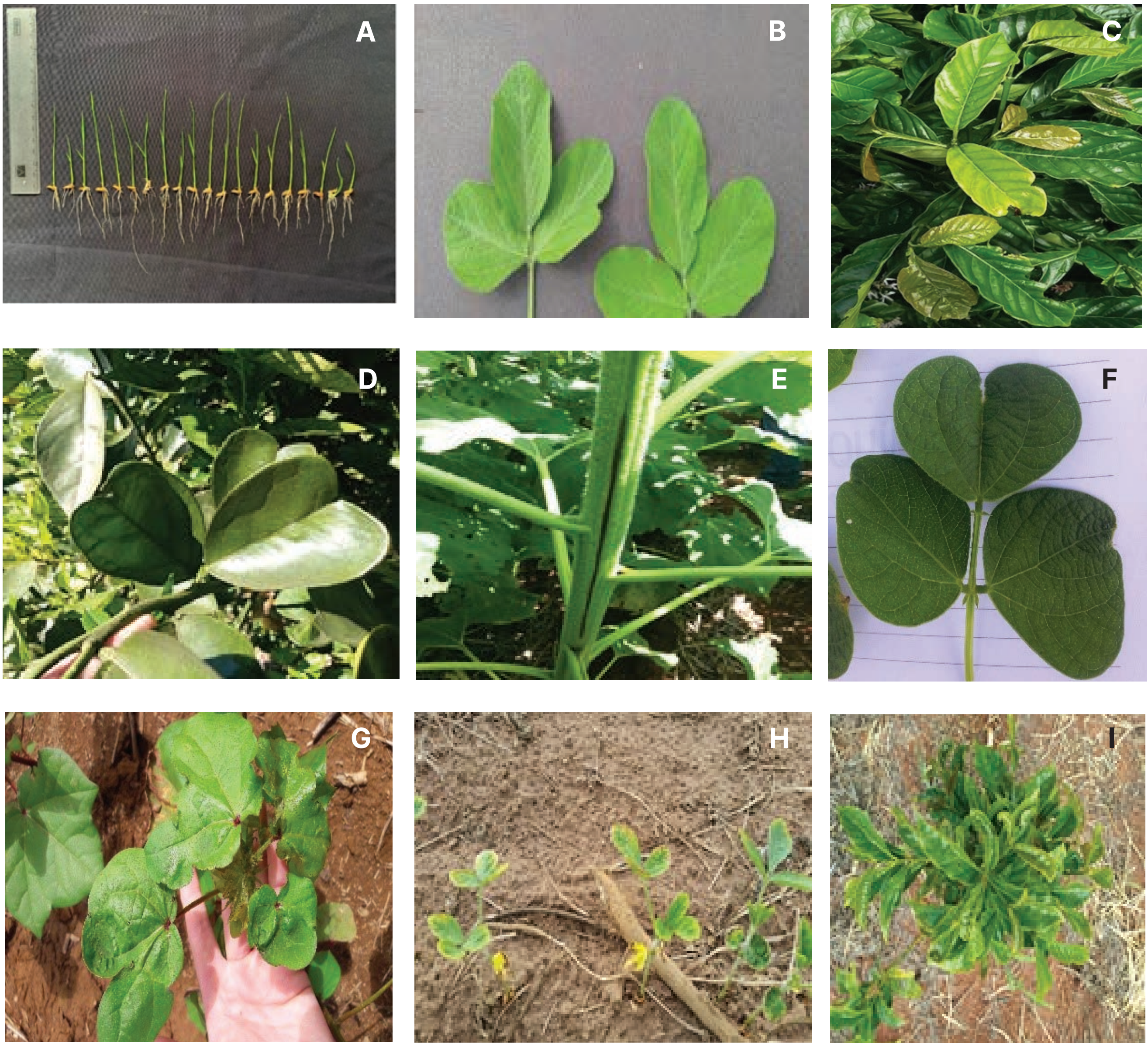

Figure 3. Photos of boron deficiency in: a) corn; b) soy; c) coffee; d) citrus; e) sunflower; f) beans; g) cotton. Boron phytotoxicity in: h) soy; i) coffee.
(Photos: **ICL**'s Technical Department).

