Effect of liming on micronutrient availability to soybean grown in soil under different lengths of time under no tillage

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ABSTRACT. The effect of liming on the availability of micronutrients to soybean cultivated during different numbers of years under no tillage (NT) was investigated. The treatments consisted of the number of years under NT (three, six, and nine years) and five rates of lime (0, 33, 67 and 100% of the amount calculated to raise soil base saturation to 70%) broadcast on soil surface plus the rate of 100% broadcast with incorporation in the 0-0.20 m layer of a clayey Red Oxisol. Soil and leaf samples were collected at two vegetative stages of the crop (vegetative V4 and blossoming R2). The soil was sampled at depths of 0-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.30 m. Surface liming had little effect on extractable soil micronutrient and nutrient concentrations in soybean leaves. In the area with three years under NT, all liming rates decreased the extractable soil Zn up to a depth of 0.20 m. Lime incorporation decreased the extractable soil Mn in the surface layer. There were no differences in the extractable soil micronutrients and nutrient concentrations in soybean leaves as a function of the number of years under NT. These data suggest that broadcasting lime at current rates on soils under NT does not necessarily lead to micronutrient deficiencies.

Keywords: copper, iron, manganese, zinc, no till.

Efeito da calagem na disponibilidade de micronutrientes para soja, cultivada em solo sob diferentes tempos de cultivo em plantio direto

RESUMO. Avaliou-se o efeito da calagem sobre a disponibilidade de micronutrientes à soja cultivada em solo, com diferentes tempos de cultivo sob sistema de semeadura direta (SD). Os tratamentos consistiram de número de anos sob SD (três, seis e nove anos) e cinco doses de calcário (0, 33, 67 e 100% da quantidade necessária para elevar a saturação por bases a 70%), aplicadas em superfície, mais a dose 100% incorporada na camada 0-0,20 m de um Latossolo Vermelho argiloso. Amostras de solo e de folha foram coletadas em dois estádios de vegetação da soja (V4: estádio vegetativo e R2: florescimento pleno). O solo foi amostrado nas profundidades de 0-0,05, 0,05-0,10, 0,10-0,20 e 0,20-0,30 m. A calagem superficial exerceu pouco efeito sobre os teores de micronutrientes no solo e nas folhas de soja. Na área com três anos sob sistema de SD todas as doses de calcário reduziram os teores de Zn até a profundidade de 0,20 m. A incorporação de calcário diminuiu o teor de Mn da camada superficial. Os teores de micronutrientes no solo e as concentrações nas folhas da soja não variaram com os anos de cultivo sob SD. Estes dados sugerem que as doses atualmente empregadas de calcário aplicadas na superfície de solos sob SD não necessariamente conduzem a deficiências de micronutrientes.

Palavras-chave: cobre, ferro, manganês, zinco, plantio direto.

Introduction

The availability of nutrients to plants is affected by several soil attributes, such as pH, organic matter (OM), redox potential, temperature, moisture, and microbial activity, in addition to competition for adsorption sites. Cultivation under no tillage (NT) increases the amount of OM in the surface layer (Thomas, Dalal, & Standley, 2007; Santiago, Quintero, & Delgado, 2008; Aziz, Mahmood, & Islam, 2013; Motschenbacher, Brye, Anders, & Gbur, 2014; Vukasinovic, Todorovic, Dordevic, & Rajkovic, 2015; Moreira, Prochnow, Kiehl, Pauletti, & Martin-Neto, 2016) as well as increases the pH when lime is applied to the surface (Caires, Blum, Barth, Garbuio, Kusman, 2003; Teixeira, Souza, Borém, & Silva, 2003; Caires et al., 2005; Fonseca, Caires, & Barth, 2010). In addition, the soil moisture increases and the temperature decreases compared with conventional tillage because organic residues

accumulate (Aziz et al., 2013; Motschenbacher et al., 2014). Such features may cause the availability of micronutrients under NT to be different than when the soil is frequently tilled (Moreira et al., 2016). However, little information is available to evaluate to what extent surface liming and cultivation under NT will affect the availability of micronutrients.

