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Cotton, bean, and soybean yield and nutrient redistribution in leaf sap in response to organic molecules complexed fertilizers

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Abstract

The self-shading of plants is usually caused by the advance of their growth and development. This reduces transpiration and, consequently, nutrients uptake via xylem in lower half of plants, resulting in yield losses. Strategies should be developed to promote greater nutrient input in these regions with low-plant transpiration. The objective of this work was to study the effect of foliar application of boron (B), copper (Cu), manganese (Mn), and zinc (Zn) complexed with organic molecules on the translocation of these micronutrients to the plant's lower half (region of low transpiration) and its relationship with soybean, common bean, and cotton yield. Two field trials were carried out on soybean, common bean, and cotton crops. The first trial evaluated foliar B, Cu, Mn, and Zn sap content in the plant's upper and lower halves along with its development. While the second trial evaluated foliar B, Cu, Mn, and Zn sap content in the plant's upper and lower-halves and crop yield in response to micronutrients complexed with organic molecules (Xiflon Technology). The results show that in lower-half plant's sap the B, Cu, Mn, and Zn contents were reduced with development of soybean, common bean, and cotton crops. Organic molecular complex application (Xiflon Technology) increased the micronutrient translocation in the lower-half of soybean, common bean, and cotton crops and their yields. Application of micronutrients along with organic molecules is a strategic tool to improve the plant's lower-half nutrition and promote crop yield. It may be used by the farmers to increase the crop's grain yield.

Keywords: *Glycine max; Gossypium hirsutum*; *Phaseolus vulgaris*; low transpiration; mobile phloem; plant nutrition.
Abbreviations: EDTA_ Ethylenediamine tetraacetic acid; NTS_ no tillage system; B_boron; Cu_copper; Mn_manganese; Zn_zinc.

Introduction

Soybean (*Glycine max*), cotton (*Gossypium hirsutum*) and common bean (*Phaseolus vulgaris*) crops are of great global importance in terms of agricultural area and production volume. In 2019, the soybean crop had a harvested area of 120,501,628 ha and a production of 333,671,692 tons. The cotton crop had a harvested area of 38,640,608 ha and a production of 82,589,031 tons, and the common bean crop had a harvested area of 33,066,183 ha and a production of 28,902,672 tons (FAOSTAT, 2021). In Brazil, these crops also have an expressive harvested area and production. In the growing season 2020/21 crop year, the soybean crop had a harvested area of 37.8 million ha and a production of almost 136 million tons, the cotton crop had a harvested area of 1.6 million ha and a low production of more than 4 million tons, and the common bean crop had a harvested area of 2.9 million ha and a production of 3.3 million tons (CONAB, 2021).

Plant nutrition management is important to improve the crop yield because significant increases in agricultural yield can be achieved with an adequate and balanced supply of nutrients to crops, through the use of fertilizer (Fageria et al., 2010; Melém Júnior et al., 2011; Fageria and Nascente, 2014). In fact, it is estimated that currently fertilizers are responsible for 40-60% of all agricultural production (Johnston and Bruulsema, 2014). Several studies have shown decreased agricultural productivity in response to micronutrient deficiencies (Fageria and Baligar, 1997; Magalhães et al., 2002; Lima et al., 2003). According to Fageria et al. (2002), micronutrient deficiency is widespread (worldwide) due to (1) increased demand for micronutrients by intensive management practices and adaptation of highly productive crops that may have greater demand for micronutrients, (2) greater use of concentrated fertilizers with small amounts of micronutrients, and (3) use of soils with low native reserves of micronutrients. Therefore, in order to keep up agricultural productivity, it is essential to carry out correct fertilization (Fageria et al., 2011; Pagani and Mallarino, 2012; Crusciol et al., 2013; Nascente and Cobucci, 2015). In this sense, sustainable fertilization must meet the 4Rs scheme (Johnston and Bruulsema, 2014). 4Rs refer to Right source, Right rate, Right time, and Right place in nutrient management (Fixen, 2020).

Growth points (such as apical meristems), flowers, and shaded parts of plants (leaves on the lower part of the plant, as well as on the sides) show low transpiration flux and low nutrient input via xylem. This can result in reduced agricultural productivity (Rosolem et al., 2020). Thus, the redistribution of nutrients in the plant (via phloem) becomes the main form to supply nutrients in these parts of the plant with low transpiration flux. However, due to mobility differences between nutrients in the phloem, the redistribution of nutrients in the plant may not be effective for its nutrition. In this way, one of the pillars of the 4R concept (making every effort to keep nutrients where crops can use them) is not being respected, compromising fertilization efficiency. Thus, plant nutrition with elements classified as partially mobile [copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn)] or immobile [boron (B) and calcium (Ca)] in the phloem may face a compromised efficiency in this situation.