Boron mitigating aluminum toxicity

Tropical soils present limitations to the growth and establishment of crops and this is mainly due to the effects of soil acidity. Among the acidity components, aluminum is one of the main limiting factors to the productivity of most crops (Fidelis et al., 2016).

In addition to the phytotoxic effects of aluminum in the soil solution, the decrease in cell division and the ability of the roots to elongate should also be mentioned, resulting in inhibition of the root system, with thicker, deformed and brittle roots (Figure 4). Furthermore, aluminum toxicity interferes with DNA synthesis, decreases cell division and replication, alters the permeability of plasma membranes and changes in the functions of mitochondria and Golgi complex (Miyasaka et al., 2009; Kopittke et al., 2015). As a consequence, there is a reduction in plant growth and development.

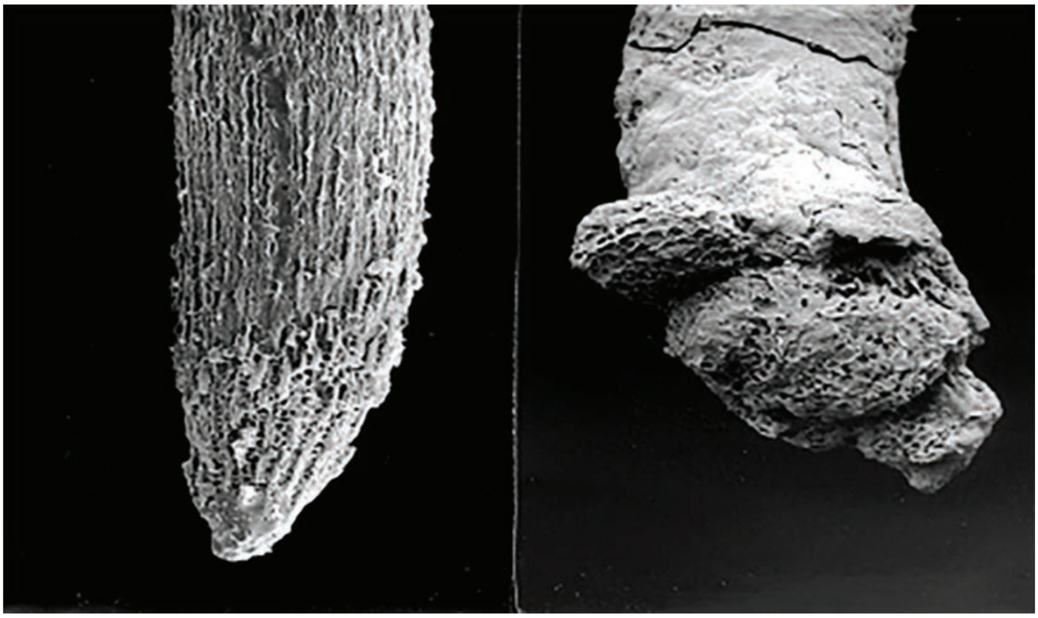

Figure 4. Apical meristem of wheat root subjected to normal treatment (left) and with 5 μM of aluminum chloride (Zhou et al., 2011).

As a way to mitigate the effects of this toxic aluminum on roots, researchers have proposed the use of B, since this micronutrient acts in maintaining membranes and cell walls (Sardar et al., 2006; Li et al., 2018; Riaz et al., 2018; Riaz et al. al., 2018).

According to Li et al. (2018), the increase of B in the solution promotes an alkalinization of the root surface, maintains the integrity of membranes, increases the formation of proteins and pectic compounds close to the roots, increasing tolerance to toxic Al. Corroborating the results, Riaz et al. (2018b) found that citrus roots (*Poncirus trifoliate*) growing in an aluminum solution (200μM) had an increase of up to 69% when B was added to this solution. According to the authors, the increase in B can be used to improve root growth and alleviate damage to root structures caused by aluminum.

Another line of research shows that, under conditions of high aluminum content, the application of B stimulates responses of the antioxidant system, especially the enzymes catalase, peroxidase, ascorbate peroxidase and glutathione reductase, which reduce the effects of aluminum on the roots (Figure 5) and also their concentrations in leaves and roots (Cakmak & Römheld, 1997; Corrales et al., 2008; Riaz et al., 2018B).