High concentrations of some micronutrients have long been reported in surface layers of North American soils cultivated under NT. In many cases, these high micronutrient levels in the soils were attributed to the application of high rates of N to maize (*Zea mays* L.) and/or monocultures of grass, which cause a reduction in the pH and, consequently, increases in the availability of certain micronutrients (Grove & Blevins, 1988; Follett & Peterson, 1988; Edwards, Wood, Thurlow, & Ruf , 1992). However, it is known that the increased availability of certain micronutrients, chiefly Mn and Zn, is highly related to the increase of OM in the surface soil (Teixeira et al., 2003; Moreira, Prochnow, Kiehl, Martin-Neto, & Pauletti, 2006; Martin-Rueda et al., 2007; Santiago et al., 2008; Motschenbacher et al., 2014; Moreira et al., 2016). On the other hand, Zn and Mn deficiencies have been noticed especially in corn and soybean crops under NT. In addition, micronutrient deficiencies may increase with increasing time under NT because OM can bind with some micronutrients and decrease their availability (Tisdale, Nelson, & Beaton, 1985; Moreira et al., 2006; Moreira et al., 2016).

The deficiencies of such nutrients have been attributed to the excessive increases in pH in the surface layer (Grupta, Kening, & Siyuan, 2008), and in Brazil, many cases are related to the application of high rates of lime. However, this explanation may not always be correct because high extractable soil Zn and Mn have been found in surface layers of soils under NT, even when the pH and OM are high (Teixeira et al., 2003; Moreira et al., 2006; Moreira et al., 2016). Soratto and Crusciol (2008) did not observe decreases in Mn, Fe and Zn absorption by black oat cultivated in a Red Latosol under NT when high rates of lime were used. On the other hand, Caires, Banzatto, & Fonseca (2000) observed decreases in Mn and Zn absorption by soybean plants cultivated in a Red Latosol under NT for 15 years when high rates of lime were used. However, Caires et al. (2003) observed decreases in

Mn and Zn absorption by soybean plants, but only in some crops. Liming and re-liming caused a decrease in the Mn concentration in wheat leaves, but leaf concentrations of Cu, Fe and Zn were not affected by liming (Fonseca et al., 2010).

Considering these facts, in the present work, lime was broadcast at different rates on the surface or broadcast with incorporation in the 0-0.20 m layer of a Red Latosol that had been previously under NT for different lengths of time in order to evaluate the effect of these treatments on the availability of micronutrients to soybean plants.

Material and methods

The work was carried out under field conditions on a very clayey Red Latosol (Oxysol) in Tibagi, State of Paraná, Brazil, that had been previously cropped under NT for three, six, and nine years. The three and six year sites were located in grain growing areas of the farms. The nine year site was located in an experimental field. Details about the cropping during the three, six and nine years prior to the treatments are presented by Moreira, Kiehl, Prochnow, and Pauletti, (2001).

The experiment was set in a randomized complete block as a split-split-plot design with four replications. The main plots were treatments arranged in a 3 x 5 factorial set (3 different lengths of time under NT x 5 rates of lime); the subplots included the two sampling times after lime application, and the sub-subplots comprised four depths of soil sampling (0-0.05, 0.05-0.10, 0.10-0.20, and 0.20-30 m). For the sites with three and six years under NT, the plots measured 6.4 m x 7.0 m (45 m^2), whereas for the nine years under NT, the dimensions were 8.30 m x 12.50 m (104 m^2).

Lime rates were 0, 33, 67 and 100% of the amount calculated to raise the base saturation to 70% that was broadcast on the surface plus the 100% broadcast rate with incorporation in the 0-0.20 m soil layer. Rates to raise the base saturation to 70%, calculated in accordance to procedures recommended by Raij et al. (1997), were 3,030, 3,380, and 2,485 kg ha^{-1}, respectively, for the sites with three, six, and nine years under NT. The calculations were based on the chemical properties of the 0-0.20 m layer. The lime was manually broadcast on the soil surface for NT treatments and was manually broadcast with incorporation in the 0-0.20 m layer with a disk plow for the incorporated lime treatment. The chemical characteristics of the 0-0.20 m soil layers prior to liming in May 1998 are shown in Table 1.

Table 1. Chemical properties of the Red Latosol prior to experiment installation.

Years under no tillage	[1]pH in CaCl₂	P_resin	OM	H+Al	Al	K	Ca	Mg	SB	CEC	BS	Al Saturation
		mg dm⁻³			mmol_c dm⁻³							— %–
Three	5.0	33	55	58	1	3.7	28	26	57.7	115.7	50	1.7
Six	4.8	41	47	72	2	6.7	47	18	71.7	143.7	50	2.7
Nine	5.1	44	47	52	0	2.6	34	21	57.6	109.6	53	0.0

[1] pH and OM, P, K, Ca, Mg and Al content determined according to Raij et al. (1987).

