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SOILS

Visual symptoms and nutritional deficiencies in olive plants subjected to nutrient deprivation

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ABSTRACT. As the fourth largest importer of olive oil and the fifth largest importer of olives, Brazil is one of the largest importers of olive (*Olea europaea* L.) products in the world. In recent decades, the introduction and growth of olive cultivars with lower chilling requirements in the south and southeast regions of Brazil have made olive production viable in the country. However, there is a dearth of information about the management of olive crops in Brazil, especially in relation to studies about the nutritional needs of olive trees grown in subtropical regions, which may enable advances in the productivity of this fruit. The aim of this study was to evaluate the growth, dry matter production and nutritional status of the olive tree under the effect of nutrient omissions, as well as to establish visual diagnostic parameters of nutrient deficiencies. We used a completely randomized design with ten treatments and three replicates grown in the Hoagland–Arnon nutrient solution and solutions with individual omissions of N, P, K, Ca, Mg, S, B, Fe, and Zn. The treatments that most limited the growth of olive trees were the N, Ca, and B omission treatments.

Keywords: *Olea europaea* L.; macronutrient; micronutrient; dry matter.

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Introduction

The olive tree (*Olea europaea* L.) is a fruit tree that originated from temperate regions, where it needs low temperatures to bloom and bear fruit. In recent decades, breeding programs have focused on cultivating olives with a lower chilling requirement, thus making it possible to introduce them to areas with higher temperatures that have little history of traditional olive cultivation. The olive tree originates in the geographic region from the southern Caucasus to the plains of Iran and Palestine and the coastal zone of Syria, extending to all countries along the shores of the Mediterranean (Civantos, 2008; Silva, Oliveira, Pio, & Zambon, 2012). This crop has wide-ranging economic and social impacts (Aguilera et al., 2015; Orlandi, Aguilera, Galan, Msallem, & Fornaciari, 2016) because the Food and Drug Administration (FDA) has implemented a "qualified health claim" on olive oil, since it protects against vascular pathologies.

Brazil is one of the largest importers of olive-derived products in the world. In the last 45 years, the Brazilian production of olive was 1042 to 300 tons, there was a decrease in production of olives (71.20%) (Pio, Souza, Kalcsits, Bisi, & Farias, Daniela da Hora, 2019). In the last 20 years, the imported volume of olive oil has increased five times, coming mainly from the European Union, Argentina and Chile. Brazil imported 109,051 tons of olives in 2015, mostly from Argentina, Spain, Peru and Egypt (Silva, Zambon, Pio, Oliveira, & Gonçalves, 2016). According to Oliveira, Ramos, Pio, and Cardoso (2012), imports of these products totaled over one billion reals in the domestic market.

Although the olive tree is considered a rustic species with a great capacity to survive and produce in low-fertility soils (Chatzistathis, Therios, & Alifragis, 2009), it must have an adequate level of nutrition to perform the essential functions of vegetative growth and reproductive development (Carvalho, Cruz, Fagundes, & Oliveira, 2013), and nutrition is also important for the quality of the olive fruit and oil (Chouliaras, Tasioula, Chatzissavvidis, Therios, & Tsabolatidou, 2009; Boussadia et al., 2010).

The importance of the olive tree nutritional status has been reported by many authors around the world (Erel et al., 2013; Chatzistathis, Therios, Alifragis, & Dimassi, 2010; Chatzistathis et al., 2009; Toplu, Uygur,

& Yildiz, 2009; Rodrigues et al., 2011); however, in Brazil, this subject requires more research, as just a few studies have been conducted (Carvalho et al., 2013; Vieira Neto, Silva, Gonçalves, Zambon, & Villa, 2014).

Particularly due to studies related to the nutritional needs of olive trees grown in subtropical regions, it is believed that the improvement in crop management may enable advances in the productivity of this fruit. In this sense, parameters such as leaf characteristics and visual diagnostics are used to assess the nutritional status of the plant, as they allow the characterization of symptoms of nutrient deficiency or toxicity (Souza, Pio, Coelho, Rodas, & Silva, 2015).

Despite the high quality of olive oil produced in Brazilian subtropical conditions, olive cultivation is still not a viable economic activity due to difficulties in adapting cultivars to the country's climate (Silva, Oliveira, Pio, & Zambon, 2012a). Arbequina cultivar is the most commonly used by the producers and hence is the most representative cultivar in the Brazilian olive groves among the cultivars with productive potential evaluated in the South and Southern regions (Silva, Oliveira, Zambon, Pio, Oliveira, & Gonçalves, 2016). It is a cultivar originating from Spain used to produce olive oil, which was very well adapted to the environmental conditions of the South and Southeast of Brazil (Silva, Oliveira, Pio, Rafael, Alves, & Zambon, 2012b).

