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Nutrition, yield and nutrient export in common bean under zinc fertilization in no-till system

Nutrição, produção e exportação de nutrientes em feijoeiro-comum sob fertilização de zinco em sistema de plantio direto

Wagner Deckij Kachinski[1], Fabrício William Ávila[2*], Marcelo Marques Lopes Muller[3], André Rodrigues dos Reis[4], Leandro Rampim[3], Julio Cezar Borecki Vidigal[1]

[1]Universidade Estadual do Centro-Oeste/UNICENTRO, Guarapuava, PR, Brasil
[2]Universidade Estadual do Centro-Oeste/UNICENTRO, Departamento de Engenharia Florestal, Irati, PR, Brasil
[3]Universidade Estadual do Centro-Oeste/UNICENTRO, Departamento de Agronomia, Guarapuava, PR, Brasil
[4]Universidade Estadual de São Paulo/UNESP, Departamento de Engenharia de Biossistemas, Tupã, SP, Brasil
[*]Corresponding author: fwavila@unicentro.br
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ABSTRACT

Zinc (Zn) is one of the most deficient plant micronutrients in agricultural crops. The objective of this study was to evaluate plant nutrition, grain yield and nutrient export rate in response to soil and foliar Zn fertilization in common bean (*Phaseolus vulgaris* L.). Two field experiments in no-till system were carried out using two common bean cultivars, BRS Esteio (black bean) and IPR Campos Gerais (Carioca bean). Treatments were composed of soil Zn application during sowing and foliar Zn spray at flowering stage. Soil Zn application had effect on leaf Zn concentration in IPR Campos Gerais and did not affect grain yield of both cultivars. Foliar Zn spray increased leaf Zn concentration by approximately two times in both cultivars, but negatively affected the grain yield in BRS Esteio. Leaf concentration of N, Ca and S were affected by soil Zn application and leaf concentration of Mn was affected by foliar Zn spray, while leaf concentration of P, K, Mg, Cu and Fe were not influenced by the soil and foliar Zn treatments. In treatments without Zn, the descending order of nutrient export rate from the experimental site was as follows: N > K > P > Ca ≈ S > Mg for macronutrients and Fe > Mn > Cu > Zn for micronutrients. Foliar Zn spray increased the export rate of Zn, P, Ca, Mg, S, Mn, Cu and Fe in IPR Campos Gerais, while soil Zn application resulted in higher export rate of P, K and Mn in BRS Esteio.

Index terms: *Phaseolus vulgaris*; tropical soil; micronutrient; grain yield.

RESUMO

O zinco (Zn) é um dos micronutrientes mais deficientes em solos agrícolas no Brasil. Objetivou-se nesse estudo avaliar a nutrição, produção de grãos e exportação de nutrientes em função da fertilização de Zn em feijoeiro-comum (*Phaseolus vulgaris* L.) cultivado sob sistema de plantio direto. Dois experimentos de campo foram conduzidos usando a cultivar IPR Campos Gerais (feijão carioca) e a cultivar BRS Esteio (feijão preto). Os tratamentos foram compostos pela aplicação de Zn no solo durante a semeadura e pela pulverização foliar de Zn no estádio fenológico de florescimento. A aplicação de Zn no solo teve efeito sobre o teor foliar de Zn da IPR Campos Gerais, mas não afetou a produtividade de grãos. Entretanto, a pulverização foliar de Zn elevou consideravelmente o teor foliar de Zn, resultando em aumento e redução na produtividade de grãos da IPR Campos Gerais e BRS Esteio, respectivamente. Os teores foliares de N, Ca, S e Mn foram afetados pela aplicação de Zn no solo e/ou foliar, enquanto que os teores foliares de P, K, Mg, Cu e Fe não foram influenciados pelos tratamentos. Considerando os tratamentos que não receberam Zn, as exportações de nutrientes obedeceram à ordem para os macronutrientes N > K > P > Ca ≈ S > Mg e à ordem para os micronutrientes Fe > Mn > Cu > Zn. A pulverização foliar de Zn elevou as exportações de Zn, P, Ca, Mg, S, Mn, Cu e Fe na IPR Campos Gerais, enquanto que a aplicação de Zn no solo resultou em maior exportação de P, K e Mn na BRS Esteio.

Termos para indexação: *Phaseolus vulgaris*; solo tropical; micronutriente; produtividade de grãos.

INTRODUCTION

As for animals and humans, zinc (Zn) is a micronutrient for plants. However, it is estimated that about 50% of the soils used for grain production worldwide are deficient in plant-available Zn (Moreira; Moraes; Reis, 2018; Ram et al., 2016). Part of the soil total Zn (30 to 60%) may be as plant-unavailable forms, trapped in organic matter or adsorbed on mineral colloids (Alonso et al., 2006). In Brazil, Zn is the most deficient plant micronutrient in soils under natural conditions, especially in the Cerrado region (Lopes; Guilherme, 2016).

Soil Zn availability to plants is affected by several factors, including soil texture, soil organic C content, soil solution pH, soil temperature, soil moisture, soil clay mineralogy, root system anatomy, rhizosphere effect, fertilizer types used, accompanying ion of the source of Zn used and contaminants that may be found in the fertilizers (Han et al., 2011).

