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Efficiency of soluble and insoluble sources of manganese for soybean nutrition in the Brazilian Cerrado

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Abstract – The objective of this work was to evaluate the efficiency of sources and rates of soluble ($MnSO_4.H_2O$) and insoluble ($MnCO_3$) manganese on the processes of uptake, transport, and redistribution of this nutrient in soybean, as well as on crop yield, in Cerrado soil. The experimental design was randomized complete blocks in a 4×2 factorial arrangement – four rates (150, 250, 350, and 450 g ha^{-1}) × two sources ($MnSO_4.H_2O$ and $MnCO_3$) of Mn –, with four replicates. In the 2015/2016 and 2016/2017 crop seasons, foliar fertilizations were carried out on the third trifoliate leaflet, and Mn content and soybean yield were evaluated. In both crop seasons, Mn foliar fertilization increased the contents of the nutrient in leaves, stems, and grains, but did not affect grain yield and dry matter production. The maximum Mn contents in leaves were obtained with rates between 150 and 450 g ha^{-1}. The fertilization with $MnSO_4.H_2O$ increased Mn uptake, transport, and redistribution in the plant, with a performance superior to that of $MnCO_3$. Foliar fertilization with $MnSO_4.H_2O$ in soybean, in a Cerrado soil, increases Mn contents in the leaves but not yield and dry matter production.

Index terms: *Glycine max*, manganese carbonate, manganese sulfate, Mn contents.

Eficiência de fontes solúveis e insolúveis de magnésio para nutrição da soja no Cerrado brasileiro

Resumo – O objetivo deste trabalho foi avaliar a eficiência de fontes e doses de magnésio solúvel ($MnSO_4.H_2O$) e insolúvel ($MnCO_3$) nos processos de absorção, transporte e redistribuição deste nutriente na soja (*Glycine max*), bem como na produtividade da cultura, em solo de Cerrado. O delineamento experimental foi em blocos ao acaso, em arranjo fatorial 4×2 – quatro doses (150, 250, 350 e 450 g ha^{-1}) × duas fontes ($MnSO_4.H_2O$ e $MnCO_3$) de Mn –, com quatro repetições. Nas safras de 2015/2016 e 2016/2017, realizaram-se adubações foliares no terceiro trifólio e avaliaram-se os conteúdos de Mn e a produtividade da soja. Em ambas as safras, a fertilização foliar com Mn aumentou os teores do nutriente nas folhas, nos caules e nos grãos, mas não afetou o rendimento de grãos e a produção de matéria seca. Os teores máximos de Mn nas folhas foram obtidos com doses entre 150 e 450 g ha^{-1}. A aplicação de $MnSO_4.H_2O$ aumentou a absorção, o transporte e a redistribuição de Mn na planta, com desempenho superior ao de $MnCO_3$. A fertilização foliar com $MnSO_4.H_2O$ em soja, em solo de Cerrado, aumenta os teores de Mn nas folhas, mas não a produtividade e a produção de matéria seca.

Termos para indexação: *Glycine max*, carbonato de manganês, sulfato de manganês, conteúdo de Mn.

Introduction

Soybean [*Glycine max* (L.) Merr.] occupies a prominent position in Brazilian agriculture. According to Conab (2022), soybean production was 138 million tons in the 2019/2020 harvest, covering an area of 39.2 million hectares. For the next harvests, there is a tendency of increasing soybean production in 0.8 to 3.0% in the planted area in Brazil (Projeções do agronegócio…, 2020).

Soybean production in the country is located mainly in the Cerrado, where soils are acid and show low levels of nutrients in natural conditions (Sousa & Rein, 2011). Therefore, these soils require applications of lime, gypsum, and fertilizers to achieve a mean yield of 3.525 kg ha^{-1} when associated with adequate climate conditions (Conab, 2022).

In soybean fields in the Cerrado, symptoms of Mn deficiency, such as interveinal chlorosis, are frequent due to the low Mn content in soil parent material and the higher pH values where lime is applied (Moreira et al., 2003). Mn deficiency can also be caused by the application of glyphosate to plants since the immobilization of bivalent cations (Fe and Mn) affects negatively photosynthesis and chlorophyll content (Zobiole et al., 2010). Duke et al. (2012) found that, with applications of glyphosate, microorganisms increased Mn oxidation in the soil, affecting Mn availability to the plants. In Brazil, the application of glyphosate to glyphosate resistant soybean cultivars (RR), which represent 95% of the area sown in the country, is a common practice (Céleres, 2018). When evaluating RR soybean, Andrade & Rosolem (2011) did not report any negative effect of glyphosate on Mn absorption, accumulation, and distribution.

In agriculture, an alternative practice for the supply of Mn and recovery of plant symptoms due to nutrient deficiency is foliar application. When foliar applications are not performed, Mn absorption is exclusively dependent on plant roots and the availability of the nutrient in the soil (Pasković et al., 2018). Therefore, an advantage of that type of application is that nutrients are absorbed directly by the leaf, requiring low rates to supply an adequate nutritional balance and avoiding losses that normally occur via soil application (Cakmak et al., 2009). Several soil factors influence the absorption of Mn from the soil, such as pH, redox potential, and population of Mn-oxidizing bacteria (Fernández et al., 2015). Mn has a low phloem mobility with a limited redistribution in various plant species (Cakmak et al., 2009). In this regard, Li et al. (2017) showed that Mn redistribution was minimal in leaves of soybean, sunflower (*Helianthus annuus* L.), and tomato (*Solanum lycopersicum* L.). Conversely, Carrasco-Gil et al. (2016) concluded that manganese sulfate, as a Mn source, was redistributed to the leaves of untreated tomato, but was not transported to the roots.