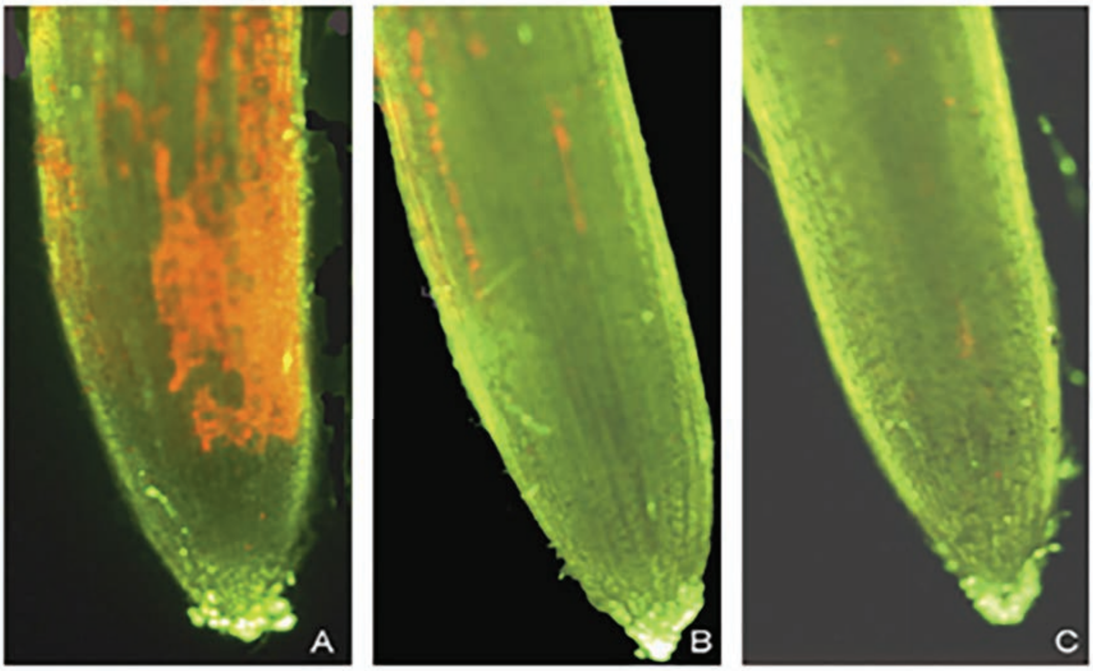

Figure 5. Fluorescence micrograph of root tips of corn seedlings doubly stained and cultivated in nutrient solutions with different concentrations of B and Al. Treatments with A) 7μM Al and 4 μM B; B) 7μM Al and 16 μM B e; C) 7μM Al and 32 μM B (Corrales et al., 2008).

Soil analysis, interpretation of results and recommendation of B

Soil analysis is an important tool to assess the availability of nutrients in the soil. However, in a large part of the country, use by producers is still quite restricted. In recent years, the use of this tool has intensified and contributed to significant increases in productivity.

The plant is considered the best extractor of nutrients from the soil, reflecting its real availability. Therefore, a good extractor must simulate the behavior of the plant. Thus, for B, extraction is performed using the hot water method and has an efficiency rate between 65-85%, depending on the methodology used by the laboratory (Abreu et al., 2007).

According to Abreu et al. (2007) B content in soils varies between 7 and 80mg.dm^{-3}, however, only between 0.1 and 3 mg.dm^{-3} is actually available to plants (Dechen and Nachtigall, 2007). This is due to the dynamics of B in the soil-plant system already discussed above.

National literature is scarce when it comes to soil micronutrient levels, especially B levels. Table 1 shows the classification of B levels for the Brazilian savannah region and the state of São Paulo.

Table 1. Percentage of soils classified by boron content class separated by region.

Content classification	% Brazilian savannah	% state of SP
Low	61.7	37.0
Average	30.0	54.0
High	8.3	9.0

Adapted from Fundação MT (2002); Prochnow et al. (2018)

The interpretation range of B in soils varies according to the recommendation manual adopted in each state and/or region. For the purposes of this bulletin, the recommendations for the Brazilian savannah (Sousa & Lobato, 2004), Minas Gerais (Ribeiro et al., 1999), São Paulo (Raij et al., 1997), Rio Grande do Sul and Santa Catarina are adopted (SBCS/CQFS, 2004) (Table 2).