Zn plays an essential role in plant metabolism such as gene regulation and expression, protein synthesis, carbohydrate metabolism, photosynthesis, phytohormone action, seed production and defense against plant disease (Marschner, 2012; Rehman et al., 2018). Zn acts on activity of various enzymes including RNA polymerase, carbonic anhydrase, alcohol dehydrogenase, glutamate dehydrogenase and superoxide dismutase (Cu/Zn-SOD) (Moreira; Moraes; Reis, 2018). The decreased photosynthetic activity of Zn-deficient plants may be due to inhibition of carbonic anhydrase activity, decreased chlorophyll content and changes in chloroplast structure. Consequently, soils with low Zn availability exhibit lower yield potential and negatively affect the nutritional quality of the harvested grain (Sadeghzadeh, 2013).

Common beans represent more than half of the leguminous foods consumed worldwide. Grains of common bean are a major source of proteins, energy and nutrients for the low-income population, particularly in Africa and Latin America (Blair et al., 2010; Blair, 2013; Broughton et al., 2003; Welch et al., 2000). Different commercial groups of common beans (*Phaseolus vulgaris* L.) are grown, such as carioca bean, black bean, purple bean, pink beans, and other colored beans (Pereira et al., 2012). In Brazil, carioca and black beans are preferred by consumers, representing approximately 70 and 20%, respectively, of the total of common beans consumed (Del Peloso; Melo, 2005; MAPA, 2008).

Currently, most grain crops in Brazil are managed under a no-tillage system. Unlike conventional tillage systems, soil mobilization in a no-tillage system is limited and limestone is applied to the soil surface without incorporation into the soil, changing the dynamics of acidity, organic matter and nutrient availability in both superficial and subsurface layers of soil (Fonseca; Caires; Barth, 2010; Vieira et al., 2016).

The micronutrient requirements for optimal growth of agricultural plants have been increasing due to higher yields associated with intensification of crop cultivation in agricultural soils, as well as the use of more concentrated NPK fertilizers, with low percentage of other nutrients such as Zn. Still, there are few field studies involving Zn nutrition in common bean plants, especially in Brazil. Zn application in common bean plants under a no-tillage system may result in higher grain yield.

In farming system, it is very important to know about the both crop nutritional requirements and nutrient export rates to adequately replenish soil nutrients. The grain removal is the main factor responsible for the nutrient export in common bean crops under a no-tillage system. Nonetheless, little is known about the nutrient exports in recent common bean cultivars with genetic potential for high grain yield.

The aim of this study was to evaluate nutrition, grain yield and nutrient export in response to soil and foliar Zn fertilization in two popular common bean cultivars widely cultivated in southern Brazil.

MATERIAL AND METHODS

Field experiments

The study was carried out at the experimental area of the Department of Agronomy, State University of Midwest (UNICENTRO), located in the municipality of Guarapuava, Paraná State (PR), Brazil, at 25°23'2" latitude South and 51°29'43" longitude West at an altitude of 1026 m. According to Köppen-Geiger Climate Classification the climate of this region is Cfb, with mild summer and frequent frosts during the winter. The average air temperatures in coldest month are below 18 ºC and those in hottest month are below 22 °C, with no defined dry season.

The experiment was carried out between December 18th, 2017 and April 5th, 2018 under a no-tillage system. Average weekly rainfall and air temperature data were recorded from a Meteorological Station of the Paraná Agronomic Institute Network, located 50 m from the experimental site (Figure 1). It was observed that the rainfall and air temperature conditions were adequate for the two common bean cultivars studied.

Experimental area has been cultivated in a no-tillage system for ten consecutive years. The last crop rotation was common bean (summer), followed by wheat (*Triticum aestivum* L.) (winter).

Experimental site soil was described as a very clayey Typic Hapludox (Soil Survey Staff, 2014), or Latossolo Bruno Distrófico according to Brazilian Soil Classification System (Santos et al., 2018). Before the installation of the experiments, soil samples were collected in the 0-20 cm depth layer in order to analyze the chemical characteristics (Table 1). The chemical analyzes were determined according to the official methodology for the Paraná State, Brazil (EMBRAPA, 2009; Pavan et al., 1992). The phosphorus (P) and micronutrients (Fe, Mn, Cu and Zn) were extracted by Mehlich-1 and $S\text{-}SO_4^{2-}$ by 0.01 mol L^{-1} calcium phosphate (Cantarella; Prochnow, 2001). Liming was done aiming to increase soil base saturation to 70% and to adjust Ca/Mg ratio to 4/1.

On December 18th, 2017, two field experiments with common bean (*Phaseolus vulgaris* L.) were installed and conducted simultaneously at the experimental site. An experiment was conducted with the common bean cultivar BRS Esteio, belonging to the black bean group, and another experiment with the common bean cultivar IPR Campos Gerais, belonging to the Carioca bean group, both cultivars having an average cycle of 88 days (EMBRAPA, 2012; IAPAR, 2019). Both experiments received the same treatments (Figure 2).