The efficiency of foliar application, therefore, varies according to the used Mn sources (solubility), crop demand, and Mn availability in the soil during the phenological stage of the plant (Fernández et al., 2015). The main sources of Mn are sulfates, oxides, and Mn-chelate, which can be applied isolated or associated with granular N-P_2O_5-K_2O fertilizers (Fernández et al., 2015). Insoluble Mn sources, as manganese carbonate, have been presented as a possible alternative to improve soybean yield. However, there is little information about the ability of the plant to absorb and use nutrients from insoluble sources applied to its leaves, and the agronomic effectiveness of foliar sprayed Mn is still unknown.

The objective of this work was to evaluate the efficiency of sources and rates of soluble ($MnSO_4.H_2O$) and insoluble ($MnCO_3$) Mn on the processes of uptake, transport, and redistribution of this nutrient in soybean, as well as on crop yield, in Cerrado soil.

Materials and Methods

Field experiments were conducted in two soybean crop seasons (2015/2016 and 2016/2017), during October and March, in a farm of the group Agroeldorado Agricultura e Pecuária, located in the municipality of Uberlândia, in the state of Minas Gerais, Brazil (19º13'35"S, 47º58'36"W, at 986 m above sea level).

The climate of the region is classified as Cwa, tropical in altitude, with hot summers and rainy winters, showing a mean temperature from 24 to 27°C and an accumulated precipitation of 1,700 and 1,400 mm, respectively, in the 2015/2016 and 2016/2017 crop seasons (Figure 1).

The soil of the experimental area is classified as a Latossolo Vermelho-Amarelo distrófico típico, according to the Brazilian soil classification system (Santos et al., 2018), which corresponds to an Oxisol (Soil Survey Staff, 2014), with a clay texture.

In the first crop season, the Pioneer 98Y30 RR cultivar, classified as tolerant to glyphosate and the soybean cyst nematode, was sown in November 2015 using 9 seeds per meter, resulting in a population of 180 thousand plants per hectare. In the second crop season, cultivar Brasmax Flecha 6266 RSF IPRO was sown in October 2016 using 14 seeds per meter, resulting in a population of 280 thousand plants per hectare. The final population was of 157 and 238 thousand plants per hectare, respectively, for each season.

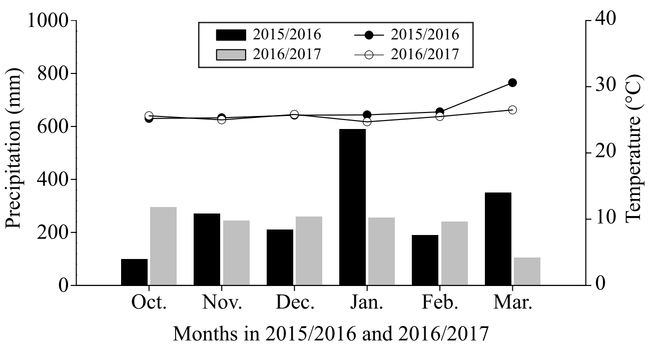

Figure 1. Precipitation and air temperature in the experimental area during the 2015/2016 and 2016/2017 soybean (*Glycine max*) crop seasons.

For soil chemical and physical characterization, before the installation of the trials in both crop seasons, a composite soil sample was taken in six positions in the field (Table 1), with 10 subsamples per position (totaling 60 subsamples), at depths from 0.0 to 0.4 m, at intervals of 0.2 m (Raij et al., 2001). In the 0.0–0.4 m layer, the soil was characterized as acidic, with a pH ranging from 5.0 to 5.5 and a low Mn level of < 1.0 mg dm^{-3} (Raij et al., 1996).

Historically, the study area has been cultivated with soybean and corn (*Zea mays* L.) for 15 years in a cropping rotation system, with soybean as the first crop and corn as the off-season crop. In the 2015/2016 crop season, before planting, fertilization was carried out to supply 14.5 kg ha^{-1} N, 70 kg ha^{-1} P_2O_5, 75 kg ha^{-1} K_2O, and 0.5 kg ha^{-1} B, using monoammonium phosphate (FertiGran P, Fertipar, Curitiba, PR, Brazil) and potassium chloride (MasterGranFertipar, Curitiba, PR, Brazil) in the 10-48-00 N-P_2O_5-K_2O + 0.2% B and 00-00-58 N-P_2O_5-K_2O + 0.2% B formulas, respectively. In the second crop season, 12.5 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, 90 kg ha^{-1} K_2O, and 0.56 kg ha^{-1} B were applied using the same fertilizers. Neither lime nor gypsum were required in either crop season according to the soil analysis (Table 1).

Table 1. Chemical and physical characterization of the soil of the experimental area in the 2015/2016 and 2016/2017 soybean (*Glycine max*) crop seasons[1].