Table 2. Limits for the interpretation of B contents in the soil in the 0-20cm layer, hot water extractor.

Interpretation range	Brazilian savannah B ($mg.dm^{-3}$)	MG B ($mg.dm^{-3}$)	SP B ($mg.dm^{-3}$)	RS/SC B ($mg.dm^{-3}$)
Low	< 0.30	≤ 0.35	< 0.20	< 0.10
Average	0.30 - 0.50	0.36 - 0.60	0.30 - 0.50	0.11 - 0.30
High	> 0.50	0.61 - 0.90	> 0.50	>0.30
Very High	-	> 0.90	-	-

As seen in table 2, most recommendation manuals stipulate that the adequate B content (critical level) in the soil for most crops is close to 0.6 $mg.dm^{-3}$, with the exception of the states of RS and SC in which the content is 0.3$mg.dm^{-3}$. In general, B levels in the Southern states are lower because the soils have a higher content of organic matter in the soils.

However, in 2016, in the competition for maximum soy yield of Comitê Estratégico Soja Brasil [Brazilian strategic soy committee] (CESB), it was shown that soy areas with yields above 78 $sc.ha^{-1}$ had B contents above 0.8 $mg.dm^{-3}$ and 0.7 $mg.dm^{-3}$, respectively, in the layers of 0-20 cm and 20-40 cm and more details can be seen in Table 3 (Sako et al., 2016; Yamada, 2017). Work like this brings to light the importance of nutrient B for high yields and the need to improve research to review tables of critical levels in the soil.

Table 3. B contents along the soil profile in areas with high soy yields (Yamada, 2017).

Productivity (sc/ha)	Boron content in the soil profile ($mg.dm^{-3}$) Depth (cm)					
	0 - 10	10 - 20	20 - 40	40 - 60	60 - 80	80 - 100
78-100	0.8	0.9	0.7	0.6	0.5	0.5
107 - 142	1.2	1.0	0.8	0.6	0.7	0.5

This fact has aroused the interest of producers in increasing B supplementation through soil by applying isolated products.

Boron sources and soil management options

Commonly, producers have used sources of B with guaranteed levels close to 10%. The main source used in borate fertilizers for application through soil is ulexite, however, some manufacturing procedures can change the composition and efficiency of these borate fertilizers composed of ulexite. This bulletin will also provide you with knowledge to differentiate between them in the market.

The main sources used to supply B are: ulexite, colemanite, hydroboracite and kernite. It is worth noting that the solubility of these sources decreases in the following order: sodium borates > sodium and calcium borates > calcium borates (Figure 6) (Manning, 2016).

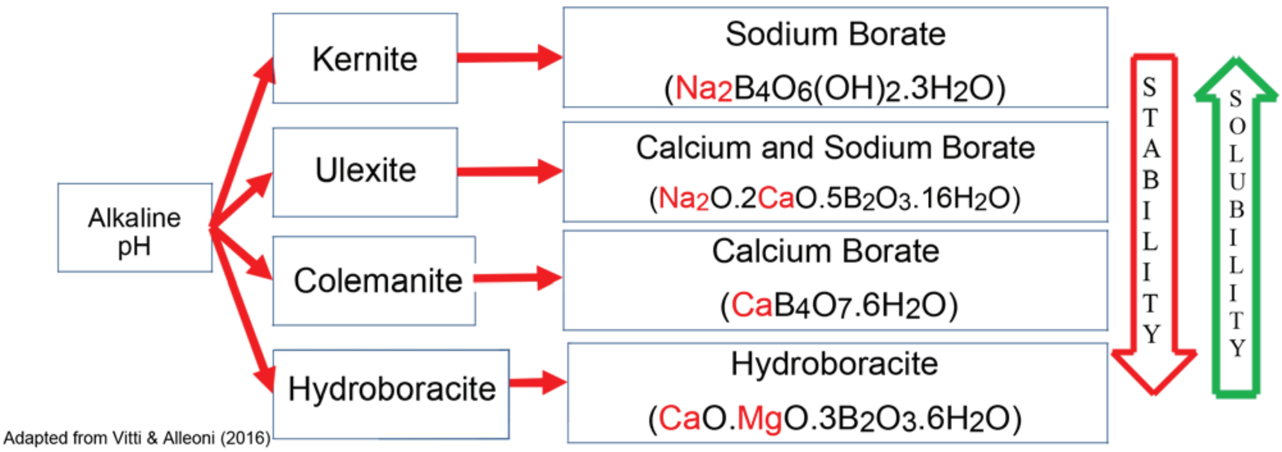

Figure 6. Chemical formula, stability and solubility of minerals containing B (Adapted from Vitti & Alleoni, 2016).