B nutrition is the most studied among nutrients with reduced mobility in the phloem (Rajesh et al., 2021; Sharma et al., 2022). Because of the cell's high permeability to boron, characteristic patterns of flux along the transpiration stream, and accumulation in the tips of the leaves, passive diffusion was long considered the only mechanism of transport (Marschner, 1995; Stangoulis et al., 2010; Onuh and Miwa, 2021; Prado, 2021). However, in the past ten years, researchers demonstrated that B presents rapid and significant mobility in the phloem of some polyol-producing species, which could complex B, giving this element some mobility within the plant (Souza et al., 2012; Demircivi et al., 2021; Sharma et al., 2022). With the help of isotopic tracers, it was possible to verify that B has significant mobility in the phloem and thus reclassify it as intermediate mobility or conditional mobility, depending on the species (Demircivi et al., 2021; Onuh and Miwa, 2021). Nicotianamine is the most important chelating agent in the phloem. This ligand binds to almost all Fe (II) (Anderegg and Ripperger, 1989) and Fe (III) (von Wiren et al., 1999), but binds only 20 to 50% of the other Cu elements (II), Ni (II), Co (II), Mn (II) and Zn (II) (Anderegg and Ripperger, 1989). The remainder of each element is mainly linked by a combination of several amino acids, mainly glutamic acid (Fe^{3+}), cysteine (Zn^{2+}), and histidine (Cu^{2+}). Carboxylic acids, including citrate, play a minor role in binding Mn^{2+} and Fe^{3+}, but have almost no impact on the speciation of the other elements. Thus, the complexation of nutrients with low mobility in the phloem with organic molecules is an alternative to promote their redistribution in the plant (translocation to the lower part of the plants), improving plant nutrition, with positive effects on agricultural productivity.

In this way, endogenous organic molecules can exert a regulatory effect on the uptake and functio of some bivalent heavy metals in plants (Scholz et al., 1988, 1992) and transport the metals mentioned above over long distances, especially for transport in the phloem (Scholz, 1992, 1989; Stephan and Scholz, 1991, 1993). Regarding B, application with sorbitol seems to increase B transport in the cotton transpiration stream (Rosolem et al., 2020). Furthermore, it was found that on cotton, foliar spraying of B together with a polyol fatty acid ester-based adjuvant was economically superior for both soil and foliar applications without the adjuvant (Roberts et al., 2000). According to Will et al. (2012), B mobility was evidenced in plants belonging mainly to the Rosaceae, Apiaceae, Brassicaceae, Fabaceae, and Oleaceae families. In other studies, it was possible to see substantial retranslocation of zinc in wheat (Erenoglu et al., 2002) and in rice (Hajiboland et al., 2001). Besides, high concentration of Mn in the phloem sap was found (Campbell and Nable, 1988). Kirkby and Romheld (2007) reported the translocation of Cu from roots to shoots. Despite some research results, little is known about the loading and unloading mechanisms of these metals, as well as how they are transported within plants (Stephan and Scholz, 1993).

Thus, this work studies 1. Monitoring development and growth of cotton, common bean, and soybean until full flowering stage, providing information on shading of lower-half's leaves, which cause decrease in circulation of micronutrients B, Cu, Mn, and Zn in the sap of the petioles 2. The elements B, Cu, Mn, and Zn, when mixed with organic molecules, increase the circulation of sap in petioles of the lower leaves (nourishing the plants in the parts of low transpiration); and 3. Higher concentrations of B, Cu, Mn, and Zn in the sap of leaf petioles on the underside of plants provide a significant crop yield increase. The objective of this work was to study the effect of foliar application of B, Cu, Mn, and Zn mixed with organic molecules on the translocation of these micronutrients to the lower part of the plants (region of low transpiration) and its relationship with soybean, common bean, and cotton crop yield.

Results

Reduction of micronutrient contents in the lower part of plants as their development progresses

For soybeans, based on the results, it appears that the levels of micronutrients (B, Cu, Mn, and Zn) in the sap of the petioles of leaves on the soybean lower parts showed a significant reduction with the advancement of crop development (Fig 1.). Thus, the values obtained in the plants at 30 days were much higher than the values obtained at 60 days after the germination of the culture. In common bean (Fig 2.) and cotton (Fig 3.) crops, the same results were observed for all micronutrients evaluated. Even though cotton had a longer cycle than soybeans and common beans, it had a low value at the beginning of the crop development. After that, the values increased, and then the micronutrient contents reduced again, especially Cu and Mn.

Correlation of yield with nutrient placement (bottom and top) in soybean plants

During the flowering of the soybean crop, a study was carried out on the Pearson correlation between the levels of B, Cu, Mn and Zn (in the sap of the petiole of the upper part of the plants and in the petiole of the lower part at the time, in the blade and saps of the leaves and flowers) and soybean yield. Thus, it was found that there was only a positive correlation between productivity and the levels of B, Mn and Zn in the sap of the petioles of the leaves of the lower part of the plants (Table 1). These results, added to the results of the decrease in the concentration of elements with the advance of plant growth, indicate the need for the development of technologies for the application of foliar in the flowering capable of translocating to the sap of the petioles of lower leaves.

Increase of micronutrient contents in the lower parts of plants by the use of organic molecular complex

In general, we found that the use of the organic molecular complex provided significant increases in the levels of micronutrients B, Cu, Mn and Zn in the petiole sap at the lower part of the plants for all crops. Comparison between nutrients mixed with organic molecules and those salts and/or chelated shows that the same dose of the nutrient for Boron, caused a 37% reduction of the element in the sap of the underside of the plant (soybean), 81% (beans) and 58% (cotton) when the salts and chelated elements were used (Supplmentary Table 1). The same was found for the other nutrients; copper [48% reduction (soybean), 91% (common bean) and 42% (cotton)]; manganese [72% reduction (soybean), 59% (common bean) and 88% (cotton)] and zinc [87% reduction (soybean), 89% (common bean) and 52% (cotton)].

Translocation of micronutrients in the lower part of plants affecting the productivity of soybean, common bean and cotton

Regarding productivity, we observed that the treatment with organic molecular complex provided greater grain productivity in the soybean crop which does not differ from the treatment with two doses of micronutrients applied in the form of salts (Table 3). The control treatment and the application of only one dose of micronutrients provided the lowest productivity values. The productivity in the lower part of the plant was higher in the treatment with the organic molecular complex and differed from the other treatments.