					2015/2016 crop season					
Soil layer (m)	pH	OM	S	P	K	Ca	Mg	Al	H+Al	SB
	$CaCl_2$	(g dm^{-3})	---------(mg dm^{-3})---------		----------(mmol$_c$ dm^{-3})----------					
0.0–0.2	5.5	31.0	29.0	22.0	1.9	29.7	11.0	-	20.7	42.7
0.2–0.4	5.0	23.2	137.7	9.5	1.5	10.5	4.2	-	26.5	16.3
	B	Cu	Fe	Zn	Mn	Sand	Silt	Clay	CEC	V
	----------(mg dm^{-3})----------					---------(g kg^{-1})---------			(mmol$_c$ dm^{-3})	(%)
0.0–0.2	0.6	0.7	26.2	1.0	<0.5	196.0	90.2	713.5	63.4	66.5
0.2–0.4	0.5	0.5	21.2	0.5	<0.5	165.0	46.0	789.2	42.8	38.2
					2016/2017 crop season					
Soil layer (m)	pH	OM	S	P	K	Ca	Mg	Al	H+Al	SB
	$CaCl_2$	(g dm^{-3})	---------(mg dm^{-3})---------		----------(mmol$_c$ dm^{-3})----------					
0.0–0.2	5.1	31.7	19.5	37.7	2.5	34.7	11.5	<0.1	29.7	48.8
0.2–0.4	5.1	22.7	94.0	12.2	1.4	16.2	5.7	<0.1	29.5	23.4
	B	Cu	Fe	Zn	Mn	Sand	Silt	Clay	CEC	V
	----------(mg dm^{-3})----------					---------(g kg^{-1})---------			(mmol$_c$ dm^{-3})	(%)
0.0–0.2	0.6	1.2	37.0	2.3	1.0	214.7	66.0	719.0	78.5	62.2
0.2–0.4	0.4	0.8	26.5	0.6	0.5	181.2	41.5	777.2	52.9	44.0

[1]OM, organic matter; SB, sum of bases; CEC, cation exchange capacity; and V, base saturation.

The experimental design was a randomized complete block in a 4×2 factorial arrangement – four rates (150, 250, 350, and 450 g ha^{-1}) × two sources (manganese sulfate monohydrate, $MnSO_4.H_2O$; and manganese carbonate, $MnCO_3$) of Mn –, with four replicates in foliar application. A check plot was used as a control without Mn application. Each experimental unit consisted of ten rows, spaced at 0.5 m, with 15 m of length, totaling 75 m^2 per experimental plot.

The tested Mn rates were based on the official recommendation for soybean in the Brazilian Cerrado, which is of 350 g ha^{-1} via foliar application (Sfredo & Borkert, 2004). Both used sources are commercial products – $MnSO_4.H_2O$ is a soluble source with 30.9% Mn and 18.0% S (weight:weight), and $MnCO_3$ is an insoluble source (polymerized concentrated suspension) with 500 g L^{-1} Mn, 3.8% N, and a density of 1,827 g dm^{-3}.

The particle size of $MnCO_3$ was measured by the technique of dynamic light scattering, using the Zetasizer Nano ZS equipment (Malvern Panalytical Ltd, Malvern, UK) calibrated to operate with water as a dispersant at a viscosity of 0.8872 cP. The electric dispersion constant was 78.5, with a refractive index of 1.33 and an analysis time of 12 s. Particle shape was visualized by scanning electron microscopy, using the Magellan 400 L field emission scanning electron microscope (FEI Company, Hillsboro, OR, USA) operated with electron beam accelerating, with voltages between 2 and 5 kV.

The particle of $MnCO_3$ presented an average size of 340.6 nm, varying from 228.3 to 452.9 nm, with a Zeta potential value for suspension in water of -24.0±4.0 mV. This Mn source was classified by a low tendency of particle agglomeration but was not characterized as a nanoparticle because its size was greater than 100 nm (Servin et al., 2015).

In both crop seasons, the foliar application of Mn sources was performed in the V4 phenological stage (three unrolled trifoliate leaflets) using a CO_2 pressurized sprayer with a constant pressure of 2.0 kgf cm^{-2} and the XR Teejet 110.02 flat-fan spray nozzle (Teejet Technologies, Wheaton, IL, USA), calibrated to a volume of 250 L ha^{-1}, mounted to a spray bar at an average height of 0.5 m from the canopy of the crop. The environmental conditions at the time of application were considered adequate: relative humidity of 60 and 65%, wind speed of 5 and 10 km h^{-1}, and temperature of 28 and 27°C in the first and second crop seasons, respectively. No rainfall was recorded in the areas 24 hours after foliar application.

The management of pests, diseases, and weeds in the experimental area followed the recommendation for soybean in Brazil (Sfredo & Borkert, 2004). In the total area, in both crop seasons, glyphosate – N-(phosphonomethyl) glycine – was applied before treatments, at a rate of 1.5 kg ha^{-1}, using a self-propelled system.

Soybean yield was assessed through mechanized harvesting of all lines in the plots (useful area of 40 m^2) at the R8 growth stage (full maturity), at 134 and 117 days after emergence in the 2015/2016 and 2016/2017 harvests, respectively. The subsamples were taken to a laboratory, to determine the weight of 1,000 grains (g), considering a standard moisture of 13% (wet basis).

At the R7 growth stage, after the beginning of maturity, plant height, stem diameter, and number of stems, nodes, pods, and grains were measured using ten plants per plot from the two central lines. Plants were collected and separated into leaves, stems, pods, and grains to determine dry matter, which was obtained by drying at 65°C, for 72 hours, followed by weighing.

The third and fourth trifoliate leaflets were collected at 5 days after Mn application (ten plants per plot) in the V5 growth stage, in the two central lines, from plants that were marked before the application. Then, the third/fourth trifoliate leaflet (diagnostic leaf with petiole) was collected randomly at 25 days after Mn application in the R1/R2 growth stage, also in the two central lines (ten plants per plot). All leaves were washed with 3.0% HCl, following the general rules to determine foliar Mn content using the technique of fluorescence X-rays for dispersion of energy, with a collimator of 3.0 mm, air atmosphere without vacuum, a current of 155 µA, and an irradiation time of 200 s (Brasil, 2013).