However, studies on the mineral nutritional requirements and fertilization of olive plants are still incipient, with little information available on the nutritional requirements of olives, especially for the soil and climatic conditions of Brazil. In this sense, the objective of this study was to evaluate the vegetative growth, dry matter production and nutritional status of 'Arbequina' olive plants grown under nutrient deficiencies in greenhouse conditions.

Material and methods

The experiment was conducted at the Soil Science Department of the Federal University of Lavras (Minas Gerais State, Brazil). The Koppen climate classification is Cwa - Subtropical climate (21°14'S, 45°00'W and 918 meters of average altitude), that is, subtropical climate with cold and dry winter and warm and moist summers (Souza, Alvarenga, Pio, Gonçalves, & Patto, 2013). The experiment was conducted in a greenhouse with Arbequina cultivar olive plants propagated by cuttings. After rooting, the plants were standardized at a 15-cm height level at the beginning of April. The seedlings were transferred to a plastic box with a capacity of 40 liters containing Hoagland-Arnon nutrient solution with 10% of its ionic strength for 90 days to allow the plants to adapt to a hydroponic medium. Subsequently, the ionic strength it was raised to 100%, and it remained at that level with constant aeration until the end of the experiment.

After the adjustment period, the plants were individualized into five-liter vases, and treatments using the missing element technique were applied. We used a completely randomized design with ten treatments and three replicates, and the plot was represented by a vase with a plant grown in Hoagland-Arnon complete solution (control) or its variations, which had individual omissions of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), iron (Fe), and zinc (Zn).

The solutions were prepared using deionized water, and during their refresh interval, the volume of the vessel was completed, when appropriate, using deionized water.

After 95 days, the plants were removed and evaluated for height and stem diameter. Then, the harvested material was washed with distilled water, packed in paper bags and dried in an oven with forced air circulation at 65°C for 72h. After determining the dry matter of the shoot and root components, the material was ground in a Willey mill and passed through a 20-mesh sieve to determine the mineral composition.

The effect was evaluated with the fill percentage or relative production method, adapted to determine the "relative growth" (RG) by the formula:

$$RG = \frac{Treatment\ with\ omitted\ nutrient\ x\ 100}{Complete\ treatment}$$

The normality of the data was verified by the Shapiro-Wilk test, and the homogeneity was verified by the Bartlett test using R software (version 3.2.2). The data were submitted to analysis of variance, and the means were evaluated by the Scott & Knott test at 5% probability with R software (version 3.2.2) using the agricolae and laercio packages.

Results and discussion

Symptoms of nutritional deficiencies in olive

Plants submitted to treatments with nutritional omissions showed visual symptoms of nutrient deficiency when the nutrient levels were lower than the values considered necessary for plant growth (Figure 1).

Plants grown under the omission of N showed symptoms starting 27 days after the beginning of the experiment, with chlorosis (yellowing) initially occurring in the older leaves, while the younger leaves remained green. According to Faquin (2005), this occurs due to the redistribution of nutrients in the leaves. During the nitrogen omission treatment, there was a drastic reduction in growth, widespread chlorosis, no issuance of new roots and rotting of the secondary roots. These are expected behaviors because N is a component of nucleic acids. The green color of older leaves gradually changed to a pale green tint, which further evolved to a deep yellow color that was distributed evenly across the blade. The yellow coloration was related to decreased chlorophyll production and the modified shape of the chloroplast. N deficiency affected several components of carbon metabolism in the olive trees. Leaf photosynthesis is largely dependent on the leaf N content, and low levels of leaf N can reduce both the chlorophyll a concentration and net photosynthetic rate of leaves (Boussadia et al., 2010).