In common bean, productivity was higher in the treatment with the organic molecular complex, which did not differ from the control treatments and with the application of a dose of micronutrients in the form of salts (Table 4). In cotton, productivity was higher in the treatment with the organic molecular complex, which did not differ from the treatment with two doses of micronutrients in the form of salts (Table 5). In this culture, the productivity of the lower part of the plants was higher than treatment with the organic complex and did not differ from the control treatments and with the application of two doses of micronutrients.

Discussion

We found reduction in the plant's sap micronutrients B, Cu, Mn, and Zn with the advancement of the development. Therefore, it is likely that the leaves of the lower part of the plant suffered shading with the advance of the development of the crop. The shading obviously comes from the leaves of the upper part of the plant and of the leaves of the plants of the lateral rows of the cultivated area. Besides, there is a reduction in the concentration of nutrients in the underside of the plant as the upward transport of the micronutrients B, Cu, Mn and Zn is made via xylem and is highly dependent on transpiration to travel to all parts of the plant (Brown and Shelp, 1997; Malavolta, 2006). Fioreze et al. (2013) also reported a reduction in the transpiration rate of soybean plants subjected to shading. This reduction in leaf transpiration, in shaded plants, was not due to stomatal closure, but to the reduction of the vapor pressure deficit in the environment, since the diffusion of water to the atmosphere is independent of the diffusion of CO_2.

White and Broadley (2003) report that nutrients that move via the xylem follow the transpiration flow and are equally affected when transpiration is reduced under unfavorable environmental conditions, such as shading. Thus, the fixation of reproductive structures in soybean plants in shaded environments may be limited by the low availability of assimilates and also by limiting the redistribution of nutrients to these structures (Brown and Shelp, 1997; Fioreze et al., 2013).

In general, it was found that the use of the organic molecular complex provided significant increases in the levels of micronutrients B, Cu, Mn, and Zn in the lower part of the plants. Endogenous organic molecules can exert a regulatory effect on the uptake and functioning of some bivalent heavy metals in plants (Scholz et al., 1988, 1992) and transport the aforementioned metals over long distances, especially for transport in the phloem (Scholz, 1989; Stephan and Scholz, 1991, 1993). It is possible that the organic molecular complex has bound itself to the micronutrients and moved to the lower parts of the plants. Other authors reached the same conclusion with the elements Fe(II) (Anderegg and Ripperger, 1989), Fe(III) (von Wiren et al., 1999), Cu(II), Ni(II), Co(II), Mn(II) and Zn(II) (Anderegg and Ripperger, 1989). Similarly, Brown and Shelp (1997), Hu et al. (1997) and Brown and Hu (1998) report micronutrient mobility in apple (*Malus domestica*), almond (*Prunus amygdalus*), peach (*Prunus persica*) and plum (*Prunus salicin*) crops. Other authors have also reported the mobility of micronutrients in plant families belonging to the botanical families Rosaceae, Apiaceae, Brassicaceae, Fabaceae and Oleaceae (Will et al., 2012). These results indicate that these micronutrients are not completely immobile as reported by other authors (Marschner, 1995; Rosolem and Costa, 2000; Mengel and Kirkby, 2001; Epstein and Bloom, 2004; Malavolta, 2006).

Similarly, in other research works it was recognized that B is mobile to varying degrees, in the phloem of several plant species, including a wide range of agricultural and vegetable crops, such as brassicas, carrots, peas, celery and onion. In these species, in which sugar alcohols and polyols (sorbitol, mannitol, and dulcitol) are the main forms of export of C from leaves, B is bound and transported in the form of polyol-B complexes (Brown and Shelp, 1997; Kirkby and Römheld, 2007). Differences in mobility of B in the phloem between species result in a typical pattern of concentration of this micronutrient in the leaves and fruits of trees that grew in the field, with a much more equitable distribution in species in which B is mobile in the phloem (Kirkby and Römheld, 2007).

In other studies, substantial retranslocation of zinc via phloem has been found in young developing wheat leaves (Erenoglu et al., 2002) and in rice (Hajiboland et al., 2001). In some legumes, a relatively high concentration of Mn has been reported in the phloem sap, possibly during the pod filling stage (Campbell and Nable, 1988). Cu mobility within plants is limited and particularly dependent on nutritional status in terms of Cu and N. Due to its strong bond with cell walls, the translocation of Cu from roots to shoots is slow, but it exists (Kirkby and Romheld, 2007).

Based on the research work, it appears that the translocation of micronutrients B, Cu, Mn and Zn is not fully understood and that their translocation through the phloem is possible, especially if these ions are complexed with organic molecules. In the present work, we found that the use of organic molecular complexes were efficient to increase the concentration of these micronutrients in the leaves of the underside of soybean, common bean and cotton plants.

Table 1. Pearson's correlation test between boron (B), copper (Cu), manganese (Mn) and zinc (Zn) contents in the sap of the petiole of the upper part of the plants and in the petiole of the lower part at the time of flowering with grain yield, grain yield of the lower part of the plants and grain yield of the upper part of the plants of soybean plants.