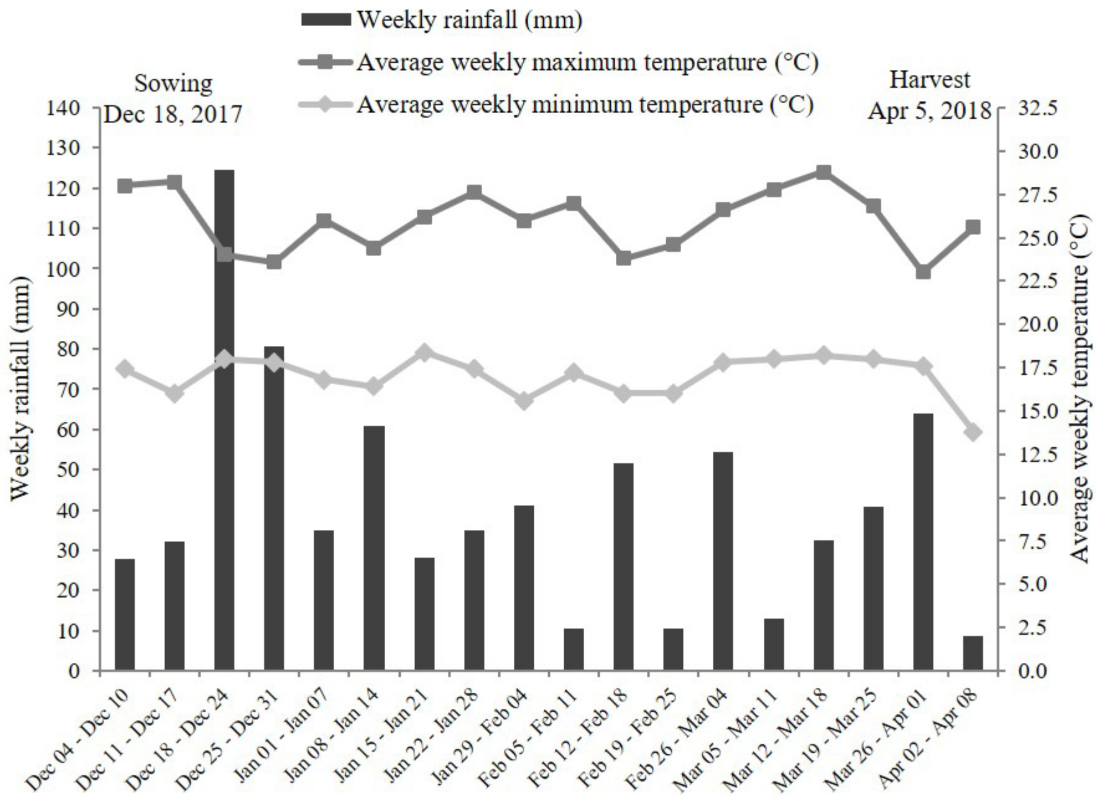

Figure 1: Weekly rainfall (mm) and air temperature (ºC) average recorded onsite during the experimental period (December 18th, 2017 to April 5th, 2018).

Table 1: Results of soil chemical analysis in the 0-20 cm layer at the experimental site prior the experiment.

pH	P (Mehlich-1)	$S\text{-}SO_4^{2-}$	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al
-----$CaCl_2$-----	-----------mg dm^{-3}---------		---------------cmol$_c$ dm^{-3}---------------				
5.06	5.85	8.46	0.50	4.41	1.30	0.0	4.34
CEC (pH 7)*	Base saturation	Organic matter		Zn	Fe	Mn	Cu
---cmol$_c$ dm^{-3}---	-------%------	--------g kg^{-1}--------		-------------mg dm^{-3}-------------			
10.25	57.6	41.03		9.86	68.79	74.44	2.46

*CEC pH 7.0: Cation exchange capacity at pH 7.0.

Figure 2: Photograph showing the two common bean cultivars at the experimental site in a no-tillage system.

The spacing between rows of 50 cm and 12 plants m^{-1} was used, resulting in a population of approximately 240000 plants ha^{-1}. Planting and top-dressing fertilization, and weed, pest and disease control were carried out according to technical recommendations for the common bean crop in the studied region (Guarapuava, Paraná State, Brazil).

Treatments and experimental design

In each experiment, a randomized complete block design was used with four replicates per treatment in a split-plot design. Each plot was composed of two treatments of Zn via soil (without and with 4 kg ha^{-1} of Zn applied in planting fertilization) and the subplots composed of two treatments of Zn via foliar (without and with foliar spray of 600 g ha^{-1} of Zn). Each experimental subplot was constituted of four plant rows with 5 m of length.

At planting, soil Zn treatments were applied into the sowing furrow (December 18th, 2017), using 400 kg ha^{-1} of either standard fertilizer (NPK, 12:27:06) or Zn-containing fertilizer (NPK, 12:27:06 + 1% Zn). Both fertilizers were purchased from the company *Yara Brasil Fertilizantes* S/A, around the same time.

When the plants were at flowering stage (phenological stage R6), foliar Zn treatments (prepared from pa grade $ZnSO_4.7H_2O$, Merck) was applied using a costal spray calibrated to deliver 160 L ha^{-1} spray solution. The crop phenological stage was determined according to the scale proposed by the International Center of Tropical Agriculture (CIAT) as described in Fernández, Gepts and López Genes (1986).

In order to evaluate the effect of the treatments on the nutritional state of the plants, after 10 days of foliar Zn spraying (with the plants initiating R7 phenological stage), the leaves were collected, taking the third leaf completely expanded from top to down (EMBRAPA, 2009), in about 30 plants of the useful area of each subplot, for subsequent determination of the leaf nutrient concentration.

Evaluation of grain yield, first pod insertion height and nutrient concentration in leaves and grains

The first pod insertion height was evaluated by measuring the distance between the plant collar and the first pod insertion in 10 plants randomly selected in each subplot. After physiological maturation (phenological stage R9), common bean grains were harvested from the three plant rows in each experimental subplot. The grain yield was estimated in kg ha^{-1} with grain moisture content adjusted to 13%.

In Laboratory of Soil and Plant Nutrition of the Department of Agronomy of the State University of Midwest (UNICENTRO), samples of plant material (both leaves harvested at flowering stage and grains) were dried in an oven with forced air circulation (58-60 °C) until reaching a constant weight. The dried plant material was ground in Wiley mill and stored until analysis.

Nutrient concentration in extracts obtained after the sulfuric (for N analysis) and nitric-perchloric acid digestions (for P, K, Ca, Mg, S, Fe, Mn, Cu and Zn analyses) were determined according to EMBRAPA (2009).