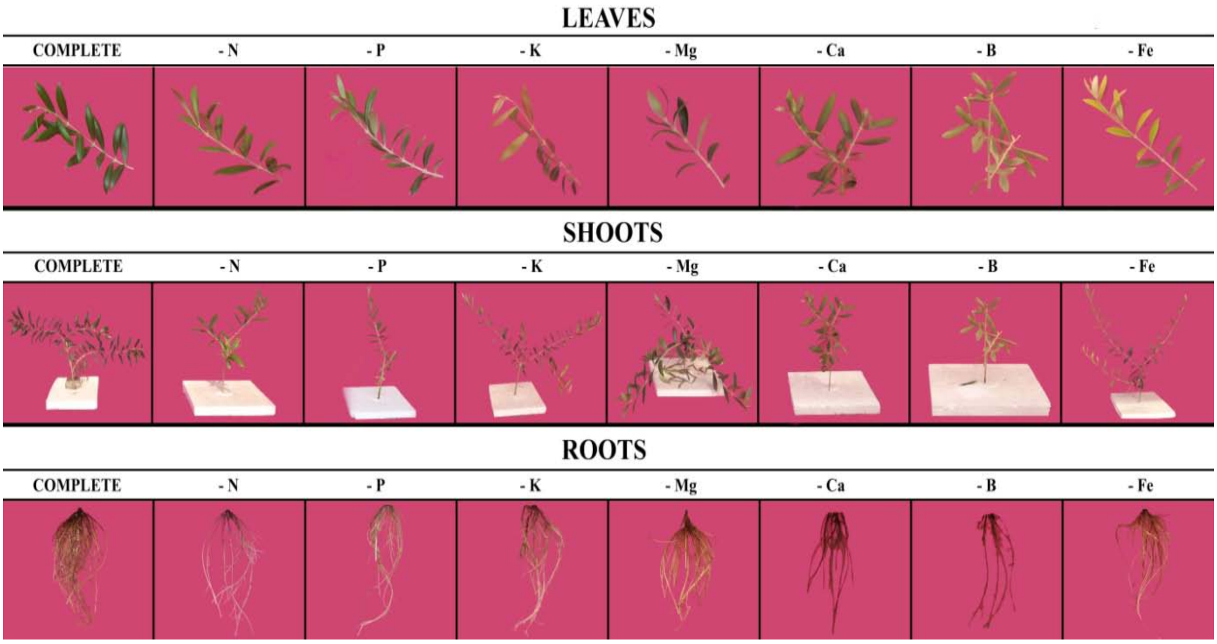

Figure 1. Symptoms of nutritional deficiencies in olive trees cv. Arbequina grown in the complete nutrient solution and solutions with omissions of N, P, K, Mg, Ca, B, and Fe 95 days after the beginning of the treatments. UFLA, Lavras, Minas Gerais, 2016.

The effects of the phosphorus omission treatment were evident after 62 days of the experiment. The omission caused wrinkling (shriveling) of the edges of older leaves and slight chlorosis, which is similar to the effects described by Alves, Prado, Gondim, Fonseca, and Cecílio Filho (2008), who initially observed intense purpura of the roots that, with the evolution of the deficiency, was also verified in the leaves. Phosphorus is significant in several plant functions, exerting a prominent role in the formation of proteins and several other processes, such as photosynthesis, cell division and energy storage (Bastos, Costa, Silva, Raposo, & Souto, 2008; Gebrim et al., 2010; Korndorfer & Mello, 2009; Simões Neto et al., 2009; Moura Filho et al., 2014). Although P is an essential macro-element, it is not commonly applied during olive cultivation (Fernández-Escobar, 2010). In the study of Erel et al. (2013), production was enhanced by increases in the P concentration of olive leaves, and the highest numbers of fruits corresponded to the highest leaf P concentrations.

The symptoms observed in the K omission treatment first occurred in older leaves after 67 days. The older leaves showed marginal chlorosis, advancing towards the central part of the limbo, initially presenting a green-yellow tint that, with the advance of time under the deficiency conditions, turned into a brown color as the leaves reached the necrosis stage. According to Faquin (2005), due to the mobility of K in tissues, symptoms occur first in older leaves, followed by chlorosis and then necrosis on the tips and margins of the leaves; in the affected regions, there was putrescine accumulation. Potassium is considered the element that causes the most severe nutritional disorders in olives when its levels in the environment are low (Fernández-Escobar, 2008). In olive, K starvation has been found to impair stomatal closure under drought conditions but not in well-irrigated plants (Benlloch-González, Arquero, Fournier, Barranco, & Benlloch, 2008).

