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# Development and Nutrition of Soybeans with Macronutrients Deficiencies

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**ABSTRACT**

Soy is to one of the main crops in the world. However, there are aspects related to its management that should be explained, especially regarding its mineral nutrition, because a proper nutritional balance is associated with productivity levels. The objective of this study was to evaluate the accumulation of nutrients in the tissues related to the deficiency of nutrients and its effects on plant development. In addition, nutritional disorder symptoms were evaluated according to the deficiency of macronutrients. For this, seven treatments were evaluated. They comprised a complete nutrient solution followed by deficiency of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) in a completely randomized design with three replications. Plant height, number of leaves, leaf area, stem diameter, relative chlorophyll content, and production of dry matter of soybean plants were evaluated. The deficiency of any macronutrient affects biometric variables, especially the production of dry matter. The nutrients that limited the most the production of dry matter were Ca>N>K>Mg>P > S. With the exception of S, all other macronutrients, when suppressed, caused nutritional disorder symptoms. The plants presented an accumulation of K > N>Ca>P>Mg>S in leaves. In the present study, soybean plants had a high nutritional requirement of K followed by N. This requires care in the development of fertilization programs in view of the essential roles these nutrients play in the life cycle of plants.

**Abbreviations**: N_Nitrogen; P_Phosphorus; K_Potassium; Ca_Calcium; Mg_Magnseium; S_Sulfur; DM_Dry matter; NL_number of leaves; H_plant height; SD_stem diameter; RCI_Relative chlorophyll index; AP_Aerial part; R_Roots; EP_Entire plant; DMS_significant mean difference; CV_Coefficient of variation; pH_hydrogen potential; NaOH_sodium hydroxide; HCl_hydrochloric acid.

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## Introduction

Brazil is the second largest producer of soybeans (Glycine max L. Merrill) in the world, with approximately 96.5 million tons produced in the 2015/16 crop and an expected 103.0 million tons in the 2016/17 crop (USDA 2016).

Soybean crops are responsible for 57% of the cultivated area of the country, with an estimated growth of 3.5%, from 32,092,900 hectares in 2014/15 to 33,228.4 million hectares in the 2015/16 crop (CONAB 2016). In the last crop, productivity levels were below expectations due to adverse weather conditions, which resulted in an average yield of 2,876 kg $ha^{-1}$ (CONAB 2016).

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Soybean crops are of great importance in the world economy. Soybean grains are used by agricultural (production of vegetable oil and animal feed), chemical, and food industries. Additionally, this oleaginous crop has been used as an alternative source of renewable energy resulting from the production of biofuel (Costa Neto et al. 2000; Koc, Abdullah, and Fereidoun 2011).

However, there are several management aspects mainly related to mineral nutrition that should be better elucidated considering that the nutritional imbalance reflects in the plant's ability to express its productive potential. The nutritional balance has a direct relation with the productivity levels of plants (Fageria et al. 2009).

Scientific advances on soil management (acidity correction techniques and gains in efficiency of biological nitrogen fixation), in addition to balanced fertilization programs, allowed the success of soybean cultivation in tropical regions such as Brazil (Lopes and Guilherme 2007).

For the success of fertilization programs, the monitoring of the entire crop cycle through chemical soil and plant analyses and/or visual diagnosis of nutritional disorders is fundamental. Some studies evaluating nutritional disorders symptoms in soybean plants (Malavolta et al. 1980; Meurer, Wang, and Wang 1981; Vernetti 1983) served as the foundation for understanding the behavior of this plant. Even though nutrient deficiencies have been studied extensively, the development of new cultivars necessitates the continuation of learning so that the efficiency of agricultural inputs in the production system of soybean is evolving.

The evaluation technique considering a missing nutrient allows assessing the effects of any nutrient on the decrease in plant development, with nutritional deficiency symptoms pointing to the lack of a nutrient, something that should be better detailed for soybeans (Moretti et al. 2011).