Characteristics correlated	Coefficient of correlation
Grain yield versus B in the upper part of the plants	-0.5135**
Grain yield versus B in the lower part of the plants	0.3542*
Grain yield versus Cu in the upper part of the plants	-0.0559^{ns}
Grain yield versus Cu in the lower part of the plants	0.2445 ^{ns}
Grain yield versus Mn in the upper part of the plants	-0.3745*
Grain yield versus Mn in the lower part of the plants	0.4534*
Grain yield versus Zn in the upper part of the plants	0.0969 ^{ns}
Grain yield versus Zn in the lower part of the plants	0.4390*
Grain yield in the upper part of the plants versus B in the upper part of the plants	-0.4053*
Grain yield in the upper part of the plants versus B in the lower part of the plants	-0.0138 ^{ns}
Grain yield in the upper part of the plants versus Cu in the upper part of the plants	-0.1167 ^{ns}
Grain yield in the upper part of the plants versus Cu in the lower part of the plants	-0.0015 ^{ns}
Grain yield in the upper part of the plants versus Mn in the upper part of the plants	-0.4427*
Grain yield in the upper part of the plants versus Mn in the lower part of the plants	-0.1046 ^{ns}
Grain yield in the upper part of the plants versus Zn in the upper part of the plants	-0.2049 ^{ns}
Grain yield in the upper part of the plants versus Zn in the lower part of the plants	-0.0155 ^{ns}
Grain yield in the lower part of the plants versus B in the upper part of the plants	-0.2647 ^{ns}
Grain yield in the lower part of the plants versus B in the lower part of the plants	0.4398*
Grain yield in the lower part of the plants versus Cu in the upper part of the plants	0.0348 ^{ns}
Grain yield in the lower part of the plants versus Cu in the lower part of the plants	0.2965 ^{ns}
Grain yield in the lower part of the plants versus Mn in the upper part of the plants	-0.0641 ^{ns}
Grain yield in the lower part of the plants versus Mn in the lower part of the plants	0.6392**
Grain yield in the lower part of the plants versus Zn in the upper part of the plants	0.2966 ^{ns}
Grain yield in the lower part of the plants versus Zn in the lower part of the plants	0.5437**

* Values followed by * means significant correlation at $p < 0.05$. ** Values followed by * means significant correlation at $p < 0.001$. ^{ns}Values followed by ^{ns} means no significant correlation.

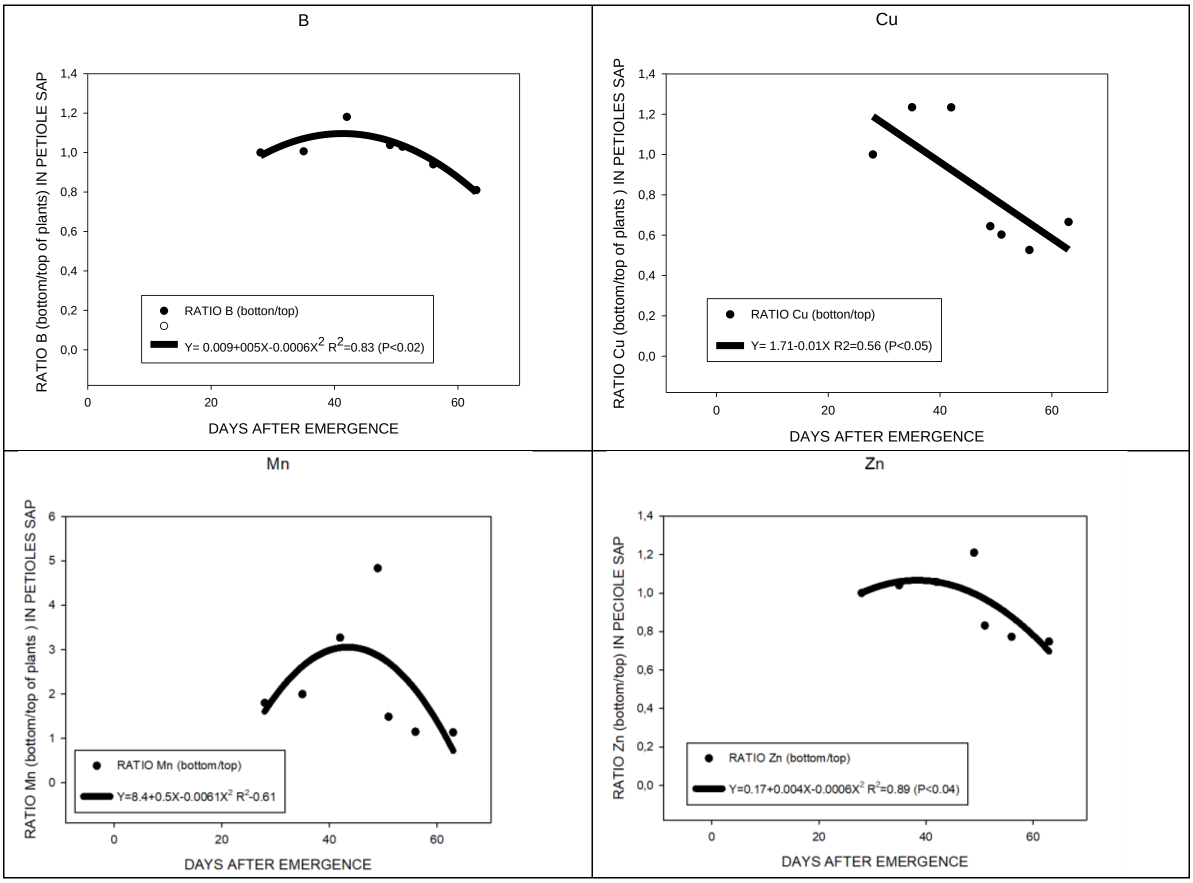

Fig 1. Ratio of micronutrients B, Cu, Mn and Zn in petiole sap of soybean plants (bottom to the top of plants) as a function of days after plant emergence.