Data were subjected to the analysis of variance, based on the F-test ($p<0.05$). When the F-test was significant, the effect of Mn rates was compared by the regression test ($p<0.05$) and that of Mn sources by Tukey's test ($p<0.05$). The statistical analysis was performed using the programming language in the R, version 4.0, software (R Core Team, 2019), and results were graphed in Sigmaplot, version 11 (Systat Software, Inc., San Jose, CA, USA).

Results and Discussion

In both crop seasons, soybean yield and weight of 1,000 grains were not affected by the foliar application of Mn rates and sources, showing a mean yield of 4,423.2±124.3 kg ha^{-1} and 166.6±42.6 g (both factorial averages), respectively (Table 2). A mean of 72.0 to 73.5 bags per hectare was harvested, with a correlation between soybean yield and weight of 1,000 grains ($r=0.43$; $p<0.0001$).

The dry matter of leaves, stems, pods, and grains were also not altered by Mn application, with an overall mean of 47.7±25.4, 102.3±24.6, 60.8±15.8, and 185.9±54.3 g, respectively, in both crop seasons. Consequently, total dry matter did not differ with Mn management, showing a total mean varying from 304.0 to 497.6 g (Table 2). Likewise, the foliar applications of Mn did not affect the number of stems, nodes, pods, and grains, as well plant height and stem diameter, which showed a general mean of 6.8±2.3, 18.4±3.5, 57.0±22.4, 134.4±47.5, 84.0±4.3 cm, and 7.2±0.9 mm, respectively (Table 3).

Soybean yield parameters were not altered by the application of Mn in both harvests. However, soybean yield was higher than the mean of 3,379 kg ha^{-1} for the last harvest in Brazil (Conab, 2022). Similarly, no effect of foliar Mn application on soybean yield and dry matter was observed in the works of Stefanello et al. (2011), who tested the rate of 332 g ha^{-1} in the V4, V8, and R2 stages in soils with 29.9 and 73.8 mg dm^{-3} Mn, and of Fenner et al. (2012), who analyzed rates from 350 to 1,050 g ha^{-1} in the V8 stage in soil with 6.0 mg dm^{-3} Mn. In contrast, Mann et al. (2002) reported a higher soybean yield with the foliar application of $MnSO_4$ at rates from 450 to 600 g ha^{-1} in soil with 3.4 mg dm^{-3} Mn. To increase fertilizer effectiveness, in recent years, there has been a growing interest in micronutrient nanoparticles (Kah et al.,

Table 2. Soybean (*Glycine max*) yield, weight of 1,000 grains (WTG), and dry mass of leaves (DML), stems (DMS), pods (DMP), and grains (DMG), as well as total dry mass (TDM), with the application of two manganese sources ($MnSO_4$ and $MnCO_3$) at four rates (0, 150, 250, 350, and 450 g ha^{-1}) in the 2015/2016 and 2016/2017 crop seasons(1).

Mn rate (g ha^{-1})	Yield (kg ha^{-1})		WTG (g)		DML (g)		DMS (g)		DMP (g)		DMG (g)		TDM (g)	
	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$
2015/2016 crop season														
0	4,407.6	4,407.6	133.1	133.1	24.9	24.9	118.3	118.3	72.1	72.1	227.7	227.7	443.2	443.2
150	4,312.9	4,364.0	128.4	131.5	27.6	22.6	132.7	135.2	79.9	78.9	246.9	260.7	487.3	497.6
250	4,233.2	4,208.8	131.3	125.9	26.1	26.0	105.2	113.4	69.5	71.8	207.9	217.2	408.9	428.6
350	4,360.6	4,308.7	131.0	127.3	30.3	25.8	133.3	125.9	77.1	80.8	240.2	248.6	480.9	481.3
450	4,431.5	4,319.0	127.3	128.2	26.0	22.9	112.7	131.0	67.3	72.8	205.0	235.0	411.2	461.9
Mean(2)	4,334.6	4,300.1	129.5	128.2	27.5	24.3	121.0	126.4	73.4	76.1	225.0	240.4	447.1	467.3
2016/2017 crop season														
0	4,603.6	4,603.6	209.5	209.5	75.7	75.7	76.2	76.2	44.8	44.8	128.3	128.3	325.2	325.2
150	4,646.0	4,561.9	211.6	210.6	70.4	80.3	77.0	73.3	46.0	42.9	134.7	123.1	333.6	313.6
250	4,521.3	4,565.6	211.1	219.3	72.4	75.5	72.4	81.8	40.4	45.9	120.7	131.5	304.0	339.6
350	4,469.4	4,402.8	210.7	209.3	75.0	78.0	75.2	77.1	43.4	44.1	126.8	129.7	318.0	326.6
450	4,590.3	4,507.6	213.4	216.8	73.4	77.0	76.4	82.7	44.6	46.2	127.0	136.4	323.2	343.3
Mean(2)	4,556.7	4509.5	211.7	214.0	70.4	80.3	75.3	78.7	43.6	44.8	127.3	130.2	319.7	330.8

Analysis of variance (p-value)ns

	2015/2016 crop season							2016/2017 crop season						
	Yield	WTG	DML	DMS	DMP	DMG	TDM	Yield	WTG	DML	DMS	DMP	DMG	TDM
P_{source}	0.70	0.42	0.15	0.53	0.50	0.36	0.49	0.45	0.30	0.19	0.15	0.42	0.43	0.24
P_{rate}	0.64	0.77	0.67	0.22	0.19	0.26	0.25	0.58	0.23	0.92	0.60	0.73	0.73	0.79
$P_{source*rate}$	0.93	0.21	0.85	0.76	0.94	0.96	0.93	0.94	0.37	0.06	0.25	0.25	0.13	0.21
$P_{control*factorial}$	0.50	0.08	0.75	0.68	0.65	0.84	0.75	0.59	0.31	0.89	0.81	0.78	0.94	0.99
CV (%)	2.55	1.34	7.74	2.00	1.90	2.10	1.40	1.50	1.80	3.25	2.60	5.10	1.35	1.80

(1)Means for Mn rates and sources were compared, respectively, by the regression test and Tukey's test, at 5% probability. (2)Average of factorial. nsNonsignificant differences.