The objective of this study was to evaluate the effects of macronutrients deficiency in the development of soybean plants based on evaluations of plant height, leaf area, number of leaves, stem diameter, relative chlorophyll content, and production of dry matter, especially evaluating the accumulation and deficiency symptoms associated with suppressed nutrients.

## Material and methods

### *Analysis and experimental design*

The experiment was conducted in a greenhouse, where seedlings of soybean (Glycine max L. Merrill) were planted, at the Faculty of Agricultural and Animal Sciences of UNESP in Jaboticabal, Brazil. It is located at 21° 15′ 22″ S and 48° 18′ 58″ W. The soybean cultivar Vencedora (BRSMG 68) was grown in containers with 8 L of nutrient solution.

The experimental design was completely randomized, with seven treatments and three replications. The treatments were (1) complete nutrient solution (N, P, K, Ca, Mg, S, boron (B), carbon (C), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn)), (2) deficiency of nitrogen (-N), (3) deficiency of phosphorus (-P), (4) deficiency of potassium (-K), (5) deficiency of calcium (-Ca), (6) deficiency of magnesium (-Mg), and (7) deficiency of sulfur (-S), according to Flores et al. (2016).

The sowing of soybeans was carried out in a 200-cell tray with the commercial substrate Bioplant® without fertilization. After the formation of the first leaves 10 days after emergence, seedlings were transplanted, and nutrient solution was added (Hoagland and Arnon 1950) diluted to 50% of the usual concentration during the first week of culture and a solution at 100% for the second week of cultivation until the end of the experiment.

The solutions were replaced every 15 days and replenished daily with deionized water according to the volume of water evapotranspired. In each pot, the nutrient solution was constantly oxygenated using an air compressor. The pH was monitored daily (twice a day: in the early morning and late afternoon) and adjusted to 5.5 (± 0.5) when needed, with the aid of CE equipment PH-009 (I). For pH correction, a diluted solution of sodium hydroxide (NaOH) or hydrochloric acid (HCl) at 0.10 mol $L^{-1}$ was used.

### Treatments measured and nutritional indices

The plants were harvested 8 weeks after transplanting. At this time, plant height, measured from the base to the apex of the last leaf, and number of leaves were determined. In addition, the relative chlorophyll index (RCI) was measured in 10 leaves per experimental unit using an OPTI-Sciences® CCM-200 chlorophyll meter. Then, the leaf area of plants was measured using the IL-3100 Area Meter, and the stem diameter (5 cm from the plant base) was measured using a digital caliper.

The plant material collected was washed with deionized water, and leaves and roots were separated and subjected to a forced-air circulation oven at 65 °C until constant weight to determine dry matter. Then, the content of nutrients in shoot and root dry matter was determined (Bataglia et al. 1983). During the experiment, descriptions of nutrient deficiency symptoms in plants were made.

### Statistical analysis

The results were submitted to analysis of variance and comparison of means by Tukey test at 5% probability ($p \leq 0.05$) using the AGROESTAT software (Barbosa and Maldonado 2012).

## Results and discussion

### Nitrogen

Nitrogen deficiency resulted in a decrease in biometric variables (plant height, leaf area, number of leaves, stem diameter) and relative chlorophyll content, which resulted in a decrease in dry matter when compared to plants grown in the complete nutrient solution (Table 1). This is because N performs essential functions in plant metabolism. It is particularly the major constituent of amino acids, proteins, nucleotides (Bloom 2015; Epstein and Bloom 2006), and chlorophylls (Mengel and Kirkby 1987; Shadchina and Dmitrieva 1995).

N is found in macromolecules and secondary signaling compounds, including cell wall components, hormones, and vitamins (Bloom 2015). Therefore, nitrogen participates in almost all the metabolic processes of the plant, including those involved in photosynthesis particularly related to the production of photoassimilates.