Soybean (cv. EMBRAPA 59) was sown in October 1998 in rows spaced 0.45 m apart, at the rate of 16 plants per metre. The seeds were previously treated with a solution containing selected species of Bradyrhizobium and sodium molybdate at 64 g of sodium molybdate per 50 kg of seeds. At seeding, 200 kg ha⁻¹ of 0-20-20 NPK fertilizer was applied in the furrow.

The soil and leaves were sampled at the following two times: stage V4 (three open trifoliolate leaves) and stage R2 (blossoming) on December 17, 1998 and January 26, 1999, respectively. Malavolta, Vitti, and Oliveira (1997) recommended sampling only one leaf at the blossoming, but an additional date was considered because Mn deficiencies in soybean and Zn deficiencies in corn have been frequent in the initial periods of crop development but subsequently disappear eventually (Pauletti, 1999; Moreira et al., 2006). Twenty open trifoliolate leaves per plot (third leaf from the top) were collected. The plant material was washed in deionized water and dried at 60°C in a ventilated chamber. The concentrations of B, Cu, Fe, Mn, and Zn were determined according to methods described by Malavolta et al. (1997).

One sampling, comprising ten samples, was taken in each plot with a tubular probe at depths of 0-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.30 m. The samples were dried in a ventilated chamber at 40°C and passed through a 2 mm sieve. The extractable soil Mn, Cu, Zn, and Fe content was determined by extraction with DTPA-TEA pH 7.3 (Lindsay & Norvell, 1978), and the extractable B content was determined by extraction with BaCl₂.H₂O 0.125% in a microwave oven (Abreu, Abreu, Raij, van, Bataglia, & Andrade, 1994).

The data were subjected to an analysis of variance (F test), and the means were compared using Tukey's test at the 5% level (Ferreira, Cavalcanti, & Nogueira, 2013). The comparison of the means was utilized instead of polynomial regressions because the method of lime application was not uniform for all treatments. A simple linear correlation analysis was estimated for the treatments without lime incorporation between extractable soil micronutrients and soil pH and soil OM and between extractable soil micronutrients and leaf micronutrient concentrations.

Results and discussion

Except for the concentrations of Cu and Fe in the soils that had six and nine years under NT and of Mn in the soil that had six years of NT, all of which decreased from the first to the second sampling, micronutrient availability was not greatly affected by the increase in soil pH (Table 2). This small pH increase was probably not enough to reduce the solubility of the micronutrients in the soil. Moreover, in some situations, a small increase in extractable soil B was observed in the second sampling. In the case of B, according to Tisdale et al. (1985), the increase in pH may accelerate the decomposition of OM and release B into the soil. In this study, some B was adsorbed to Al(OH)₃ in the second sample, which may have been released into the soil solution and contributed to the increased B levels in the soil solution and, consequently, in plant leaves. Rosolem and Biscaro (2007) showed that even with high doses of lime, the B adsorption by soil was observed only in the first year of limestone application. The authors report that, over time, the amount of B increased in the soil solution and was able to be absorbed by plants.

Although Fe and Mn concentrations in soybean leaves decreased from the first to the second sampling, no visible nutrient deficiencies in the soybean plants were detected. However, the leaf concentrations of Cu were below a level considered adequate by Malavolta et al. (1997) (Table 3) for conventional tillage. In general, under field conditions, deficiencies of Zn in corn and of Mn in soybean plants have been observed during the first stages of development (Pauletti, 1999; Moreira et al., 2006), approximately equivalent to vegetative stage V4 (first sampling) in this study. Perhaps the amount of lime that was used was excessive for these crops.

Table 2. Soil pH and extractable soil micronutrients in a Red Latosol after three, six and nine years of soybean cultivation under no tillage at two sampling times.