The calcium omission treatment caused visible abnormalities in younger leaves at 35 days. Initially, necrosis was observed along the top edge of the apex of some leaves, while the other leaves had a regular green color. The younger leaves curved downward, presenting chlorosis followed by necrosis of their tips. Compared with the control, the calcium-deficient plants had a lower number of leaves and roots that were darker, less developed and thicker with fewer lateral roots. In addition, there was a drastic reduction in the growth height, and the stem became slenderer, which affected the root development. According to previous studies, Ca deficiency usually delays the growth of plants and causes the death of their pointers (Silva, Tanure, Santos, & Júnior, 2009). Because of the low translocation of calcium in the plants, the nutrient deficiency symptoms occur in the growing points of shoots and roots, and the regions of the greatest cell expansion are most affected by Ca deficiency (Faquin, 2005).

Unlike Ca and similar to K, Mg is mobile in the phloem, so the symptoms of Mg deficiency first manifested in older leaves as internerval chlorosis. The Mg deficiency symptoms were similar to those observed by Viégas, Thomaz, Silva, Conceição, and Naiff Viégas (2004) in camucamuzeiro, where chlorosis occurred along the edges of older leaves and yellowing appearing between the secondary ribs: as the intensity of the deficiency increased, necrosis occurred. However, Ca and Mg deficiencies should not be a serious problem in most olive groves, since Ca and Mg occur in the soil solution in great abundance (Freeman & Carlson, 2005).

Symptoms of boron deficiency in plants were noticeable 41 days after the start of the experiment. The symptoms presented as gnarled, stunted, small and thick new leaves, and with the intensification of the symptoms, death occurred in the apical meristem of the stem. Furthermore, the deficiency of this nutrient caused serious damage to plant growth and stopped the emission of new roots while secondary root rot occurred. Boron accumulates in older leaves, with higher levels in the corners and edges, and the transport of this micronutrient occurs via transpiration, which would explain why the deficiency symptoms manifested in the growing points (Jones Jr., Wolf, & Mills, 1991). Boron requirements differ among plant species. Olive is considered a crop with a high demand for B (Fernández-Escobar, 2001).

Symptoms caused by the absence of iron were observed at 35 days, manifesting as a change in the color of new leaves, which showed very pronounced, green-hued ribs that contrasted sharply with the rest of the yellow limb. With the severity of the deficiency and associated decrease in chlorophyll, the leaves first became completely chlorotic and then became whitish. In addition, there was a slight delay in the leaf and plant growth. The lower and middle leaves showed normal colors and sizes. The root system became a brown or rusty hue, and the lack of secondary roots resulted in a short root system that was thicker and more brittle than the control roots. The olive leaves stored 47.7% of the total tree Ca, while the fruits (pulp plus pit) only stored 13.1%. Calcium is translocated in the xylem mainly through the transpiration stream, and lowering the transpiration rate further decreases the Ca content of fruits (Rodrigues, Ferreira, Claro, & Arrobas, 2012).

Omitting sulfur and zinc from the nutrient solution caused a reduction in the dry matter production of the roots, which consequently decreased from the full treatment. Although these attributes were affected by the omissions of the elements, no visual deficiency symptoms were observed during the trial period.

Vegetative growth and dry matter production of olive plants

Based on growth variables (height and diameter), the effect of the dry matter production of the shoots and roots on the growth and the shoot/root ratio of the dry matter, the omission of nutrients significantly affected the plants grown under nutrient deficiency conditions. These data are shown in

Table 1. The plants grown under Zn and S omission treatments and the control plants (complete nutritional solution) were taller than the others and did not differ among each other. These results corroborate those of Miranda, Sudério, Sousa, and Gomes Filho (2010). In contrast, the shortest plants were obtained by the treatments omitting P, Ca, and N, for which plants were 41.23, 54.23, and 56.22% shorter, respectively, than the plants of the complete treatment. This fact underscores the importance of using these nutrients during the fertilization of olive cultivars because in the absence of these nutrients, the entire development of the olive plant may be compromised.

Table 1. Height (H), diameter (D), the production of dry matter of the aerial part (PA) and the roots (R), the relative growth rate (RG) and the relationship between the dry matter of the shoots and roots (PA / R) in olive plants grown under the omission of nutrients. UFLA, Lavras, MG, 2016.