The deficiency of the supply of N in the nutrient solution caused a decrease of 65.6 and 52.4% in its levels in shoots and roots, respectively, compared to the treatment supplied with the complete nutrient solution (Table 2).

**Table 1.** Biometric variables, relative chlorophyll content, dry matter production of soybean plants grown in nutrient solution.

| | | | | | | Dry matter | | |
|---|---|---|---|---|---|---|---|---|
| | H | LA | | SD | | AP | R | EP |
| Treatments | cm | $cm^2$ | NL | mm | RCI | —— g $plant^{-1}$ —— | | |
| Complete | 51.00 | 524.14 | 25.00 | 6.26 | 16.45 | 7.97 | 2.14 | 10.12 |
| - N | 35.50* | 65.56* | 5.66* | 2.46* | 2.56* | 2.63* | 2.01 | 4.65* |
| - P | 81.50* | 213.76* | 14.00* | 3.79* | 17.20 | 5.45* | 2.40 | 7.85* |
| - K | 31.75* | 83.70* | 2.33* | 3.10* | 5.00* | 3.11* | 1.89 | 5.00* |
| - Ca | 17.25* | 17.07* | 2.00* | 3.10* | 9.15* | 3.63* | 0.76* | 4.40* |
| - Mg | 25.50* | 129.36* | 12.33* | 3.23* | 7.55* | 4.72* | 1.98 | 6.71* |
| - S | 50.33 | 271.29* | 16.00* | 3.86* | 8.05* | 6.03* | 1.83 | 7.86* |
| F | 121.57 | 414.83 | 37.73 | 13.13 | 131.99 | 33.12 | 162.92 | 39.22 |
| DMS | 9.36 | 40.96 | 6.71 | 1.63 | 2.31 | 1.56 | 0.20 | 1.67 |
| CV% | 8.00 | 7.80 | 21.20 | 15.90 | 8.80 | 11.70 | 3.70 | 8.70 |

H: height; LA: leaf area; NL: number of leaves; SD: steam diameter; RCI: relative chlorophyll index; DM: dry matter; AP: aerial part; R: roots; EP: entire plant. DMS: significant mean difference; CV: coefficient of variation; *Significantly different by Tukey test ($p \leq 0.05$) column, compared to treatment with complete nutrient solution.

**Table 2.** Macronutrient in shoots and roots of soybean plants grown in nutrient solution.

| Treatments | N | P | K | Ca | Mg | S |
|---|---|---|---|---|---|---|
| | | | Aerial part — g kg$^{-1}$ | | | |
| Complete | 30.50 | 10.20 | 30.70 | 18.70 | 5.50 | 4.6 |
| - N | 10.50* | 11.90 | 48.10* | 25.10* | 6.00 | 5.70 |
| - P | 24.60 | 1.00* | 24.10 | 13.70* | 5.40 | 2.30* |
| - K | 50.70* | 9.90 | 14.70* | 16.30 | 4.40 | 4.90 |
| - Ca | 52.80* | 7.60* | 29.20 | 1.80* | 4.70 | 4.10 |
| - Mg | 46.90* | 10.60 | 30.70 | 17.80 | 1.40* | 5.60 |
| - S | 31.80 | 10.50 | 31.10 | 19.50 | 5.60 | 3.80 |
| F | 62.91 | 106.82 | 41.16 | 70.97 | 22.35 | 7.20 |
| DMS | 9.44 | 1.71 | 7.52 | 4.14 | 1.58 | 2.12 |
| CV(%) | 9.50 | 6.90 | 9.00 | 9.10 | 11.90 | 17.00 |
| | | | Roots — g kg$^{-1}$ | | | |
| Complete | 29.40 | 11.70 | 42.10 | 4.90 | 9.10 | 6.30 |
| - N | 14.00* | 11.70 | 39.70 | 6.30* | 3.60* | 5.30 |
| - P | 30.30 | 1.00* | 38.30 | 4.40 | 1.70* | 5.20 |
| - K | 28.00* | 9.00* | 3.10* | 14.20* | 2.20* | 5.20 |
| - Ca | - | 10.10 | 12.60* | 0.80* | 5.20* | 5.40 |
| - Mg | 35.30* | 11.40 | 40.10 | 5.40 | 0.70* | 6.00 |
| - S | 28.20 | 11.70 | 43.60 | 5.60 | 6.30* | 3.70* |
| F | 280.82 | 122.51 | 265.64 | 389.51 | 190.58 | 2.48 |
| DMS | 3.54 | 1.69 | 4.85 | 0.98 | 1.02 | 2.49 |
| CV(%) | 5.30 | 6.30 | 5.50 | 5.90 | 8.90 | 16.80 |