Data for grain nutrient concentration were related to data of grain yield, and nutrient export rate from the experimental site was estimated (in kg ha^{-1} for macronutrients and g ha^{-1} for micronutrients).

Statistical analysis of data

The data normality test (Shapiro-Wilk's test, $p \leq 0.05$) was performed using the R software version 3.5.1. (R Development Core Team, 2020). Data were subjected to analysis of variance (ANOVA, $p \leq 0.05$) according to split-plot design, using the SISVAR software (Ferreira, 2011). Plots were composed by the treatments of Zn via soil and subplots composed by the treatments of Zn via foliar.

RESULTS AND DISCUSSION

Grain yield and first pod insertion height

Grain yield in both common bean cultivars was significantly affected by the foliar Zn treatments ($p \leq 0.05$), but it was not affected by the soil Zn treatments ($p > 0.05$) (Figure 3).

Comparing the treatments without the foliar Zn application, average grain yield in both cultivars were similar, being 3399 and 3212 kg ha^{-1} for the cultivars BRS Esteio and IPR Campos Gerais, respectively. However, with the foliar Zn application (600 g ha^{-1} of Zn) at flowering stage, there were divergent effects on grain yield between both cultivars. For the cultivar BRS Esteio (Figure 2A), foliar Zn application resulted in a toxic effect, reducing grain yield from 3399 to 2643 kg ha^{-1}, while for the cultivar IPR Campos Gerais (Figure 2B) grain yield increased from 3212 to 3744 kg ha^{-1}. Thus, common bean plants exhibit genotype variation in grain yield response to fertilization with Zn via foliar spray at flowering period (phenological stage R6).

In soybean cultivated in soil from the Cerrado region of Brazil, Oliveira et al. (2017) observed that the application of Zn via soil (0, 3, 6, 9 and 12 kg ha^{-1} of Zn) during phenological stage V9 (eighth fully developed trifoliate leaf) linearly increased leaf Zn concentration, thousand grain mass and grain yield.

The first pod insertion height in cultivar BRS Esteio was significantly affected by the soil Zn treatments ($p \leq 0.01$) and foliar Zn treatments ($p \leq 0.001$) (Figure 4). For the cultivar IPR Campos Gerais there was no significant effect of the treatments ($p > 0.05$) on the first pod insertion height with an average value of 8.4 cm. Thus, Zn fertilization effects on first pod insertion height in common bean crop were influenced by the genotype.

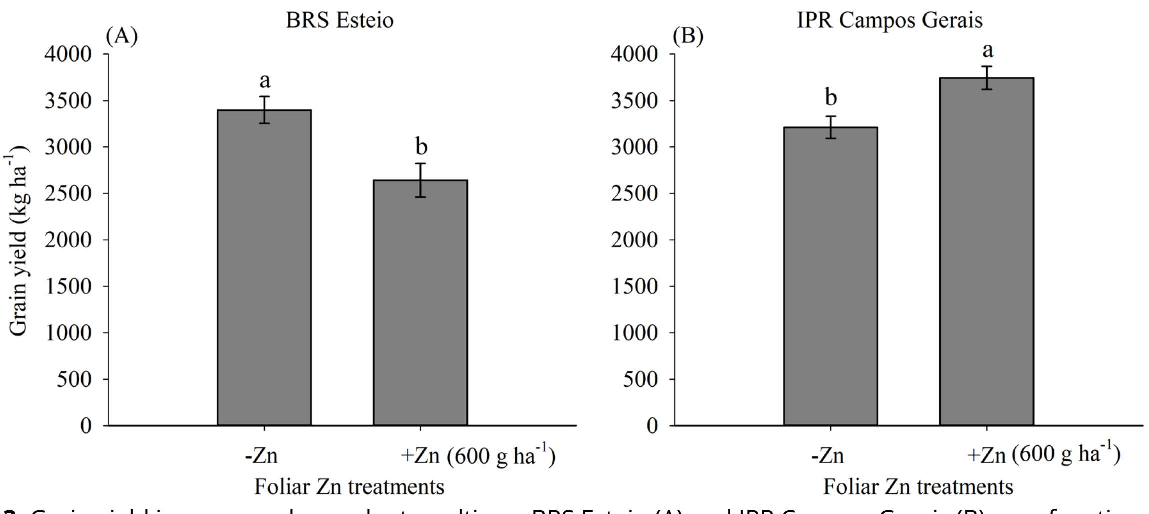

Figure 3: Grain yield in common bean plants, cultivars BRS Esteio (A) and IPR Campos Gerais (B), as a function of the foliar Zn treatments. Means followed by different letter denote significant differences (t test, $p \leq 0.05$). Error bars indicate standard error of the mean (SEM).

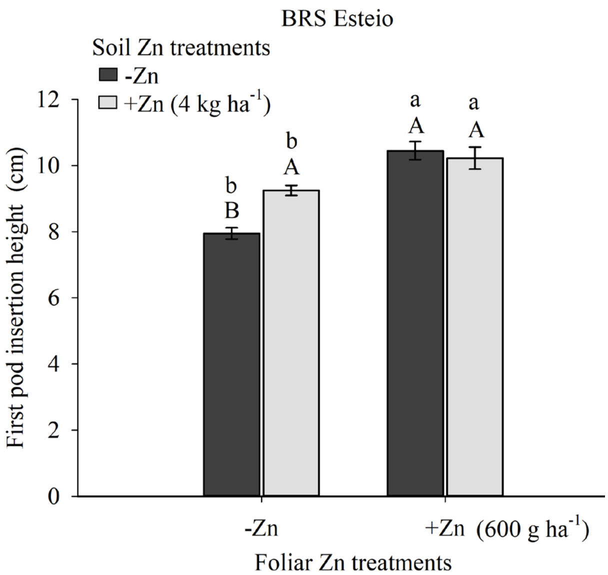

Figure 4: First pod insertion height in common bean cultivar BRS Esteio, as a function of the soil and foliar Zn treatments. Means followed by different letter, lower case letter (comparing foliar Zn treatments within each soil Zn treatment) and upper case letter (comparing soil Zn treatments within each foliar Zn treatment), denote significant differences (t test, $p \leq 0.05$). Error bars indicate standard error of the mean (SEM).