2018). Dimkpa et al. (2018) found that foliar-applied MnO nanoparticles increased the transportation of Mn in wheat (*Triticum aestivum* L.) seeds. In the present study, however, this perspective was not explored because the $MnCO_3$ particle showed an average size of 340.6 nm, varying from 228.3 to 452.9 nm, and, therefore, could not be characterized as a nanoparticle, which should be smaller than 100 nm according to Servin et al. (2015).

The lack of soybean response to Mn application is an indicative that the low levels of Mn in the soil, ranging from 0.5 to 1.0 mg dm^{-3}, were sufficient for a good cultivar performance. Raij et al. (1996) also reported a low level of Mn in the soil (<1.2 mg dm^{-3}), with no effect of Mn application.

In RR soybean, a positive effect of Mn application is expected due to the common use of glyphosate in Brazil. However, in the present study and in that of Basso et al. (2011), the applications of Mn isolated or associated with glyphosate did not influence Mn application. Cakmak et al. (2009) concluded that glyphosate actually promotes Mn deficiency due to Mn-oxidizing bacteria and an impairment in plant uptake and transport of Mn.

In the first crop season, the application of $MnSO_4$ fitted a linear response to Mn content in the third and fourth trifoliate leaflets, which was 34 and 53% superior to that obtained with $MnCO_3$, respectively. The application of $MnCO_3$ also fitted a linear response in the fourth trifoliate leaflet, but without any effect on the third trifoliate leaflet (Table 4). In the second crop season, in the third trifoliate leaflet, $MnCO_3$ application fitted a linear response to Mn content, and $MnSO_4$ showed a quadratic response, with a maximum value at the rate of 294 g ha^{-1}. However, in the fourth

Table 3. Number of stems (NSS), nodes (NNS), pods (NPS), and grains (NGS), as well as plant height (HPS) and stem diameter (DSS), of soybean (*Glycine max*) with the application of two manganese sources ($MnSO_4$ and $MnCO_3$) at four rates (0, 150, 250, 350, and 450 g ha^{-1}) in the 2015/2016 and 2016/2017 crop seasons(1).

Mn rate (g ha^{-1})	NSS		NNS		NPS		NGS		HPS (cm)		DSS (mm)	
	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$	$MnSO_4$	$MnCO_3$
2015/2016 crop season												
0	8.2	8.2	21.5	21.5	73.4	73.4	167.6	167.6	80.2	80.2	8.3	8.3
150	9.4	9.1	21.9	21.1	86.1	79.7	197.1	202.9	82.1	80.3	8.3	8.3
250	8.6	8.6	21.6	21.2	70.6	71.2	158.6	171.3	75.5	77.5	7.3	7.9
350	9.0	9.2	21.3	21.5	82.2	79.0	180.2	177.1	82.7	80.8	8.2	8.2
450	9.1	8.8	21.4	22.1	69.8	76.6	162.2	161.5	83.7	88.8	7.5	8.5
Mean(2)	9.0	8.9	21.5	21.5	77.2	76.6	174.5	178.2	81.0	81.8	7.8	8.2
2016/2017 crop season												
0	4.5	4.5	14.8	14.8	34.7	34.7	85.9	85.9	86.8	86.8	6.2	6.2
150	4.4	4.0	14.6	14.6	35.2	32.2	89.7	80.7	85.1	87.1	6.2	6.2
250	4.0	4.4	14.2	14.7	30.6	31.7	76.9	86.7	87.7	88.2	6.2	6.4
350	4.4	4.2	14.6	14.7	34.3	33.7	83.8	81.1	86.8	88.9	6.2	6.2
450	4.2	4.3	14.6	14.9	32.6	34.4	83.2	92.0	88.0	89.6	6.5	6.5
Mean(2)	4.2	4.2	14.5	14.7	33.2	33.0	83.4	85.1	86.9	88.4	6.3	6.4

Analysis of variance (p-value)ns

	2015/2016 crop season						2016/2017 crop season					
	NSS	NNS	NPS	NGS	HPS	DSS	NSS	NNS	NPS	NGS	HPS	DSS
P_{source}	0.86	0.87	0.89	0.75	0.39	0.68	0.90	0.25	0.85	0.54	0.74	0.16
P_{rate}	0.50	0.84	0.13	0.11	0.72	0.34	0.99	0.70	0.18	0.46	0.08	0.32
$P_{source*rate}$	0.91	0.47	0.68	0.96	0.98	0.95	0.06	0.80	0.34	0.07	0.72	0.52
$P_{control*factorial}$	0.14	0.97	0.56	0.61	0.73	0.58	0.40	0.59	0.29	0.69	0.75	0.99
CV (%)	25.10	11.37	3.26	1.00	3.10	24.7	6.10	15.20	6.70	2.90	2.80	35.10

(1)Means for Mn rates and sources were compared, respectively, by the regression test and Tukey's test, at 5% probability. (2)Average of factorial. nsNonsignificant difference.

trifoliate leaflet, the Mn sources did not differ, with a linear response to Mn rates (Figure 2).