N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; S: sulfur. DMS: significant mean difference; CV: coefficient of variation; *Significantly different by Tukey test ($p \leq 0.05$) column, compared to treatment with complete nutrient solution.

In the literature, some sufficiency ranges of N are established to soybean plants: 55.0–58.0 g kg$^{-1}$ (Malavolta 2006), 40.0–54.0 g kg$^{-1}$ (Ambrosano et al. 1996), and 41.0–55.0 g kg$^{-1}$ (Embrapa 1996). Thus, in this experiment, the plants subjected to the treatment with the complete nutrient solution showed levels slightly below the range considered appropriate, while the treatment with N deficiency had much lower levels than the recommended.

The N deficiency caused an increase of 56 and 34% in K and Ca levels in shoots, respectively (Table 2). This behavior, especially considering K in shoots, may have been due to the concentration effect associated with limited growth, a fact already reported by other authors (Jarrel and Beverly 1981).

With the N deficiency in the nutrient solution, the accumulation of this nutrient was approximately 88.6% lower compared with the control treatment, that is, from 243.7 mg plant$^{-1}$ in the control treatment to 27.7 mg plant$^{-1}$ (Table 3).

The N deficiency triggered visual symptoms of nutritional disorders such as uniform chlorosis of the vegetative part, especially in older leaves. Leaves therefore dried from the edges to the ribs, followed by an intense and uniform yellowing in younger leaves. According to some authors, the symptoms of N deficiency in soybeans correspond to a uniform loss of the green color in leaves, changing to pale green and to yellow (Malavolta et al. 1980; Meurer, Wang, and Wang 1981).

Nitrogen deficiency, because it is a main constituent of chlorophylls, triggers leaf chlorosis followed by a decrease in the production of photoassimilates (Godoy, Villas Bôas, and Büll 2003; Mengel and Kirkby 1987; Shadchina and Dmitrieva 1995), and consequently a decrease in the production of dry matter, directly affecting crop yield.

### *Phosphorus*

The P deficiency in the nutrient solution decreased biometric variables, relative chlorophyll content, and production of dry matter (Table 1).

The P performs a structural function in the plant. It is related to the processes of transfer and energy storage, especially regarding metabolic processes related to the synthesis of proteins and nucleic acid (Malavolta 2006).