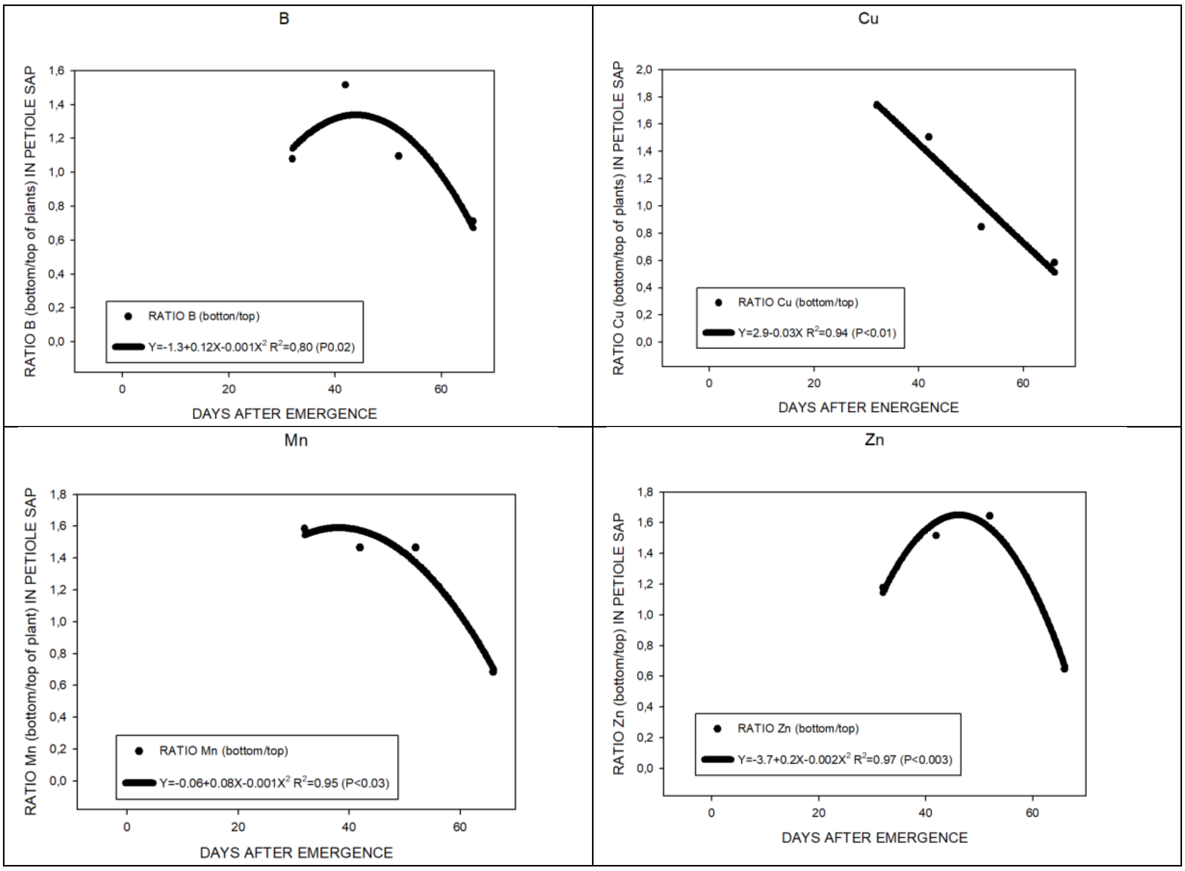

Fig 2. Ratio of micronutrients B, Cu, Mn and Zn in petiole sap of common bean plants (bottom to top of plants) as a function of days after plant emergence.

Table 3. Soybean grain yield in the upper part of the plant (ProdUpper), in the lower part of the plant (ProdLower) and total (ProdTotal) as a function of the application of the micronutrients B, Cu, Mn and Zn.

Treatments	ProdUpper	ProdLower	ProdTotal
	-------------------kg ha^{-1}---------------		
Control (No application of micronutrients)	1895 a	1352 b	3246 b
Aplication of 2 doses of micronutrient salts	1841 a	1394 b	3234 b
Aplication of 1 doses of micronutrient salts	1947 a	1331 b	3278 b
Aplication of organic molecular complex	1945 a	1684 a	3628 a

Means followed by the same letter horizontally did not differ from each other by the Tukey test for p<0.05.

For example, sorbitol synthesis markedly increased B mobility within the plant, which in turn increased plant growth and productivity by helping to overcome transient B deficiencies in the soil (Brown et al., 1999).