The contents of Mn in the third and fourth trifoliate leaflets were within the range of 2.0–48.0 g kg^{-1} Mn considered sufficient for soybean according to Raij et al. (2001). However, there was no correlation between yield and Mn content in the third and fourth trifoliate leaflets and in the diagnostic leaf, represented by an r of 0.11, -0.02, and -0.19, respectively. This is an indicative that Mn was absorbed by the plant, but did not affect soybean yield, as also reported by Basso et al. (2011) and Stefanello et al. (2011).

The application of $MnSO_4$ increased Mn contents in the third and fourth trifoliate leaflets, when compared with that of $MnCO_3$ in the 2015/2016 crop season, but had no significant effect on the diagnostic leaf. The varying results between harvests can be associated with genotypic differences in plant absorption, transport, and distribution of Mn (Lavres Junior et al., 2008), which was the case in present study, where 'Pioneer 98Y30 RR' was evaluated in the first cycle and 'Brasmax Flecha 6266 RSF IPRO' in the second.

The diagnostic leaf was not influenced by any Mn source or rate, with a mean of 29 mg kg^{-1} Mn (average of all treatments), similar to that of 30 mg kg^{-1} obtained for the control (Table 4). The contents of Mn in the third and fourth trifoliate leaflets were higher with the application of Mn, being 63 and 35% greater than that in the control, respectively. In the same sampling stage, Mann et al. (2002) observed a higher soybean yield due to the foliar application of Mn, with averages from 6.8 to 74.5 mg kg^{-1} Mn in the diagnostic leaf.

In the 2015/2016 crop season, $MnSO_4$ application fitted quadratic responses to Mn contents in stems and grains, with maximum values at the rates of 303.3 and 306.0 g ha^{-1}, respectively. However, there was

Table 4. Manganese contents in the third and fourth trifoliate leaflets and in the diagnostic leaf of soybean (*Glycine max*) with the application of two manganese sources ($MnSO_4$ and $MnCO_3$) at four rates (0, 150, 250, 350, and 450 g ha^{-1}) in the 2015/2016 and 2016/2017 crop seasons[(1)].

Mn rate (g ha^{-1})	Third trifoliate leaflet			Fourth trifoliate leaflet			Diagnostic leaf		
	$MnSO_4$	$MnCO_3$	Mean	$MnSO_4$	$MnCO_3$	Mean	$MnSO_4$	$MnCO_3$	Mean
	Manganese content (mg kg^{-1}) – 2015/2016 crop season								
0	16.1	16.1	16.1b	14.5	14.5	14.5b	29.3	29.3	29.3
150	61.8A	26.3B	44.0	28.7A	15.5B	22.1	26.8	28.1	27.5
250	80.0A	36.6B	58.3	38.6 A	20.0B	29.3	23.8	25.4	24.6
350	119.3A	35.5B	77.4	47.3 A	20.8B	34.0	27.7	24.9	26.3
450	140.7A	45.3B	93.0	59.0A	24.7B	41.9	26.3	27.8	27.1
Mean[(2)]	100.4	35.9	68.2a	43.4	20.3	31.8a	26.1	26.6	26.3
	Manganese content (mg kg^{-1}) – 2016/2017 crop season								
0	24.4	24.4	24.4b	27.1	27.1	27.1b	31.1	31.1	31.1
150	33.9A	31.6A	32.8	29.3	29.6	29.4	32.7	27.0	29.8
250	42.1A	39.8A	40.9	31.7	32.2	31.9	31.3	34.2	32.8
350	52.8A	42.4B	47.6	34.8	30.7	32.8	33.8	30.4	32.1
450	46.5A	52.9A	49.7	36.7	36.0	36.3	33.4	31.8	32.6
Mean[(2)]	43.8	41.7	42.8a	33.1	32.1	32.6a	32.8	30.8	31.8

Analysis of variance (p-value)	2015/2016 crop season			2016/2017 crop season		
	Third trifoliate	Fourth trifoliate	Diagnostic	Third trifoliate	Fourth trifoliate	Diagnostic
P_{Source}	<0.001	<0.001	0.69	0.22	0.42	0.13
P_{rate}	<0.001	<0.001	0.25	<0.01	<0.01	0.35
$P_{Source*rate}$	<0.001	<0.001	0.41	<0.01	0.54	0.13
$P_{Control*Factorial}$	<0.001	<0.001	0.07	<0.01	<0.01	0.69
CV (%)	4.24	5.78	9.16	4.30	6.24	5.50

[(1)]Means followed by equal letters, in the columns, do not differ by Tukey's test, at 5% probability. Means for Mn rates and sources were compared, respectively, by the regression test and Tukey's test, at 5% probability. [(2)]Average of factorial.

no significant effect in the 2016/2017 crop season. In addition, no significant difference was observed between Mn sources at all rates regarding the contents of the nutrient in stems and grains, except for 350 g ha^{-1} since $MnSO_4$ resulted in a higher concentration than $MnCO_3$ (Table 5). The foliar application of $MnCO_3$, however, fitted a linear response to Mn content in stems, with the highest concentration of 26.3 mg kg^{-1} (Figure 3). In 2015/2016, the contents of Mn were higher in the grain, followed by stems, leaves, and pods; however, in 2016/2017, they were higher in leaves, followed by grains, pods, and stems. Mann et al. (2002) and Carvalho et al. (2014) reported a similar result due to Mn contents, which led to soybean seeds with a higher germination, electrical conductivity, and emergence. Machado et al. (2019) concluded that $MnSO_4.H_2O$ was a better Mn source than MnEDTA for soybean growth, whereas Megliavacca et al. (2022) found that $MnSO_4.H_2O$ was a better alternative than $MnCO_3$ due to its solubility that promotes a better