Without soil Zn application, foliar Zn spraying in cultivar BRS Esteio at flowering stage elevated the first pod insertion height from 8.0 to 10.5 cm (increase of 31.2%), and with soil Zn application, the change was from 9.3 to 10.2 cm (increase of 9.7%). Thus, the effect of foliar Zn spraying on the increase of the first pod insertion height of this cultivar was increased without soil Zn application. However, it is interesting to note a decrease in grain yield of cultivar BRS Esteio due to a possible abortion of flowers/pods occurred in the lower third ('bottom') of the plants, consequently altering first pod insertion height.

Soil Zn application had significant effect on the first pod insertion height in cultivar BRS Esteio, but to a lesser extent than that observed with the foliar Zn spray. Without foliar Zn spraying, soil Zn application resulted in a 16.2% increase in first pod insertion height, but with foliar Zn spraying there was no significant effect of soil Zn application.

In mechanized systems of bean harvesting, it is important to note that the first pod insertion height recommended for mechanical harvesting in Brazil is at least 9.3 cm (Silva; Abreu; Ramalho, 2009). Oliveira et al. (2018) did not find a significant increase of first pod insertion height with soybean Zn fertilization, only variations between different cultivars were observed.

Nutrient concentration in leaves

In this work, effects of soil and foliar Zn treatments on the nutritional state of the common bean was verified by analyzing the nutrient concentration in leaves collected from plants during full flowering stage, at initial phenological stage R7 (Fernández; Gepts; López Genes, 1986), after 10 days of exposition to foliar Zn spraying.

Leaf Zn concentration in both common bean cultivars were significantly affected by foliar Zn treatments ($p \leq 0.001$). However, soil Zn treatments significantly affected only the leaf Zn concentration of the cultivar IPR Campos Gerais ($p \leq 0.05$) (Figure 5).

The application of 600 g ha^{-1} of Zn via foliar during the flowering stage increased the leaf Zn concentration in the magnitude of 180.5 and 209.9% in cultivars BRS Esteio (Figure 5A) and IPR Campos Gerais (Figure 5B), respectively.

It is noteworthy that the increase of Zn concentration in the leaves during the flowering stage resulted in a toxic effect to the cultivar BRS Esteio, reducing grain yield (Figure 3A). On the other hand, for the cultivar IPR Campos Gerais, a small increase in grain yield was observed (Figure 3B) with increasing leaf Zn concentration, showing that during flowering stage there is a genotypic variation for an adequate leaf Zn concentration in common bean plants.

Adequate leaf Zn concentration for common bean growth at the Paraná State of the Brazil ranges from 26 to 60 mg kg^{-1} (NEPAR-SBCS, 2017). In this study, leaf Zn concentration (20.5 and 19.1 mg kg^{-1} in BRS Esteio and IPR Campos Gerais, respectively) were lower than reference limit, even experimental area soil having high Zn level available under natural conditions (9.86 mg dm^{-3}, Table 1). However, with foliar spray of Zn at flowering stage, the mean leaf Zn concentration was close to the upper reference limit (57.2 and 59.2 mg kg^{-1} in BRS Esteio and IPR Campos Gerais, respectively). This response occurs due to effect of genetic regulation on Zn uptake and translocation in plants (Moreira; Moraes; Reis, 2018).

Soil Zn application had little effect on leaf Zn concentration of the common bean plants, being significant only in treatments without foliar Zn application for the cultivar IPR Campos Gerais. The low effect of soil Zn application on both grain yield and leaf Zn concentration in common bean cultivars, even the micronutrient being supplied in the sowing furrow, may be due to soil characteristic of the experimental site, which is composed of a very clayey Typic Hapludox with high level of organic matter, managed in a no-tillage system.

Increased leaf Zn concentration in common bean plants after Zn supply via foliar was also found by other authors (Oliveira Junior et al., 1995; Teixeira et al., 2003; 2008). Corroborating our study, Teixeira et al. (2008) found that foliar Zn application at dose of 800 g ha^{-1}, regardless of Zn sources used, increased leaf Zn concentration in common bean plants. In addition, phosphorus fertilization carried out in the sowing furrow (about 108 kg ha^{-1} of P_2O_5) may exert negative effects on uptake, translocation and use of Zn by plants (Alonso et al., 2006; Behera et al., 2011; Hafeez; Khanif; Saleem, 2013; Zhao; Selim, 2010;). Table 1 shows that soil available Zn concentration (9.86 mg dm^{-3}) of the experimental site before the experiment implantation is considered as high by the Manual of Fertilization and Liming for the Paraná State of the Brazil (NEPAR-SBCS, 2017).