Based on the experiments carried out, it was found that the application of the organic molecular complex provided increments in the levels of micronutrients B, Cu, Mn and Zn in the lower part of the plants, with positive effects on the grain yield of soybean, common bean and cotton. Corroborating this information, there was a positive correlation between the levels of B, Mn and Zn in the lower part of the plants with the total grain yield (sum of lower and upper part of the plant) of the crop. According to Kirkby and Römheld (2007), the micronutrients Cu, Mn, Zn, B, in addition to other functions in plants, are particularly involved in the reproductive phase of plant growth and, consequently, in determining the productivity and quality of the crop harvested. Wilker et al. (2020) reported that the increase in doses of zinc associated with the addition of boron provided a linear increase in the variables grain mass, productivity and pods per hectare in the common bean crop. Moura et al. (2021), also using organic molecular complex, reported significant increases in corn grain yield and justified the results by the greater availability of micronutrients for plants, especially in the reproductive phase. Micronutrients are elements required by plants in small amounts. However, even in small amounts, they can cause significant drops in crop productivity. Soils with low natural fertility, such as soils in tropical regions, are deficient in micronutrients and their application favors the development of crops. Added to this there are problems in the redistribution of micronutrients within the plant to lower regions of the plants. Our results are promising and may be an important strategy to improve plant nutrition with a direct effect on crop productivity. Thus, it was found that the use of organic molecular complexes provided higher levels of micronutrients B, Cu, Mn, and Zn in the lower part of the plants and these higher levels provided significant increases in the productivity of soybean, common bean and cotton.

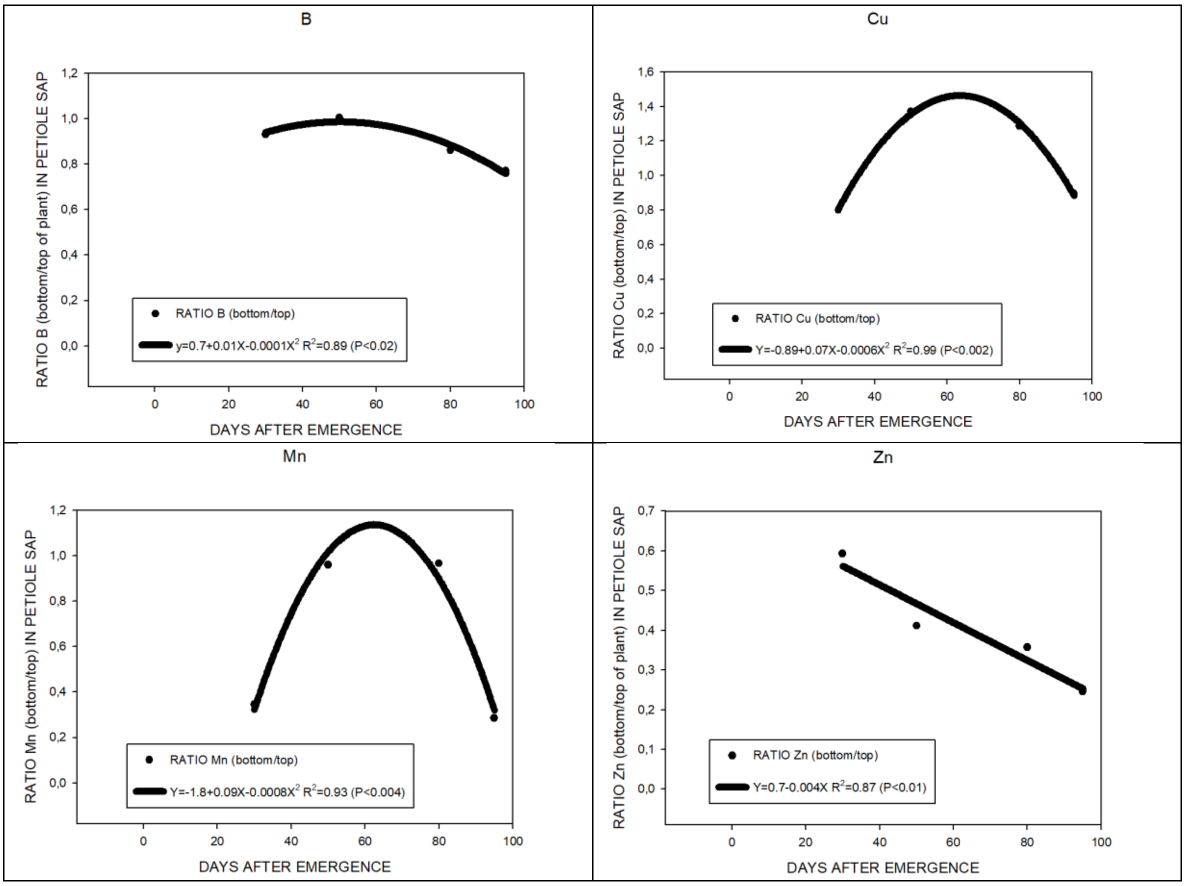

Fig 3. Ratio (bottom to top of plants) of micronutrients B, Cu, Mn and Zn in petiole sap of cotton plants as a function of days after plant emergence.

Table 4. Grain yield of common bean crop as a function of application of micronutrients B, Cu, Mn, and Zn.

Treatments	Grain yield (kg ha^{-1})
Control (No application of micronutrients)	2088 b
Aplication of 2 doses of micronutrient salts	2355 ab
Aplication of 1 doses of micronutrient salts	2046 b
Aplication of organic molecular complex	2563 a

Means followed by the same letter horizontally did not differ from each other by the Tukey test for p<0.05.

Table 5. Seed cotton productivity in the upper part of the plant (ProdUpper), in the lower part of the plant (ProdLower) and total (ProdTotal) as a function of the application of micronutrients B, Cu, Mn, and Zn.

Tratamentos	**ProdUpper**	**ProdLower**	**ProdTotal**
	------------------kg ha^{-1}----------------		
Control (No application of micronutrients)	3538 b	2262 a	4934 b
Aplication of 2 doses of micronutrient salts	3829 ab	2107 a	4999 ab
Aplication of 1 doses of micronutrient salts	3682 b	2108 a	4888 b
Aplication of organic molecular complex	3905 a	2297 a	5245 a

Means followed by the same letter horizontally did not differ from each other by the Tukey test for p<0.05.