**Table 3.** Macronutrients accumulation in shoots, roots, and whole plant soybeans grown in nutrient solution.

| Treatments | N | P | K | Ca | Mg | S |
|---|---|---|---|---|---|---|
| | | | Aerial part — mg plant$^{-1}$ | | | |
| Complete | 243.70 | 81.30 | 244.40 | 148.20 | 44.20 | 36.60 |
| - N | 27.70* | 31.40* | 126.70* | 66.40* | 15.90* | 15.20* |
| - P | 133.70* | 5.80* | 131.80* | 74.90* | 29.50* | 12.40* |
| - K | 157.30* | 30.80* | 46.00* | 50.80* | 13.80* | 15.30* |
| - Ca | 191.50 | 27.60* | 106.60* | 6.50* | 17.10* | 14.90* |
| - Mg | 222.50 | 49.80* | 145.50* | 83.90* | 7.00* | 26.20 |
| - S | 192.10 | 63.70* | 187.60* | 117.60* | 33.80* | 23.40* |
| F | 24.43 | 170.82 | 34.92 | 78.26 | 58.38 | 13.56 |
| DMS | 70.02 | 9.33 | 51.00 | 24.93 | 8.30 | 11.39 |
| CV(%) | 15.00 | 8.00 | 12.90 | 11.40 | 12.90 | 19.80 |
| | | | Roots — mg plant$^{-1}$ | | | |
| Complete | 63.10 | 25.20 | 90.50 | 10.50 | 19.50 | 13.40 |
| - N | 28.10* | 23.50 | 80.00 | 12.80* | 7.20* | 10.60 |
| - P | 72.80 | 2.50* | 91.90 | 10.50 | 4.20* | 12.50 |
| - K | 53.00 | 17.00* | 5.80* | 26.80* | 4.20* | 9.80 |
| - Ca | - | 7.80* | 9.70* | 0.70* | 4.00* | 4.20* |
| - Mg | 70.20 | 22.60 | 79.70 | 10.80 | 1.30* | 11.80 |
| - S | 51.80* | 21.50* | 79.90 | 10.30 | 11.50* | 6.80* |
| F | 129.17 | 302.84 | 193.18 | 302.75 | 250.60 | 8.32 |
| DMS | 11.35 | 2.48 | 13.46 | 2.19 | 1.94 | 5.70 |
| CV(%) | 8.20 | 5.00 | 7.5 | 6.5 | 9.10 | 20.1 |
| | | | Entire plant — mg plant$^{-1}$ | | | |
| Complete | 306.80 | 106.60 | 334.90 | 158.70 | 63.70 | 50.20 |
| - N | 55.80* | 55.00* | 206.80* | 79.20* | 23.10* | 25.80* |
| - P | 206.50* | 8.30* | 223.80* | 85.40* | 33.70* | 24.90* |
| - K | 210.30* | 47.80* | 51.90* | 77.60* | 18.00* | 25.20* |
| - Ca | 191.50* | 35.40* | 116.30* | 7.20* | 21.10* | 19.00* |
| - Mg | 292.80 | 72.40* | 225.20* | 94.80* | 8.30* | 38.10* |
| - S | 243.90 | 85.20* | 267.60* | 127.80* | 45.30* | 30.20* |
| F | 31.42 | 357.28 | 76.45 | 84.55 | 131.64 | 19.72 |
| DMS | 73.30 | 8.55 | 53.18 | 25.38 | 8.12 | 11.66 |
| CV% | 11.90 | 5.10 | 9.10 | 9.80 | 9.30 | 13.30 |

N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; S: sulfur. DMS: significant mean difference; CV: coefficient of variation; *Significantly different by Tukey test ($p \leq 0.05$) column, compared to treatment with complete nutrient solution.

The P deficiency caused a significant decrease in shoots and roots of soybeans, about 90.2 and 91.4%, respectively, when compared to the control treatment. In addition, decreases in Ca (26.7%) and S (50%) in shoots and Mg (81.3%) in the roots, respectively, were observed (Table 2).

There was a decrease of 92.3% in P accumulation in shoots of soybean plants in relation to the control, while in roots the decrease was 90.1% (Table 3). In this study, the P content in soybean shoots (10.2 g kg$^{-1}$) was higher than that obtained by Malavolta et al. (1980) in a similar study using the cultivar Santa Rosa (4.6 g kg$^{-1}$). However, as for the P content in the treatment with P deficiency, contents were similar to that observed by these authors (Table 2).

In the literature, some sufficiency ranges of P are established to soybean plants: 4.0–5.0 g kg$^{-1}$ (Malavolta 2006), 2.5–5.0 g kg$^{-1}$ (Ambrosano et al. 1996), and 2.6–5.0 g kg$^{-1}$ (Embrapa 1996). Thus, plants subjected to the treatment with the complete nutrient solution presented levels above those recommended in the literature. In plants with P deficiency, the contents of this nutrient were considerably below the levels considered adequate.