Table 2 shows the effect of treatments studied on leaf concentrations of nutrients in both common bean cultivars (except for leaf Zn concentration which was already discussed). It was observed that common bean plants did not present visual symptoms of deficiency in any nutrient. Based on standard reference values for leaf concentrations of macronutrients (g kg^{-1}: N = 30-40, P = 3.5-8.0, K = 28-35, Ca = 15-30, Mg = 3-6; S = 2-5) and micronutrients (in mg kg^{-1}: Mn = 50-120, Cu = 8-20, and Fe = 250-500) for adequate common bean growth in the study region (NEPAR-SBCS, 2017), in general, the leaf concentrations found for N, K and S are above the standard reference values, for P, Ca, Mn and Cu are within the standard reference values, and Mg and Fe are below the standard reference values.

Leaf N concentration in cultivar IPR Campos Gerais was influenced by the interaction both independent variables (soil Zn treatments × foliar Zn treatments). Without foliar Zn spraying, leaf N concentration was reduced by 11% with the soil Zn application, however, this effect was not statistically significant in treatments with foliar Zn spray. Perez et al. (2013) observed that N fertilization in pre-sowing decreased grain Zn concentration of common bean plants, showing that there is interaction between N and Zn.

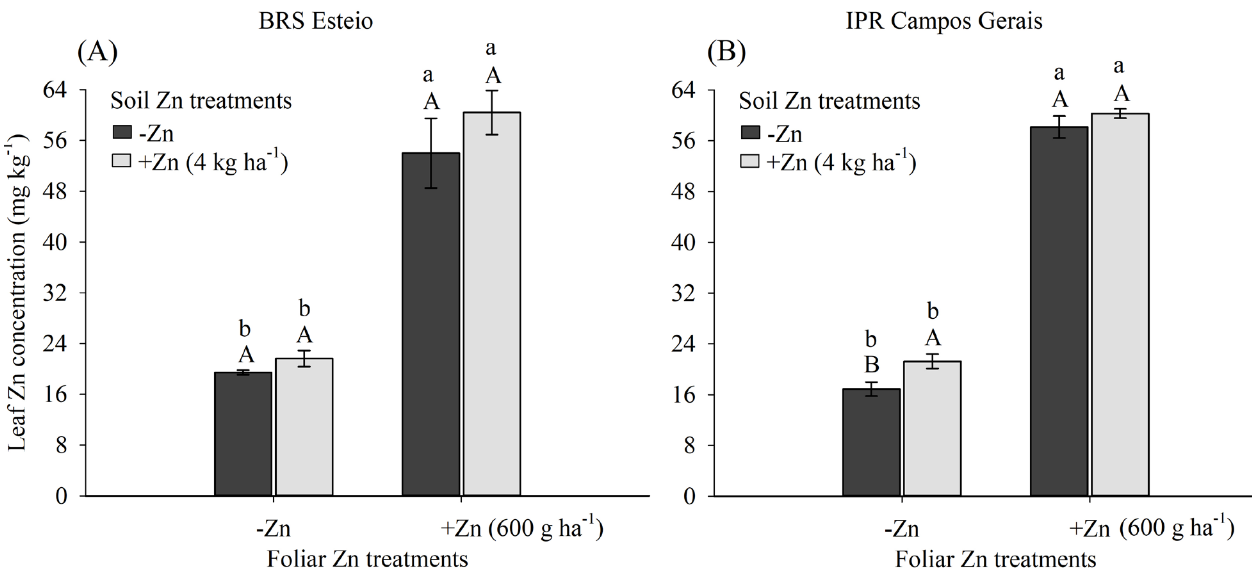

Figure 5: Leaf Zn concentration (3rd leaf with petiole from the middle third of the plants, collected 10 days after application of foliar Zn treatments) in common bean plants, cultivars BRS Esteio (A) and IPR Campos Gerais (B), as a function of soil and foliar Zn treatments. Means followed by different letter, lower case letter (comparing foliar Zn treatments within each soil Zn treatment) and upper case letter (comparing soil Zn treatments within each foliar Zn treatment), denote significant differences (t test, $p \leq 0.05$). Error bars indicate standard error of the mean (SEM).

Table 2: Leaf nutrient concentrations (3rd leaf with petiole from the middle third of the plants, collected 10 days after application of foliar Zn treatments) in common bean, cultivars BRS Esteio and IPR Campos Gerais, as a function of soil and foliar Zn treatments.

Macronutrient	Soil Treatments	Cultivar BRS Esteio			Cultivar IPR Campos Gerais		
		Foliar treatments			Foliar treatments		
		-Zn	+Zn	Mean	-Zn	+Zn	Mean
		------------------g kg^{-1}----------------			------------------g kg^{-1}----------------		
N	-Zn	81.3	75.1	78.2	90.0 aA	86.3 aA	88.2 a
	+Zn	84.2	83.2	83.7	79.4 bB	84.4 aA	81.9 b
	Mean	82.8	79.2		84.7	85.4	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)** / (Foliar)$^{n.s.}$ / (Soil×Foliar)**		
P	-Zn	5.75	5.25	5.50	5.44	5.28	5.36
	+Zn	5.28	5.04	5.16	5.98	5.61	5.79
	Mean	5.52	5.15		5.71	5.44	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
K	-Zn	40.9	41.7	41.3	35.5	36.0	35.7
	+Zn	39.0	44.4	41.7	35.2	35.3	35.3
	Mean	40.0	43.0		35.3	35.6	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
Ca	-Zn	29.4	28.8	29.1 a	23.8	27.2	25.5
	+Zn	25.1	26.6	25.9 b	26.9	27.9	27.4
	Mean	27.2	27.7		25.3	27.5	
		(Soil)* / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
Mg	-Zn	2.56	2.49	2.53	2.59	2.64	2.61
	+Zn	2.60	2.60	2.60	2.56	2.57	2.56
	Mean	2.58	2.54		2.58	2.60	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
S	-Zn	15.8	15.0	15.4 a	6.3	7.3	6.8 b
	+Zn	9.2	10.8	10.0 b	15.0	13.2	14.1 a
	Mean	12.5	12.9		10.6	10.2	
		(Soil)** / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)** / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
Micronutrient							
		-----------------mg kg^{-1}---------------			----------------mg kg^{-1}----------------		
Mn	-Zn	56.6	67.7	62.2	50.1	46.6	48.3
	+Zn	47.4	78.5	63.0	49.3	37.2	43.3
	Mean	52.0 B	73.1 A		49.7	41.9	
		(Soil)$^{n.s.}$ / (Foliar)* / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
Cu	-Zn	12.3	11.8	12.0	12.3	12.0	12.1
	+Zn	12.7	12.1	12.4	11.7	11.1	11.4
	Mean	12.5	11.9		12.0	11.5	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		