Sampling time[1]	pH[2]	B	Cu	Fe	Mn	Zn
			mg dm^{-3}			
			No tillage for three years			
V4 stage	5.1 b[3]	0.15 b	2.7 a	27.7 a	3.1 a	2.9 a
R2 stage	5.2 a	0.23 a	2.5 a	24.7 a	3.0 a	2.7 a
			No tillage for six years			
V4 Stage	4.6 b	0.29 a	1.9 a	59.0 a	4.4 a	0.9 a
R2 Stage	4.8 a	0.31 a	1.4 b	37.2 b	2.9 b	0.8 a
			No tillage for nine years			
V4 Stage	4.9 b	0.15 b	4.2 a	39.2 a	2.2 b	1.8 a
R2 Stage	5.1 a	0.23 a	3.4 b	31.1 b	2.9 a	1.6 a

[1] The sampling times were related to soybean growth stages. [2] Letters compare the sampling time within each cultivation time using the Tukey test at a significance level of 5%. Zn data were transformed into (Zn)$^{1/2}$. [3] pH values determined according to Raij et al. (1987). Extractable soil Mn, Cu, Zn, and Fe content was determined by extraction with DTPA-TEA pH 7.3 (Lindsay and Norvell, 1978) and B with BaCl$_2$.H$_2$O 0.125% in a microwave oven (Abreu et al., 1994).

Table 3. Micronutrient concentration in soybean leaves cultivated under no tillage in a Red Latosol for three, six and nine years at two sampling times.

Sampling time[1]	B	Cu	Fe	Mn	Zn
			g kg^{-1}		
			No tillage for three years		
V4 Stage	20 b[1]	8 b	136 a	36 a	25 b
R2 Stage	41 a	11 a	69 b	30 b	33 a
			No tillage for six years		
V4 Stage	28 b	7 b	114 a	53 a	31 a
R2 Stage	40 a	8 a	54 b	32 b	30 a
			No tillage for nine years		
V4 Stage	24 a	9 a	215 a	34 a	33 a
R2 Stage	25 a	9 a	60 b	25 b	29 b

[1] Letters compare the sampling time within each number of years of cultivation using the Tukey test at a significance level of 5%.

The effect of liming on the extractable soil Fe, Mn, and Zn content was studied within each year under NT and each depth because the interaction between lime rates, years under NT, and depths was significant. For the cases in which the triple interaction was not significant (B and Cu), the significant double interactions were studied.

Extractable soil B and Cu were not influenced by the lime rate and the number of years under NT (B average = 0.23 mg dm^{-3}; C.V. 27.3% and Cu average = 2.5 mg dm^{-3}; C.V. 22%). Liming generally decreases the B content because Al^{3+} in solution is precipitated in the form of Al(OH)$_3$, which has the ability to adsorb large amounts of B (Tisdale et al., 1985; Prodromu, 2004; Rosolem & Bíscaro, 2007). The low exchangeable Al in these soils (Table 1) may explain the lack of response of B to liming.

The extractable soil B in the surface layer seems to have been related more to the amount of OM, which is an important source of this element (Tisdale et al., 1985; Rosolem & Bíscaro, 2007; Rosolem, Zancanaro, & Bíscaro, 2008), than to the soil pH. In the first sampling (V4 stage), the correlation coefficient between extractable soil B and OM was positive for all layers (correlation coefficient in the surface layer was 0.56), thus agreeing with results obtained by Alleoni, Camargo, and Valadares (1999) for soils in the State of São Paulo.

In the case of extractable soil Cu, it is possible that the increase in pH in the present study was not enough to reduce the solubility of Cu^{2+}. Increases in soil pH above 6.0 induce the hydrolysis of hydrated Cu, which can lead to a stronger Cu adsorption by clay minerals and organic matter. Thus, the Cu2+ solubility is soil pH dependent and decreases 100-fold for each pH unit increase (Fageria, Baligar, & Clark, 2002). In a study by Fonseca et al. (2010), the soil extractable Cu decreased linearly with increasing lime application rates in a soil under NT due to the increased pH. Nachtigall, Nogueirol, and Alleoni (2007) reported that as the pH decreased, the exchangeable Cu content increased, while the amount of Cu bound to OM, oxides and residual fractions decreased.

For all sites, the surface layer presented the lowest extractable soil Cu (Table 4), which disagreed with the results of Teixeira et al. (2003) for soils in São Paulo State. In the study, the lower extractable soil Cu was attributed to the presence of more OM on the surface, thus resulting in more complexation of the element (Fageria et al., 2002). In the present work, correlation coefficients between the extractable soil Cu and OM were also low or non-significant (data not shown); these results are in disagreement with results by many authors for NT soils (Teixeira et al., 2003; Santiago et al., 2008; Martin-Rueda et al., 2007; Vukasinovic et al., 2015). However, extractable soil Cu is mostly governed by OM in many soils because it can form complexes and chelates with a large portion of the soil Cu^{2+} (Tisdale et al., 1985).