Although these commercialized sources present around 10% of B, the chemical composition of the rocks is different, altering the stability and solubility as seen in figure 6. In addition, within the same group of rocks, there may be manufacturing processes of extraction and/or concentrations of B (Figure 7) that can directly affect the solubility in the field and the availability to plants (Vitti & Alleoni, 2016). In other words, in terms of B content in the final product, they are similar, however, when comparing the characteristics and benefits of commercial products in the field, there is a big difference!

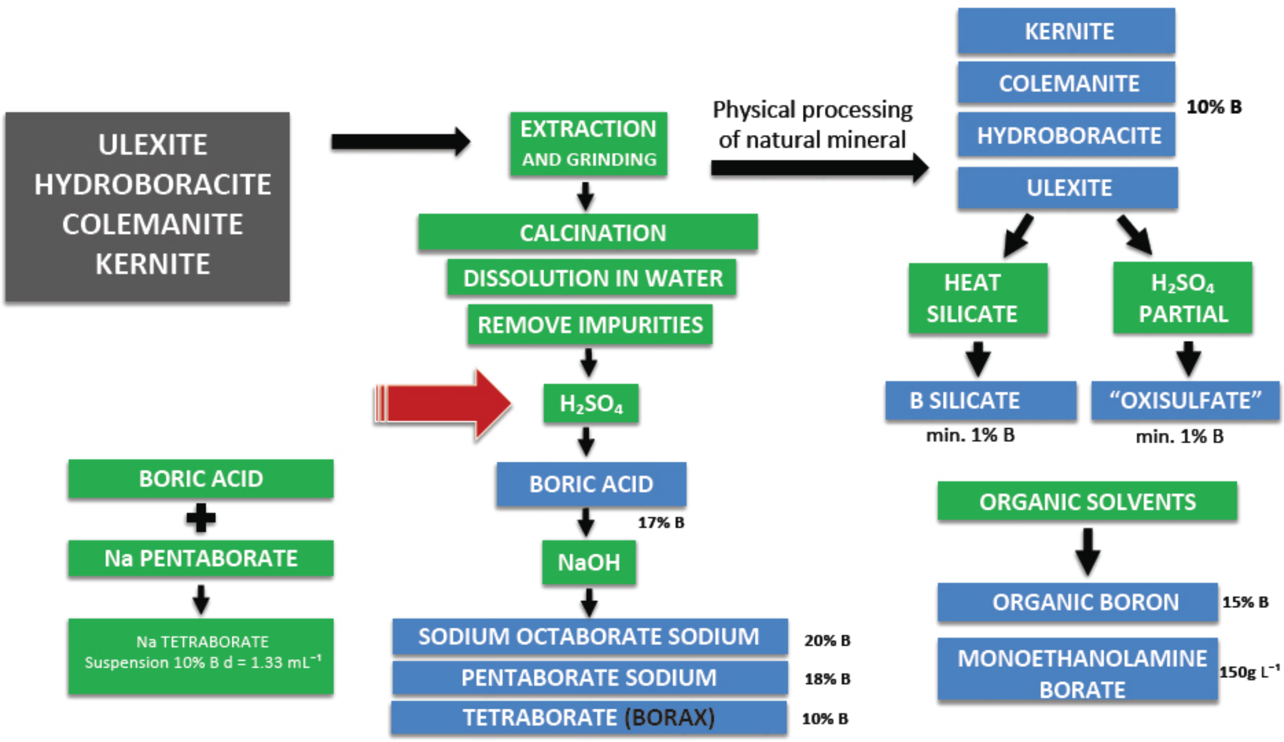

Figure 7. Sources, extraction process and fertilizers with B used in agriculture (Vitti & Alleoni, 2016).

As previously mentioned, based on the manufacturing processes, variations in the solubility of the B sources to be applied through soil are verified. Also, the higher the solubility, the more the risks of phytotoxicity and losses through leaching and adsorption increase.