Treatment	Growth		Dry matter		Proportion indices	
	H	D	PA	R	RG (%)	PA/R
	—— (cm) ——		—— (g) ——			
Complete	59.00 a	0.50 a	13.91 a	2.98 a	100	4.66
-N	25.83 c	0.43 b	3.37 d	0.78 d	24.57	4.32
-P	34.67 c	0.50 a	1.35 d	4.23 a	33.03	0.32
-K	44.17 b	0.57 a	9.18 c	2.03 c	66.37	4.52
-Ca	27.00 c	0.33 b	2.77 d	0.52 d	19.47	5.32
-Mg	42.67 b	0.47 a	11.12 b	1.57 c	75.13	7.08
-S	55.33 a	0.63 a	13.76 a	3.01 a	99.28	4.57
-B	18.83 c	0.33 b	1.84 d	0.28 d	12.55	6.57
-Fe	47.17 b	0.53 a	8.57 c	2.14 c	63.41	4.00
-Zn	57.66 a	0.50 a	13.71 a	2.85 a	98.46	4.81
CV (%)	13.56	16.48	18.87	14.45	15.18	13.67

*Means followed by the same letter in a column do not differ from one another by the Scott Knott test at a 5% probability.

Based on the stem diameter analysis, the plants with the full treatment and the treatments with omissions of P, K, Mg, S, Fe, and Zn had higher stem diameters than the other plants and did not differ statistically, while omissions of N, Ca and B produced decreases of 14, 34, and 34%, respectively, for this variable compared to the control. The high importance of N in olive fertilization has been confirmed by more recent studies (Rodrigues et al., 2012). Rodrigues et al. (2011) reported a significant and progressive decrease in olive yield when N was eliminated from the fertilization plan for four years in comparison with treatments where N was applied annually. Several studies have continued to report the importance of B fertilization as a means of increasing olive productivity (Larbi, Gargouri, Ayadi, Dhiab, & Msallem, 2011; Soyergin, 2010).

Regarding the production of dry matter in the aerial part, the production rates in plants that received the full treatment and those grown under the S and Zn omissions did not differ and were superior to those of the other plants. In contrast, there were dramatic reductions in the dry matter contents of the plants grown under the omissions of B, N, Ca, and P, demonstrating reductions of 86.78, 75.78, 80.09, and 90.3%, respectively, in relation to the control treatment. N deficiency caused a decrease in the leaf N content, the chlorophyll a content and the carbon assimilation of olive plants, resulting in a lower rate of dry matter accumulation (Boussadia et al., 2010). Nitrogen, phosphorus, potassium and boron are essential nutrients in olive orchards (López-Granados, Jurado-Expósito, Alamo, & Garcıa-Torres, 2004). According to Therios (2009), the most appropriate soils for the growth and fruiting of olive trees are sandy-loam ones supplied with adequate N, P, K, and water.

At the root, there were also considerable reductions in dry matter. The lowest root dry matter yields were observed in plants grown under the omission of N, Ca, and B, with reductions of 73.82, 82.55, and 90.60%, respectively. In general, it was observed that the omissions of N, Ca and B caused the most damage to the production of dry matter in the shoots and roots. Nitrogen is considered the most important nutrient in olive orchards (Therios, 2009). According Rodrigues et al. (2012), olive leaves store 47.7% of the total tree Ca and deficiencies in this element cause high biomass losses. Several studies have reported the importance of B fertilization as a means of increasing olive productivity (Larbi et al., 2011; Soyergin, 2010).

During the analysis of the relative growth (RG) in dry matter production, the relative growth of the complete solution treatment was considered to equal 100%. This study found that the RG of the plants grown under the element deficiency treatments decreased in the following order: complete >S>Zn>K>Fe>P>N>Ca>B. The RG values of the S and Zn omission treatments were similar to those of the complete treatment; thus, the olive crop does not have high demands for these nutrients. The omissions of the other nutrients affected the relative growth of the olive plants and were more pronounced for the omissions of B, Ca, N, and P. Nitrogen (N) and boron (B) are frequently included in the fertilization programs suggested by regional laboratories of soil testing and plant analysis. As N and B are mobile elements in soils, fertilization practices should strive to improve the efficiency of N and B utilization by olive trees (Rodrigues et al., 2011).

The treatments with the highest shoot/root ratios were the Mg and B omission treatments, which had values of 7.08 and 6.57, respectively, whereas the treatment that had the lowest value (0.32) was the omission of P. Plants constantly sense changes in their environment, and when mineral elements are scarce, they often allocate a higher proportion of their biomass to the root system (Lawlor, Lemaire, & Gastal, 2001). This response is a consequence of metabolic changes in the shoots and a redirection of carbohydrate transport to the roots (Boussadia et al., 2010). According to Moretti, Furtini Neto, Pinto, Furtini, and Magalhães (2011), in environments with low fertility, the root/shoot ratio is smaller; i.e., the volume of the roots is greater than that of the shoots as the plant increases the volume of explored soil to maximize the intake of nutrients in these conditions.