As a consequence of the P deficiency, nutritional deficiency symptoms were diagnosed. There was a low growth rate since the early culture stages, followed by older leaves with a dark green and a "purplish" color. These symptoms corroborate those described by Vernetti (1983).

The decrease in plant development, when subjected to the P deficiency, is associated with storage and energy transfer functions (Malavolta, Vitti, and Oliveira 1997). This therefore affects metabolic functions, particularly reducing the production of photoassimilates at the expense of many physiological disorders.

### Potassium

With the deficiency of the supply of K in the nutrient solution, there was a decrease in the values of all biometric variables, relative chlorophyll content, and production of dry matter of soybean plants when compared to the treatment with the complete solution (Table 1). The decreases observed were 37.7, 84, 90.7, 50.5, and 69.6% for plant height, leaf area, number of leaves, stem diameter, and relative chlorophyll content, respectively, compared to the treatment with the complete nutrient solution. There was also a decrease in the production of shoot and total dry matter, about 61 and 51%, respectively, compared to the control treatment (Table 1).

The K deficiency reduces plant growth (Pettigrew 2008) due to its role in the activation of enzyme systems related to photosynthesis and respiration (Ahmad et al. 2012; Ashraf, Ahmad, and McNeilly 2001), protein synthesis (Ashraf, Ahmad, and McNeilly 2001), carbohydrates, adenosine triphosphate (ATP) (Pettigrew 2008), and osmotic regulation (Ahmad et al. 2012; Arquero, Barranco, and Benlloch 2006).

The K in shoots, both with the complete nutrient solution and the treatment with K deficiency, was higher than that obtained by Malavolta et al. (1980) (20.9 and 12 g $kg^{-1}$). Such results can be explained by the genetic improvement carried out during the 35 years between the studies, increasing the productive capacity of cultivars and consequently the nutritional requirement of soybeans to achieve maximum production rates.

In the literature, some sufficiency ranges of K are established to soybean plants: 22–25 g $kg^{-1}$ (Malavolta 2006), 17.0–25.0 g $kg^{-1}$ (Ambrosano et al. 1996), and 17.1–25.0 g $kg^{-1}$ (Embrapa 1996). Thus, in this experiment, plants subjected to the treatment with the complete nutrient solution presented levels above those considered adequate for the culture. In the treatment with K deficiency, the levels were below those recommended.

However, there was a significant decrease in K contents compared to the complete treatment: approximately 52.1% in shoots and 92% in roots (Table 2).

The K deficiency directly affected the accumulation of K in the plant, decreasing it by 81.2, 93.6, and 84.5% in shoots, roots, and whole plant, respectively, in relation to the treatment with the complete nutrient solution (Table 3).

Soybean plants, when subjected to K deficiency, showed symptoms of nutritional deficiency, mainly chlorosis, on the margins of older leaves followed by necrosis of leaf tissue. However, Mascarenhas et al. (1988), upon growing soybeans in soils with low K levels, observed yellowing of leaf edges. Malavolta et al. (1980), in addition to these symptoms, observed that chlorosis and necrosis progressed to the central region of the leaves.

### Calcium

Soybean plants, when subjected to Ca deficiency, showed a significant decrease in plant height (66.2%), leaf area (96.7%), number of leaves (92%), stem diameter (50.5%), relative chlorophyll index (44.4%), consequently reducing the production of shoots (54.4%), roots (64.5%), and total dry matter (56.5%) (Table 1).

In the literature, some sufficiency ranges of Ca are established to soybean plants: 6.0–10.0 g $kg^{-1}$ (Malavolta 2006), 4.0–20.0 g $kg^{-1}$ (Ambrosano et al. 1996) and 3.6–20.0 g $kg^{-1}$ (Embrapa 1996). Thus, in this experiment, plants subjected to the treatment with the complete nutrient solution presented levels considered adequate for the culture. In the treatment with Ca deficiency, the levels were below those recommended.