Continue...

Table 2: Continuation.

Fe	-Zn	139.8	114.3	127.0	137.0	143.1	140.01
	+Zn	126.0	124.3	125.2	133.6	136.1	134.9
	Mean	132.9	119.3		135.3	139.61	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		

**, * and ns = $p \leq 0.01$, $p \leq 0.05$ and $p > 0.05$, respectively, by the F-test. Means followed by different letter, lowercase in column and upper case in line, are significantly different from each other (t test, $p \leq 0.05$).

Leaf Ca concentration of cultivar BR Esteio decreased in 12.4% with soil Zn application but was not affected by the foliar Zn treatments. However, leaf S concentration was reduced by 35.1% in cultivar BRS Esteio and was increased by 107.3% in cultivar IPR Campos Gerais with soil Zn supply, showing a divergent effect between cultivars. Leaf Mn concentration in BRS Esteio cultivar was increased by 40.6% with foliar Zn application. Leaf concentrations of P, K, Mg, Cu and Fe of both common bean cultivars were not significantly influenced by soil and foliar Zn treatments. Compared to other studies, Teixeira et al. (2003) observed that foliar spraying of Zn and Mn increased leaf concentrations of N, K, Ca, Mg, S, B, Cu and Fe in common bean plants.

Nutrient export rate

The knowledge about the amount of nutrients exported from the agricultural area with the harvesting of agricultural products has been of great relevance for soil fertility maintenance and replenishment, aiming only the restitution of nutrients lost. In this work, it was observed that average grain yield was 3000 and 3500 kg ha^{-1} for cultivar BRS Esteio e IPR Campos Gerais, respectively (Figure 3), which provided high nutrient exports.

The Zn export rate from the experimental site with grain harvest was considered statistically significant only for foliar Zn treatments on the cultivar IPR Campos Gerais ($p \leq 0.05$) (Figure 6).

Foliar Zn spraying in cultivar IPR Campos Gerais increased grain yield (Figure 3B), leaf Zn concentration (Figure 5B) and, consequently, increasing Zn export rate from 26.5 to 30.6 g ha^{-1} (Figure 6), an increase of 15.5%. In cultivar BRS Esteio there was no significant effect of the soil and foliar Zn treatments on Zn export rate, since, although the foliar Zn spray increased the leaf Zn concentration (Figure 5A), there was a decrease of grain yield (Figure 3A), which was determinant so that it did not result in a significant change in Zn export rate of the experimental site. According to our results, Moreira, Moraes and Fageria (2015) found that Zn concentration in the soil, photosynthesis rate and Zn concentration in the plant tissue were correlated with the shoot dry weight in alfalfa grown in pots under greenhouse conditions.

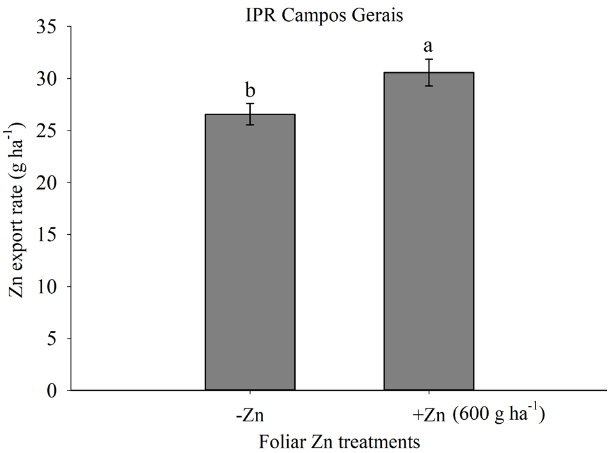

Figure 6: Zn export rate from the experimental site (after harvesting of the grains) cultivated with common bean, cultivar IPR Campos Gerais, as a function of the foliar Zn treatments, in a no-tillage system. Means followed by different letter denote significant differences (t test, $p \leq 0.05$). Error bars indicate standard error of the mean (SEM).

Barbosa Filho and Silva (2000) reported average export of 25 g ha^{-1} Zn in a common bean crop area with an average grain yield of 2500 kg ha^{-1}, presenting values close to those found in our study. On the other hand, Fernandes, Soratto and Santos (2013) found much higher amount of Zn exported from the experimental area with the harvested grains, ranging from 40 to 96 g ha^{-1}.

Table 3 presents the nutrient export rate from the experimental site for both cultivars as a function of the soil and foliar Zn treatments (except for the Zn export rate which was already discussed).

Table 3: Nutrient export rate from the experimental site (after harvesting of the grains) cultivated with common bean, cultivars BRS Esteio and IPR Campos Gerais, in response to soil and foliar Zn treatments in a no-tillage system.