S and Zn were the least limiting nutrients for the production of biomass in the olive tree. In Jatropha trees, Silva et al. (2009) found that deficiencies in S and P were less limiting on the dry weight production of plants than deficiencies in other nutrients. According to these authors, this result may have occurred because the supply of S and P in the complete solution, which was used in the adaptation phase, was high enough for the initial development of plants.

Nutrient content of the shoot and root systems of the olive plants

The nutrient content (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) for both the shoot and the root system of the olive trees was significantly different at 5% probability (Table 2).

Table 2. Nutritional content in the aerial and root parts of olive plants under the omission of nutrients. UFLA, Lavras, Minas Gerais, 2016.

Nutritional contents in the aerial part											
Treatment	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	(g kg^{-1})						(mg kg^{-1})				
Complete	28.5b	2.4b	7.2b	4.5c	1.1a	1.4a	18.1e	2.7c	135.9a	59.1b	15.1b
-N	10.7d	2.1b	8.6b	3.4c	0.7b	0.9b	15.4f	3.2c	66.7c	43.4b	11.2b
-P	24.2c	0.8c	13.9a	1.8c	0.5b	0.9b	14.2f	6.0c	108.7b	55.0b	14.8b
-K	30.0a	3.1b	6.3b	4.0c	1.4a	1.3a	21.3d	5.9c	100.6b	54.1b	11.9b
-Ca	22.9c	1.4c	10.3b	2.6c	1.0a	1.2a	20.1d	22.6a	138.2a	67.0b	20.5b
-Mg	24.6c	2.7b	15.1a	4.3c	0.3b	0.7b	24.6c	4.8c	128.8a	59.0b	12.8b
-S	26.0c	2.2b	15.7a	5.3b	0.9a	0.7b	18.6e	1.7c	136.5a	51.9b	17.0b
-B	21.1c	1.5c	13.2a	3.7c	0.9a	0.5b	18.6e	11.6b	136.8a	66.8b	18.9b
-Fe	32.0a	4.3a	16.2a	7.6a	1.7a	1.6a	28.3b	10.6b	50.3b	101.5a	36.9a
-Zn	27.0b	2.4b	11.7a	5.6b	1.3a	1.1a	39.7a	3.4c	141.5a	56.0b	13.2b
CV (%)	7.5	13.2	21.0	8.2	11.2	24.5	4.6	22.1	14.0	21.1	20.5
Nutritional contents of the root system											
Treatment	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	(g kg^{-1})						(mg kg^{-1})				
Complete	31.6a	4.9b	15.8b	6.2b	2.6a	2.0a	25.8c	9.7b	802.8b	512.2a	25.6b
-N	10.7b	11.9a	26.9a	12.0a	2.5a	1.5a	14.9d	6.6b	1420.7a	383.1b	38.9b
-P	32.3a	1.3c	13.3b	2.8b	1.3b	1.4a	23.3c	9.7b	755.3b	280.7c	25.0b
-K	36.1a	5.8b	11.4b	1.5c	1.0b	2.0a	22.4c	22.4b	849.2b	214.4c	21.9b
-Ca	30.2a	1.2c	11.6b	1.0c	1.5b	0.6b	21.7b	7.0b	693.2b	61.8d	17.4b
-Mg	31.4a	7.4b	31.5a	9.8a	1.3b	3.3a	15.8d	13.8b	839.2b	334.6b	28.4b
-S	31.6a	6.6b	12.1b	12.8a	2.6a	0.7b	37.0a	8.0b	773.9b	499.6a	26.6b
-B	28.5a	0.7c	11.3b	0.7c	0.4b	0.2b	29.0b	3.6b	418.4c	80.3d	8.4b
-Fe	29.5a	3.5c	13.8b	4.5b	2.4a	0.6b	35.8a	48.8a	107.6d	553.6a	77.8a
-Zn	32.2a	5.9b	13.9b	9.9a	2.1a	0.8b	31.2b	12.6b	882.6b	485.1a	24.3b
CV (%)	9.7	5.6	7.3	8.3	16.9	17.7	11.3	7.5	15.8	25.1	10.9

*Means followed by the same letter in the column do not differ from one another by the Scott Knott test at a 5% probability.