As observed for K in shoots, the Ca contents were higher than 8.8 g $kg^{-1}$ in studies conducted by Malavolta et al. (1980). The explanation for the increased absorption of Ca in relation to that

reported in the literature is the same as the previously presented, that is, genetic improvement programs that increased the nutritional requirements to achieve higher production rates of the culture over the last three decades.

Soybean plants, when subjected to Ca deficiency, showed a significant decrease in this nutrient in shoots and roots, approximately 90.4 and 83.7%, respectively, compared to the treatment with the complete nutrient solution. The accumulation of Ca also decreased with the deficiency of the supply of this nutrient in the nutrient solution by approximately 95.6 and 93.3% in shoots and roots, respectively, compared to the treatment with the complete nutrient solution (Table 3).

Plants, when subjected to Ca deficiency, showed internerval chlorosis in younger leaves, with a deformation in the blade, followed by lodging. A decrease in the size and coarsening of roots of soybean plants was also observed. Calcium is a component of the plant cell wall essential to maintain its structure and activate amylase. When balanced, it may change the cell division rate (White and Broadley 2003).

Upon evaluating soybean plants, Mascarenhas, Miranda, and Tanaka (1992) observed the occurrence of a collapse of petioles of leaves. This deformation, followed by plant lodging, stems from the nutritional disorder caused by the Ca deficiency because this nutrient is a plant structure component linked to the pectates of the cell wall and membranes. It interconnects phosphate/carboxylic phospholipid groups and provides stability to proteins, especially peripheral proteins (Marschner 1995).

### *Magnesium*

Soybean plants, when subjected to Mg deficiency, had a significant decrease in plant height (50%), leaf area (75.3%), number of leaves (50.7%), stem diameter (48.4%), and relative chlorophyll content (54.1%), reflecting a decrease of 33.7% in the production of total dry matter when compared to the treatment with the complete nutrient solution (Table 1).

Magnesium is an essential nutrient for photosynthesis as it is part of the metabolic processes of ATP formation in chloroplasts and aggregation of ribosomes, regulates ion currents, and operates in the protein synthesis, chlorophyll formation, phloem loading, separation, and use of assimilates (Shaul 2002). All these aspects are related to the capacity for production of dry matter of plants and, consequently, to crop productivity.

In the literature, some sufficiency ranges of Mg are established to soybean plants: 3.5–4.0 g $kg^{-1}$ (Malavolta 2006), 3.0–10.0 g $kg^{-1}$ (Ambrosano et al. 1996), and 2.6–10.0 g $kg^{-1}$ (Embrapa 1996). Thus, in this experiment, plants subjected to the treatment with the complete nutrient solution presented levels considered adequate for the culture. In the treatment with Mg deficiency, the levels were below those recommended.

Soybean plants subjected to Mg deficiency had a significant decrease in Mg contents both in shoots and in roots of approximately 74.5 and 92.3%, respectively (Table 2). Following the same tendency, the Mg contents obtained in the leaf tissue with the complete nutrient solution were higher than 3.8 g $kg^{-1}$, a value observed by Malavolta et al. (1980) upon evaluating soybean plants cv. Santa Rosa, probably due to the same reason as previously reported.

The accumulation of Mg by soybeans was affected by the deficiency of the supply of this nutrient to the plant, decreasing it by 84.2, 93.3, and 86.9% in shoots, roots, and whole plant, respectively, when compared to the treatment with the complete nutrient solution (Table 3).

Soybean plants, after the Mg deficiency, showed internerval chlorosis of older leaves. Possibly, this was because Mg is a component of the chlorophyll molecule (Malavolta, Vitti, and Oliveira 1997) especially linked to the energy metabolism of plants (Shaul 2002). Upon evaluating soybean plants submitted to Mg deficiency, Vernetti (1983) observed marginal and internerval chlorosis in soybean leaves.