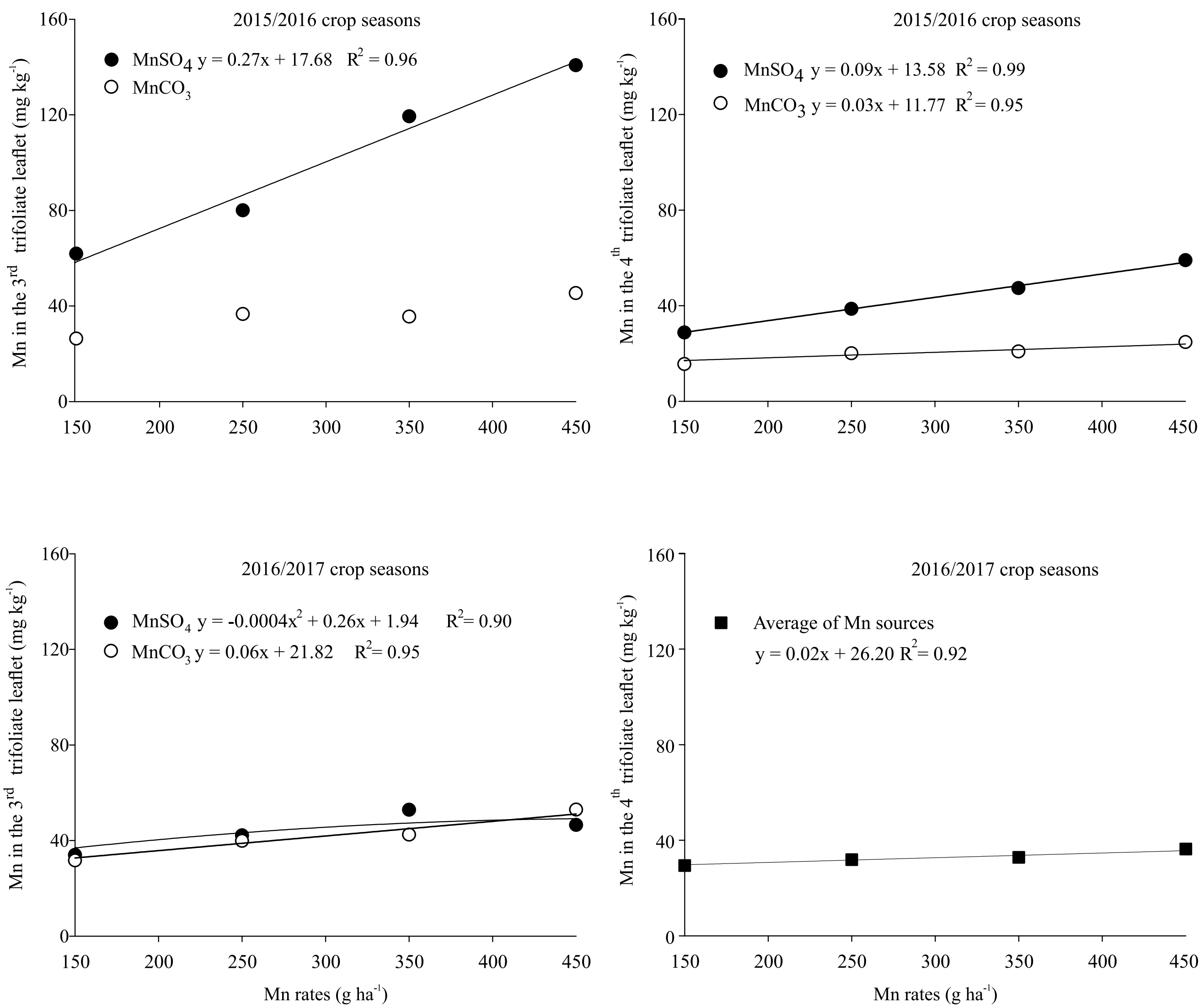

Figure 2. Manganese contents in the third and fourth trifoliate leaflets of soybean (*Glycine max*) with the foliar application of two manganese sources ($MnSO_4$ and $MnCO_3$) at four rates (0, 150, 250, 350, and 450 g ha^{-1}) in the 2015/2016 and 2016/2017 crop seasons. Means for manganese rates were compared by the regression test, at 5% probability, and adjusted by linear and quadratic models.

Table 5. Manganese contents in the leaves (MnL), stems (MnS), pods (MnP), and grains (MnG) of soybean (*Glycine max*) with the application of two manganese sources ($MnSO_4$ and $MnCO_3$) at four rates (0, 150, 250, 350, and 450 g ha^{-1}) in the 2015/2016 and 2016/2017 crop seasons(1).

Mn rate	MnL (mg kg^{-1})			MnS (mg kg^{-1})			MnP (mg kg^{-1})			MnG (mg kg^{-1})		
(g ha^{-1})	$MnSO_4$	$MnCO_3$	Mean	$MnSO_4$	$MnCO_3$	Mean	$MnSO_4$	$MnCO_3$	Mean	$MnSO_4$	$MnCO_3$	Mean
2015/2016 crop season												
0	19.0	19.0	19.0	19.5	19.5	19.5b	15.8	15.8	15.8	25.7	25.7	25.7
150	23.2	19.4	21.3	22.5A	20.1A	22.3	16.5	16.4	16.4	27.0A	26.3 A	26.7
250	20.7	16.7	18.7	23.4 A	21.1A	22.3	16.6	17.5	17.0	27.3A	27.0 A	27.1
350	29.2	22.5	25.8	32.8A	19.2B	26.0	18.6	15.6	17.1	29.2A	26.1 B	27.7
450	22.3	25.7	24.0	22.1 A	26.3A	24.2	16.0	18.6	17.3	26.2A	28.5 A	27.3
Mean(2)	23.9	21.1	22.5	25.2	22.22	23.4a	16.9	17.0	17.0	27.45	27.02	27.2
2016/2017 crop season												
0	26.5	26.5	26.5	14.4	14.4	14.4	16.6	16.6	16.6	27.8	27.8	27.8
150	26.8	29.9	28.3	15.1	14.7	14.9	16.3	16.5	16.4	26.9	28.8	27.9
250	26.8	28.7	27.8	14.5	12.8	13.7	17.8	17.6	17.7	28.0	27.4	27.7
350	26.6	27.0	26.8	12.9	11.6	12.3	15.4	16.6	16.0	28.5	28.0	28.2
450	28.5	28.1	28.3	13.9	13.3	13.6	18.7	15.8	17.3	26.7	26.9	26.8
Mean(2)	27.2	28.4	27.8	14.1	13.1	13.6	17.0	16.6	16.8	27.5	27.8	27.6