Macronutrient	Soil Treatments	Cultivar BRS Esteio			Cultivar IPR Campos Gerais		
		Foliar treatments			Foliar treatments		
		-Zn	+Zn	Mean	-Zn	+Zn	Mean
		----------------kg ha^{-1}----------------			----------------- kg ha^{-1}----------------		
N	-Zn	167.5	121.2	144.3	148.8	167.0	157.9
	+Zn	154.9	173.9	164.4	172.4	160.5	166.4
	Mean	161.2	147.5		160.6	163.7	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
P	-Zn	10.2	6.6	8.4 b	9.3	12.3	10.8
	+Zn	9.5	9.7	9.6 a	10.1	11.0	10.5
	Mean	9.9	8.2		9.7 B	11.6 A	
		(Soil)* / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)** / (Soil×Foliar)$^{n.s.}$		
K	-Zn	48.6	32.2	40.4 b	46.7	55.0	50.9 b
	+Zn	58.1	60.2	59.1 a	59.9	61.8	60.8 a
	Mean	53.3	46.2		53.3	58.4	
		(Soil)** / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)* / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$		
Ca	-Zn	7.7	6.5	7.1	7.4	9.2	8.3
	+Zn	7.7	7.2	7.5	6.2	8.6	7.4
	Mean	7.7	6.9		6.8 B	8.9 A	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)** / (Soil×Foliar)$^{n.s.}$		
Mg	-Zn	5.4	3.5	4.4	5.2	6.3	5.7
	+Zn	5.3	5.4	5.4	5.5	6.1	5.8
	Mean	5.3	4.5		5.3 B	6.2 A	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)* / (Soil×Foliar)$^{n.s.}$		
S	-Zn	6.8	4.7	5.7	8.2	12.0	10.1
	+Zn	5.3	6.5	5.9	8.5	10.8	9.7
	Mean	6.0	5.6		8.4 B	11.4 A	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)*** / (Soil×Foliar)$^{n.s.}$		
Micronutrient							
		-------------------g ha^{-1}---------------			------------------ g ha^{-1}----------------		
Mn	-Zn	60.2	81.0	70.6 b	79.2	108.2	93.7
	+Zn	101.9	111.5	106.7 a	92.5	111.8	102.1
	Mean	81.1	96.3		85.8 B	110.0 A	
		(Soil)*** / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)** / (Soil×Foliar)$^{n.s.}$		
Cu	-Zn	44.9	34.8	39.8	34.5	46.6	40.5
	+Zn	40.0	38.6	39.3	36.5	41.7	39.1
	Mean	42.5	36.7		35.5 B	44.2 A	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)* / (Soil×Foliar)$^{n.s.}$		

Continue...

Table 3: Continuation.

Fe	-Zn	252.4	252.4	252.4	181.2	229.0	205.1
	+Zn	235.3	235.3	235.3	193.2	221.0	207.1
	Mean	243.9	243.9	243.9	187.2 B	225.0 A	
		(Soil)$^{n.s.}$ / (Foliar)$^{n.s.}$ / (Soil×Foliar)$^{n.s.}$			(Soil)$^{n.s.}$ / (Foliar)* / (Soil×Foliar)$^{n.s.}$		

**, * and ^{ns} = $p \leq 0.01$, $p \leq 0.05$ and $p > 0.05$, respectively, by the F-test. Means followed by different letter, lowercase in column and upper case in line, are significantly different from each other (t test, $p \leq 0.05$).

The effect of soil and foliar Zn treatments on nutrients export rate from the experimental site was different between both common bean cultivars. In cultivar BRS Esteio there was no significant effect of soil and foliar treatments on export of N, Ca, Mg, S, Fe and Cu. However, soil Zn application increased the export of P, K and Mn by 14.3, 46.3 and 51.1%, respectively.

For cultivar IPR Campos Gerais, Zn foliar spraying resulted in increases of the order of 19.6, 30.9, 17.0, 35.7, 28.2, 24.5 and 20.2% in export of P, Ca, Mg, S, Mn, Cu and Fe, respectively. This increase in nutrient exports from the experimental site was due to the effect of foliar Zn spraying on grain yield (Figure 3B). Soil Zn application for this cultivar affected only the export of K, increasing the value by 19.4%.

Considering the treatments that did not receive soil Zn fertilization, the average nutrient exports from the experimental site in both cultivars follows the order for macronutrients N > K > P > Ca ≈ S > Mg while the order for micronutrients was Fe > Mn > Cu > Zn.

CONCLUSIONS

Soil and/or foliar Zn applications increased first pod insertion height of the BRS Esteio cultivar, but there was no effect on the cultivar IPR Campos Gerais. Foliar spray of 600 g ha^{-1} of Zn at flowering phenological stage increased leaf Zn concentration by approximately two times in both common bean cultivars, but negatively affected grain yield in cultivar BRS Esteio. Soil Zn application decreased leaf concentration of Ca and S in cultivar BRS Esteio, and reduced and increased leaf concentrations of N and S in cultivar IPR Campos Gerais, respectively. Leaf Mn concentration of cultivar BRS Esteio increased with foliar Zn application. Without soil and foliar Zn treatments, the average nutrient exports from the experiment site (after harvesting of the grains) in both cultivars follows the order for macronutrients N > K > P > Ca ≈ S > Mg while the order for micronutrients was Fe > Mn > Cu > Zn. Soil Zn application resulted in higher export of P, K and Mn for cultivar BRS Esteio and also higher export of K for cultivar IPR Campos Gerais. Foliar Zn spray increased export of Zn, P, Ca, Mg, S, Mn, Fe and Cu of cultivar IPR Campos Gerais.

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