Table 4. B sources, solubility and their relationships in the soil-plant system.

Source class	Market products	Solubility	Loss through leaching	Loss through adsorption	Risk of phytotoxicity
Boric acid	Boric acid	↑	↑	↑	↑
Sodium borates	Sodium Octaborate				
	Sodium Tetraborate (borax)				
Sodium and Calcium borates	Ulexite				
	Calcined ulexite				
Calcium borate	Colemanite				
Calcium borate and magnesium	Hydroboracite				
	Boracite				

Within the manufacturing processes, for ulexite for example, there can be two types of processing, the first through calcination and the second through acidulation.

Calcination exposes the raw material to high drying temperatures, aiming at dehydration and, consequently, increasing B levels in the fertilizer. However, this process reduces the solubility and availability of B to plants. In general, the calcined ulexites sold in Brazil have a concentration of around 12 to 15% of B (Table 4).

Table 5. Different degrees of hydration, B concentration and Ulexite solubility subjected to calcination (Adapted from Manning, 2016).

Chemical formula	Degree of hydration	B concentration	Solubility
$NaCaB_5O_9.16H_2O$	High	6 to 8 %	Average/High
$NaCaB_5O_9.8H_2O$	Average	10 to 12 %	Medium/Low
$NaCaB_5O_9.5H_2O$	Low	12 to 15 %	Low

For the supply of B through ulexite, **ICL** makes the **Produbor 10** technology available, where natural (non-calcined) ulexite is used, which, within the beneficiation processes, receive partial acidulation. In other words, in addition to **Produbor** having 10% of B in its concentration, it is also 90% soluble in water. Added to this benefit, there is a uniformity of the granules that are in the range of 2 to 4 mm, high granule hardness and a high level of uniformity index (Table 6). As practical implications of uniformity and hardness of the granules, we can mention the lower formation of dust and, consequently, lower segregation; better quality in fertilizer distribution and operational performance. For all these characteristics, **Produbor 10** proves to be an excellent management option for B correction in soils.

Table 6. Analytical results of **Produbor 10** against some market competitors (**ICL**´s data).

Description	Extrator	Competitor					Produbor
-	-	1	2	3	4	5	-
P_2O_5	CNA+Water	-	-	-	-	-	1.06
Sulphur (S)	HC1	2.25	ND*	ND*	1.118	4.36	5.21
Boron (B)	HC1	9.97	15.60	9.84	10.03	9.80	9.85
	Water	9.79	15.46	9.46	9.51	9.70	9.39
Hardness (Kg $grain^{-1}$)		0.97	3.17	0.39	1.82	1.90	3.07
Screens	Mesh 4 (4.8mm)	100	100	100	100	93	100
	Mesh 5 (4.0mm)	95	79	64	95	91	99
	Mesh 9 (2.0mm)	5	20	27	5	2	1
	Bottom (<2.0mm)	1	1	9	0	0	0

*ND – Not detected

For soil conditions where, in addition to low B contents, there is a deficiency of sulfur (S) in the 0-20 cm layer, **Sulfurgran B-Max** can be applied. With formulas containing 1 or 2% of B and high concentrations of sulfur, **Sulfurgran B-Max** presents an exclusive technology in the national market. This technology provides operational gains, gradual supply of B and S to plants, improving the efficiency of fertilizer use and minimizing leaching losses.

In addition to all these benefits, productivity gains are apparent for crops. In a trial conducted in the South of Minas for soy farming, **Sulfurgran B-max 2%** increased productivity by 21%. These results show that in addition to the reduction in application, the gradual release contributed to these increases (Table 7).

Table 7. Fertilizer rate applied, nutrient rate applied, productivity and increment of B and sulfur sources (**ICL**´s internal data).

Treatment	Applied dose ($kg.ha^{-1}$)	Applied Nutrient ($kg.ha^{-1}$)		Productivity ($sc.ha^{-1}$)	Increment (%)
		B	S		
Control	-	-	-	61.88	-
Sulfurgran	81	-	73	70.25	13.5
Sulfurgran+ Boric Acid	81+11	1.94	73	71.65	15.8
Sulfurgran B-Max 2%	97	1.94	73	75.10	21.4

Thus, **Produbor 10** and **Sulfurgran B-Max** are the best options for B correction and nutrition through soil.

Meet the authors

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