p-value

	2015/2016 crop season				2016/2017 crop season			
	MnL	MnS	MnP	MnG	MnL	MnS	MnP	MnG
$P_{Sources}$	0.15	0.02	0.91	0.46	0.34	0.23	0.63	0.77
P_{rate}	0.07	0.07	0.96	0.67	0.84	0.20	0.46	0.71
$P_{Sources* rate}$	0.31	<0.01	0.42	0.02	0.78	0.95	0.36	0.76
$P_{Control* Factorial}$	0.23	<0.01	0.51	0.09	0.52	0.52	0.82	0.93
CV (%)	6.39	10.6	13.24	9.05	6.25	14.60	14.50	9.50

(1)Means followed by equal letters, in the columns, do not differ by Tukey's test, at 5% probability. Means for Mn rates and sources were compared, respectively, by the regression test and Tukey's test, at 5% probability. (2)Average of factorial.

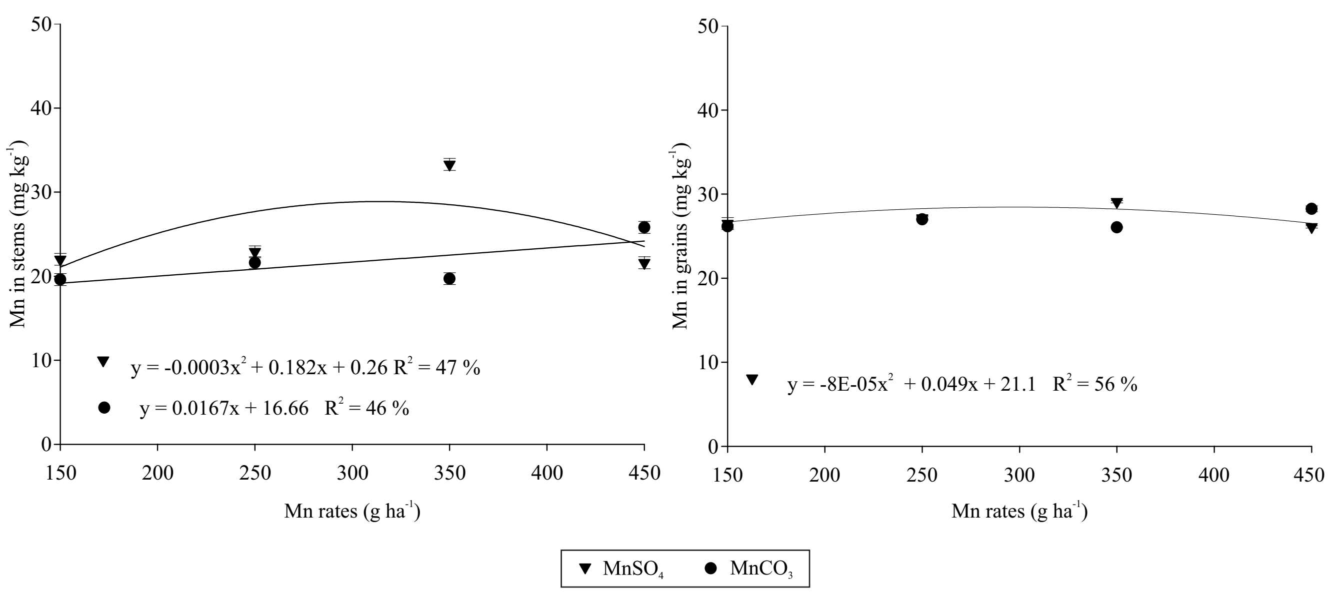

Figure 3. Manganese contents in stems and grains of soybean (*Glycine max*) with the application of two manganese sources ($MnSO_4$ and $MnCO_3$) at four rates (0, 150, 250, 350, and 450 g ha^{-1}) in the 2015/2016 crop season. Means for manganese rates were compared by the regression test, at 5% probability, and adjusted by linear and quadratic models.

plant uptake and retranslocation of Mn. Alejandro et al. (2020) point out that Mn is also required for the detoxification of highly toxic superoxide radicals through Mn-containing superoxide dismutase. In general, in the present study, the Mn contents were increased in the plants but did not influence soybean yield and dry matter production.

Conclusions

1. The foliar fertilization with $MnSO_4.H_2O$, as a manganese source, in soybean (*Glycine max*), in a Brazilian Cerrado soil, increases Mn contents in leaves, stems, and grains, but does not affect yield and dry matter production.
2. Maximum foliar Mn contents are obtained with the application of Mn rates ranging from 150 to 450 g ha^{-1}.
3. The foliar application of $MnSO_4.H_2O$ increases Mn contents in soybean leaves, showing a superior performance to that of $MnCO_3$.

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