There were greater N contents in plants grown under the omissions of Fe and K, which showed superior results to the other plants, and the N content of the plants in the Zn omission treatment was close that of the complete treatment plants. It is common for inhibitory interactions to occur between N and K; however, this was not observed in the K omission treatment. Nitrogen is considered the most important nutrient in olive orchards (Therios, 2009).

Lower levels were observed in plants grown under the P, Ca, Mg, S and B omission treatments. Barroso, Figueiredo, Pereira, Mendonça, and Silva (2005) noted that the omission of N resulted in the reduction in Ca contents, while the Ca contents increased under the omission of Fe and Zn.

For the shoots and roots, the lowest N levels were observed for the N omission treatment (both were 10.7 g kg^{-1}) and were three times lower than those of the full treatment. These results were lower than those reported by Rodrigues et al. (2012), and these authors reported that the leaves presented the highest N concentration among all plant tissues, 16.0 g kg^{-1}, which represents 44.5% of the total N in a tree. Nitrogen is an integral constituent of proteins, nucleic acids and many other organic structures of living cells (Scherer & Mengel, 2007), which explains its abundance in the leaves (Rodrigues et al., 2012).

Regarding the P content, the highest level in the shoots was observed in plants grown under the Fe omission treatment; it was 79.16% higher than that of the full treatment. The lowest levels occurred under the omission of B, Ca, and P, with values that were 66.6, 41.66, and 37.5% lower than the control, respectively. Rodrigues et al. (2012) found the olive leaf proportion of N:P was 15.7:1 and that the total N: P was 8.4:1 due to the higher relative importance of P in the fruit. The lower levels in the aerial part and the root system were found in plants grown under the Ca, P, and B omission treatments.

The lowest levels of K in the shoots were observed in the full treatment and the N, K, and Ca omission treatments, which had similar values to the complete treatment. For the roots, the highest K levels were found in plants grown under the Mg and N omission treatments, which were 99.36 and 69.62% higher, respectively, than the control treatment level. The interaction between K and Mg has been discussed extensively due to the antagonism between these nutrients, so the absence of K favors the absorption of Mg ions, whose chemical properties are similar enough to compete for uptake sites. According Faquin (2005), high concentrations of Ca and Mg reduce the absorption of K by competitive inhibition. Freitas, Monnerat, and Vieira (2008) found high Mg contents in passion fruit deficient in K and Ca. The regular potassium content found by Martins, Cruz, Oliveira, Santos, and Fagundes (2015) in olive leaves was 35.8 kg g^{-1}, which is 5 and 2.5 times higher than the values for the shoots and roots, respectively, in this study.

Regarding the Ca in the shoots, the highest content was observed in the treatment that omitted Fe, which was 68.88% of the control value; the lowest, which was 60% lower than the complete value, was observed in the treatment that omitted P. The Ca concentration in the complete treatment (4.5 g kg^{-1}) was similar to that obtained by Ramos, Monnerat, Pinho, and Silva (2011) for the complete treatment (4.3 g kg^{-1}) in pineapple. In the roots, the highest values were observed in plants grown under S, N, and Zn deficiencies at levels of 106.45, 93.5, and 58.06% more than the complete treatment, respectively; the lowest values were observed for the deficiencies of P, K, Ca and B. These results corroborate those of Vidigal, Pacheco, Costa, and Facion (2009). Ca deficiency reduced the absorption of P and K, and there was an increase in Mg, suggesting that Ca omission favors the absorption of Mg.

Based on the analysis of the Mg nutritional content in the shoots, the omissions of K, Ca, S, B, Fe, and Zn and the complete treatment had better results than the other treatments, while there was a decrease in the plants grown under the omissions of N (0.7 g kg^{-1}), P (0.5 g kg^{-1}), and Mg (0.3 g kg^{-1}). In the roots, the lowest levels of this nutrient were found in the plants with omissions of B (0.7 g kg^{-1}), K (1.0 g kg^{-1}), P (1.3 g kg^{-1}), Mg (1.3), and Ca (1.5 g kg^{-1}). Moretti et al. (2011) observed a higher Mg content in plants treated with an omission of K; this possibly occurred due to a reduction in the competitive inhibition between K and Mg, as described by Faquin (2005). According to Panagiotopoulos (2001), Mg concentrations in the olive leaves of annual shoots that are lower than 1 g kg^{-1} are relatively but not seriously low.