Table 6. Soil chemical analysis (0,0 – 20,0 cm depth) from Hidrolândia (H) and Campo Novo do Parecis (CNP).

	pH	OM	P	K	Ca	Mg	CEC	Cu	Fe	Mn	Zn	Clay	Silt	Sand
	(H_2O)	g kg^{-1}	g kg^{-1}	g kg^{-1}	mmolc dm^{-3}			m dm^{-3}				g kg^{-1}		
H	5.40	29.0	32.3	60.0	34.0	6.0	57.0	2.4	100	23.9	12.0	300	200	500
CNP	6.05	33.6	37.8	142.9	31.7	11.6	92.7	3.8	67.0	10.7	4.5	625	168	207

*Extractors: P, K, Cu, Fe, Mn and Zn - Mehlich-1; OM = soil organic matter determined by oxidation with potassium dichromate.

Table 7. Treatments used in Experiment II.

		Treatment 1	Treatment 2	Treatment 3	Treatment 4
Cotton	30 DAE (03/24/21)	-	130 g Mn ha^{-1} ($MnSO_4$ chelated)	65 g Mn ha^{-1} ($MnSO_4$ chelated)	65 g Mn ha^{-1} (Asgard Impact)
	50 DAE (04/13/21)	-	262 g Cu ha^{-1} (Copper hydroxide) 400 g B ha^{-1} (Boric acid)	100 g Cu ha^{-1} (Copper hydroxide) 180 g B ha^{-1} (Boric acid)	100 g Cu ha^{-1} (Asgard Kupfer) 180 g B ha^{-1} (Xiflon Boro Max)
	80 DAE (05/11/21)	-	262 g Cu ha^{-1} (Copper hydroxide) 400 g B/ha (Boric acid)	100 g Cu ha^{-1} (Copper hydroxide) 180 g B ha^{-1} (Boric acid)	100 g Cu ha^{-1} (Asgard Kupfer) 180 g B/ha (Xiflon Boro Max)
	95 DAE (06/05/21)	-	262 g Cu ha^{-1} (Copper hydroxide)	100 g Cu ha^{-1} (Copper hydroxide)	100 g Cu ha^{-1} (Asgard Kupfer)
Common bean	26 DAE (Phase V4)	-	130 g Mn ha^{-1} ($MnSO_4$ chelated) 130 g Zn ha^{-1} ($ZnSO_4$ chelated)	65 g Mn ha^{-1} ($MnSO_4$ chelated) 65 g Zn ha^{-1} ($ZnSO_4$ chelated)	65 g Mn + 65 g Zn ha^{-1} (Asgard Impact)
	35 DAE Phase R5	-	262 g Cu ha^{-1} (Copper hydroxide) 180 g B ha^{-1} (Boric acid)	65 g Cu ha^{-1} (Copper hydroxide) 62 g B ha^{-1} (Boric acid)	65 g Cu ha^{-1} (Asgard Kupfer) 62 g B ha^{-1} (Xiflon Boro Max)
	44 DAE Phase R7	-	262 g Cu ha^{-1} (Copper hydroxide) 180 g B ha^{-1} (Boric acid)	65 g Cu ha^{-1} (Copper hydroxide) 62 g B ha^{-1} (Boric acid)	65 g Cu ha^{-1} (Asgard Kupfer) 62 g B ha^{-1} (Xiflon Boro Max)
	59 DAE	-	262 g Cu ha^{-1} (Copper hydroxide)	65 g Cu ha^{-1} (Copper hydroxide)	65 g Cu ha^{-1} (Asgard Kupfer)
Soybean	26 DAE (V4 Stage)	-	130 g Mn ha^{-1} ($MnSO_4$ quelatizado) 130 g Zn ha^{-1} ($ZnSO_4$ chelated)	65 g Mn ha^{-1} ($MnSO_4$ chelated) 65 g Zn ha^{-1} ($ZnSO_4$ chelated)	65 g Mn ha^{-1} (Asgard Impact)
	35 DAE (V8 Stage)	-	262 g Cu ha^{-1} (Copper hydroxide)	68 g Cu ha^{-1} (Copper hydroxide)	68 g ha^{-1} (Asgard Kupfer)
	44 DAE (R1 Stage)	-	262 g Cu ha^{-1} (Copper hydroxide) 180 g B ha^{-1} (Boric acid)	68 g Cu ha^{-1} (Copper hydroxide) 62 g B ha^{-1} (Boric acid)	68 g Cu ha^{-1} (Asgard Kupfer) 62 g B ha^{-1} (Xiflon Boro Max)
	59 DAE (R1 Stage+15 days)	-	262 g Cu ha^{-1} (Copper hydroxide)	68 g Cu ha^{-1} (Copper hydroxide)	68 g Cu ha^{-1} (Asgard Kupfer)

DAE: days after plant emergence; Chelated $MnSO_4$ (Nutrafol): 10% Mn, chelated with EDTA; Chelated $ZnSO_4$ (Nutrafol): 10% Zn, chelated with EDTA; Boric Acid: 17% B; Overcomes: copper hydroxide, 35% Cu (w/v); Asgard Impact: 4.0% N, 3.0% S, 0.25% B, 3.0% Mn, 3.0% Zn, d = 1.26 g ml^{-1}; Xiflon Boron Max: 5% N, 8.5% B, d = 1.20 g ml^{-1}; Asgard Kupfer: 1% N, 7.0% S, 13% Cu, d = 1.48 g ml^{-1}.