### *Sulfur*

Soybean plants, when subjected to S deficiency, showed a significant decrease in leaf area (75.3%), number of leaves (50.7%), stem diameter (48.4%), and relative chlorophyll index (54.1%), consequently decreasing the production of shoot (40.8%) and total dry matter (33.7%) (Table 1). Sulfur has a structural function in plants. It is a constituent of some amino acids and is particularly and indirectly involved in the synthesis of chlorophyll, which interferes with photosynthesis and respiration rates especially in the production of assimilates, holding back the development of plants (Vitti, Lima, and Cicarone 2006).

The S deficiency did not affect the content of this nutrient in shoots when compared to the treatment with the complete nutrient solution. However, there was a decrease in the content of this nutrient in roots (41.3%) compared to the control treatment. This behavior is because S is the least required nutrient by soybean crops among macronutrients (Table 3), and also because it has been used for transplanted plants, which justifies the initial reserve of S and the low response to treatments to which it was applied.

In the literature, some sufficiency ranges of S are established to soybean plants: 2.5–3.5 g $kg^{-1}$ (Malavolta 2006) and 2.1–4.0 g $kg^{-1}$ (Ambrosano et al. 1996; Embrapa 1996). Thus, in this experiment, plants subjected to the treatment with the complete nutrient solution and deficiency presented levels above those considered adequate.

The accumulations of S in shoots, roots, and the whole plant were also affected by the S deficiency, with a decrease of 36.1, 49.2, and 39.8%, respectively, when compared to the treatment with the complete nutrient solution (Table 3).

Even with a decrease in the production of dry matter of soybean plants, no symptoms of nutritional deficiency were observed. However, Silva et al. (2003), in a similar study, observed a light bright green color in new soybean leaves and leaves newly formed, evidencing the main physiologic drains of sulfur, symptoms that are analogous to those observed in plants subjected to nitrogen deficiency. The non-appearance of symptoms of S deficiency is possibly due to its accumulation during the initial period (two weeks) in which the seedlings received a complete nutrient solution. It corroborates the studies conducted by Malavolta et al. (1980).

The S is a component of proteins associated with nitrogen. It mainly participates in the formation of amino acids essential to energy metabolism and may intervene in the synthesis of vitamins and enzymes (Vitti, Lima, and Cicarone 2006).

In summary, the treatment with the complete nutrient solution showed an accumulation of nutrients in shoots in the following order: K > N>Ca>P>Mg>S. In roots, the accumulation was K > N > P>Mg>S>Ca. In the whole plant, the accumulation was K > N>Ca>P>Mg>S. In the present study, Table 3 shows that K was the nutrient most extracted by soybean crop, followed by nitrogen. Let us know potassium is known to be a "luxury consumption" essential nutrient. This means that K uptake will continue to increase (as long as there is ample K available to the root system) even if final yield is not affected. Both perform key roles in the plant development cycle. K is the main activator of enzymatic functions and maintenance of cell turgor (Pettigrew 2008), while N directly participates in the formation of organic compounds (Bloom 2015; Epstein and Bloom 2006).

## Conclusions

The deficiency of any macronutrient in the production of soybeans directly affects biometric variables, which is then reflected in plant development, especially in production of dry matter.

The nutrients that limited the most the production of dry matter were Ca>N > K>Mg>P > S.

With the exception of S, all other macronutrients, when suppressed, result in the appearance of visual symptoms of nutritional disorders.

Soybean plants have the following order of macronutrient accumulation in leaves: K > N>Ca>P>Mg>S.

In the present study, soybean plants had a high nutritional requirement of K followed by N. This requires care regarding plant nutrition in the development of fertilization programs in view of the essential roles these nutrients play in the life cycle of plants.

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