For the S content of the shoots, the lowest values were observed in plants grown under the omission of N, P, Mg, S, and B, with values that were 35.71, 35.71, 50.00, 50.00, and 64.28% lower, respectively, than the control value; the content was higher for the Fe, K, and Ca omission treatments. According to Barroso et al. (2005), the omission of S caused teak seedlings to favor the absorption of Ca in the root system, and the lowest values, which were 90, 70, 65, and 60% lower than the control value, were in plants deficient in B, Ca, Fe, and Zn, respectively. The complete treatment levels (1.4 g kg^{-1}) correspond to those presented by Carvalho et al. (2013), who reported levels from 1.3 to 3.6 g kg^{-1}.

There was an increase in the B content in shoots in plants grown under Zn deficiency conditions. In contrast, it decreased in those grown under N and P deficiency conditions, with decreases of 14.91 and 21.51%, respectively, compared to the complete treatment value. In the roots, the highest B levels were observed in plants grown under the S and Fe omission treatments, and the lowest levels, 42.24 and 38.75% of the control value, were observed in plants in the N and Mg omission treatment groups, respectively. The mean leaf B concentrations in the B omission treatment were 18.6 g mg^{-1} (shoot) and 29 g mg^{-1} (root), which are corroborated by Rodrigues et al. (2011), who found concentrations between 19.2 mg g^{-1} and 26.4 mg g^{-1} in olive leaves grown under the omission of B.

The highest content of Cu was found in the aerial part of plants grown under the Ca omission treatment; it was seven times greater than the value found in the control and five times greater than the value of the Fe omission treatment (root system). The value of Cu in the aerial part of the complete treatment plants was 2.7 mg kg^{-1} lower than the levels found in the full treatment reported by Moretti et al. (2011), which varied between 7.5 and 9.5 mg kg^{-1}.

Based on the analysis of the Fe content in the shoots, the value of the plants grown under the omission of N was 50.91% less than that of the full treatment, while in the root, the opposite trend was observed, which suggests that Fe was not translocated to the shoots. In the root system, the lowest content, which was 47.88% below that of the complete solution, was found in plants with a B deficiency. The treatment with an Fe deficiency had an Fe content of 50.3 mg kg^{-1} in the shoots and 553.6 mg kg^{-1} in the roots. According to Panagiotopoulos (2001) and Therios (2009), Fe concentrations ranging from 50 to 150 mg kg^{-1} are considered optimal for olive tree mineral nutrition, while values between 20 mg kg^{-1} and 50 mg kg^{-1} are considered relatively deficient.

Based on the Mn content of the shoots, the values for the Fe, Ca, and B omission treatments were statistically superior. In the root system, the highest values of Mn contents were found in the complete treatment and in plants grown under the Fe omission treatment. The lowest Mn contents in the roots were observed in plants grown under Fe (61.8 mg kg^{-1}) and B (80.3 mg kg^{-1}) omissions; the lowest Mn contents in the shoots were observed in plants grown under the N omission treatment (43.4 mg kg^{-1}). According to Panagiotopoulos (2001), when the Mn concentration of mature leaves is less than 20 mg kg^{-1}, olive trees suffer from mild Mn deficiency symptoms, and olive trees suffer from severe Mn deficiency only when the Mn concentration is lower than 5 mg kg^{-1}.

Finally, the Zn contents in the shoots and roots were higher in plants treated with the Fe omission. The interactions between Fe and Zn are commonly cited in the literature and often contradictory, and they may be synergistic or antagonistic (Kabata-Pendias, 2011). The contents of Zn in plants grown under the Zn omission treatment were 13.2 mg kg^{-1} in the shoots and 24.3 mg kg^{-1} in the roots. These results were also observed by Chatzistathis et al. (2010), and the lowest Zn concentrations did not drop below 10 mg kg^{-1}, which is, according to Panagiotopoulos (2001), the critical concentration for Zn deficiency in olive plants.

The nutritional content of olive plants grown under nutritional omission conditions demonstrated the following decreasing order in the shoots: N>K>Ca>P>S>Mg (macronutrients) and Fe>Mn>B>Zn>Cu (micronutrients); and in the roots: N>K>Ca>P>Mg>S (macronutrients) and Fe>Mn>B>Zn>Cu (micronutrients).

Conclusion

Among all the nutrients studied, the omissions of B, Ca, and N limited the growth of olive plants, resulting in lower biomass production.

Based on dry matter production, the following nutritional requirements were presented by olive seedlings, in descending order of importance: B>N>Ca>P>Fe>K>Mg>Zn>S.

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