Materials and methods

Two field trials were carried out on soybean, common bean, and cotton crops. The first trial (Exp I) evaluated foliar B, Cu, Mn, and Zn sap content in the plant's upper and lower parts throughout its development. While the second trial (Exp II) evaluated foliar B, Cu, Mn, and Zn sap content in the plant's upper and lower parts and crop yield in response to different micronutrients appliance (conventional micronutrient sources x Xiflon Technology: micronutrients complexed with organic molecules, commercialized by Harvest Agro).

Sites characterization

The common bean and soybean experiments were carried out in an Acric Red Latosol (Santos et al., 2018), in Hidrolândia city, Goiás State, Brazil (16º28'00" S and 49º17'00" W, and 823 m asl), while the cotton experiments in a Dystrophic Red Latosol (Santos et al., 2018) were conducted in Campo Novo dos Parecis city, Mato Grosso State, Brazil (13°34'38''S, 57°54'48''W and 552 m asl). The climate in Hidrolândia and Campo Novo dos Parecis is classified, according to Köppen-Geiger, as Aw (tropical climate with dry season). The average annual temperatures and precipitation of Hidrolândia and Campo Novo dos Parecis are 23.8 ºC and 24.6 ºC, respectively, and 1498 mm and 1529 mm, respectively. Before installing the experiments, chemical analysis was performed at a depth of 0-0.20 m to characterize the experimental area (Table 6). Chemical analyzes were performed according to the methodology proposed by Donagema et al. (2011).

Crop management

The cotton (cultivar IMA 5801 B2RF), common bean (cultivar Pérola) and soybean (cultivar Nidera 7209) were sown at 0.76 m, 0.50 m, and 0.50 m spacing on 12/02/2021, 12/15/2020, 11/24/2020, respetively. Crop fertilization managements were performed according to soil analysis (Sousa and Lobato, 2004). Crop managements were done to keep the crops free of diseases, insects, and weeds.

Experimental design, treatments, and B, Cu, Mn, and Zn petiole sap content determination

The experiments were carried out under a randomized block design, with three (Exp I) and six (Exp II) replications. The experimental plots were 10 meters long by two meters wide. The useful plot consisted of the two central lines, disregarding one meter from each end of the plot.

Sampling times were the treatments in Exp I, while different micronutrient management were the treatments in Exp II (Table 7).

Leaf petioles (from the lower) were sampled at 38, 57, 90, and 105 days after plant emergence (DAE) on cotton crop, and at 30, 42, 52, and 66 DAE on common bean and soybean crops, on Exp II, to determine B, Cu, Mn, and Zn petiole sap content. For Exp I, leaf petioles (from the lower and the upper) were sampled at days after plant emergence (DAE) on cotton crop, at 30, 50, 80 and 95 DAE on soybean crops 28, 35, 42, 49, 51, 56 and 63 DAE and on drybeans crops 32, 42, 52 and 66 DAE.

In soybean, the Pearson's correlation between productivity and concentrations of micronutrients in the sap, petioles from the upper leaves of the plant were also calculated. Twenty petioles, from plant's upper and lower halves, in each crop, were collected to determine B, Cu, Mn and Zn petiole sap content according to the methodology described by Dong et al. (2021). The ratio between lower and upper halves were calculated to B, Cu, Mn, and Zn petiole sap content in Exp I.

The petiole sap element contents for each treatment were transformed in percentage in relation to the control, in the Exp II. After that, regressions were performed to obtain the equations which were derived to find the area under the curve. These areas were compared to define the quantitative ratio of nutrients that arrived in the sap of the petioles on the lowpart of the plants.

Crop yield

Soybean, common bean, and cotton yield evaluated at Exp II.

To evaluate the grain yield in the top and bottom, the soybean was harvested after physiological maturation on 03/22/21. The havest was carried out manually by pulling the plants from useful plots and subsequently threshing in a Nux cereal mixer, BC 80 model. III. The grains were weighted (adjusted to 130 g kg^{-1} humidity, wet sowing) and transformed to kg ha^{-1}. The total soybean yield was obtained with the sum of the bass and top yields.

The number of reproductive structures/plant in the cotton crop was counted on 04/06/21. The evaluation of the productivity of seed cotton, of the pointer and of the cotton base, was carried out with the manual harvesting of the seed cotton, with subsequent weighting and transformation into kg ha^{-1}. The total productivity of seed cotton was obtained with the sum of the productivity of the bass and the pointer.

The common bean harvesting (03/17/22), was also carried out after the physiological maturation and the grain yield was evaluated, with manual pulling of the plants of the useful plot and subsequent threshing in a Nux cereal mixer (BC 80 III model), with the weighing of the grains (adjusted to the humidity of 130 g kg^{-1}) and transformed to kg ha^{-1}.

Statistical analysis

The data were subjected to analysis of variance by the F test. Graphs were made using the Sigmaplot program. For yield data and yield components, means were compared by Tukey test at 5% probability. For these analyses, the SAS statistical program was used (SAS, 2002).

Conclusion

The lower-half plant sap B, Cu, Mn, and Zn contents reduced with plant's advancing development in soybean, common bean, and cotton crops. Organic molecular complex application (Xiflon Technology) increased the micronutrient translocation in the plant's lower half of soybean, common bean, and cotton crops and its yields. Micronutrients complexed with organic molecules are a strategic tool to improve the plant's lower-half nutrition and promote crop yield increases.

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