Table 4. Extractable soil Cu in a Red Latosol after three, six and nine years of soybean cultivation under no tillage at different soil depths.

Soil depth	Three years	Six years	Nine years
m		mg dm^{-3}	
0-0.05	2.3 b[1]	1.4 b	3.2 b
0.05-0.10	2.6 a	1.7 ab	4.3 a
0.10-0.20	2.7 a	1.8 a	4.0 a
0.20-0.30	2.7 a	1.7 ab	4.0 a

[1] Lower case letters compare soil depths within each number of years under no tillage using the Tukey test at a significance level of 5%.

Soil extractable Fe varied little with the lime rate (Table 5). In the site with six years under NT, the incorporation of the total rate resulted in lower extractable soil Fe in the 0.05-0.10 m layer than when 67% of the rate was applied on the surface. In the surface layer, the opposite occurred. This effect may have taken place because incorporation causes a better distribution of lime in the soil profile. In the soil with nine years under NT, all rates applied on the surface reduced Fe content in the 0-0.05 m layer. On the other hand, Fonseca et al. (2010) observed that liming caused a linear decrease in the extractable Fe content. Alleoni, Cambri, and Caires (2005) also observed a decrease in Fe concentrations extracted by DTPA at the 0.10 m depth after the application of surface liming under an NT system.

A greater effect of lime on soil extractable Fe was expected because ferric (Fe^{3+}) and ferrous (Fe^{2+}) activity in the soil solution decreases 1000-fold and 100-fold, respectively, for each pH unit increase (Fageria et al., 2002). Additionally, with increasing soil acidification, the available Fe content increases (Rutkowska, Szulc, Sosulski, & Stepien, 2014). However, in these soils, other factors, such as the redox potential and OM, must be considered. According to Follett and Peterson (1988), the accumulation of both OM and water close to the surface may decrease the soil redox potential and thus increase the Fe availability to crops. In many cases, the high exchangeable Fe content in the surface layers of the soil is related to the higher concentrations of OM in these layers (Teixeira et al., 2003; Santiago et al., 2008; Martin-Rueda et al., 2007; Vukasinovic et al., 2015).

Significant negative correlations were found between pH values and the Fe content (values of -0.5, -0.8, -0.7, and -0.7 at the depths of 0.0-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.30, respectively, at the V4 stage); these results agree with those shown by Ferreira et al. (2013) and Fonseca et al. (2010) for soil under NT. Correlations with OM were positive at the first sampling (values of 0.55, 0.68, 0.67, and

0.53 at the depths of 0.0-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.30, respectively), and some were negative at the second sampling (data not shown). In the first case, OM may have supplied the soil solution with chelating agents, which increased the Fe availability (Tisdale et al., 1985) and, in the second case, caused the formation of insoluble complexes with Fe. Walters, Aulakh, and Doran (1992) noticed higher extractable soil Fe in the soil during the initial period of decomposition of the residues of hairy vetch (*Vicia villosa* L.) than at the end of this period. They suggested that after total decomposition occurred, there was a re-oxidation of the element, which decreased its availability. Teixeira et al. (2003) also observed negative correlations of Fe with OM in soil under NT, which was attributed to OM's ability to form complexes with the nutrient.

Extractable soil Mn in the surface layer of sites with three and six years under NT decreased more when the lime was broadcast with incorporation in the 0-0.20 m layer than when it was broadcast at the highest rate on the surface (Table 6). In the nine-year NT soil, the incorporation of lime also decreased extractable soil Mn in the 0-0.05 m layer compared to 67 % of the dose applied superficially.

The practice of incorporating lime into the soil may have increased the contact of lime with soil particles, thus increasing its action in decreasing soluble forms of Mn. Furthermore, Mn in the surface layer may have been diluted in the lower layers through the incorporation of lime. In addition, the practice of incorporating lime may have increased the oxidation reactions of Mn^{2+} to Mn^{4+} because it increases soil aeration. Alleoni et al. (2005) observed that the Mn concentration decreased at the 0.10 m depth after surface liming, which was attributed to the increase in pH. Fonseca et al. (2010) observed an unusual effect of surface liming upon Mn availability in NT soils: the Mn concentration increased quadratically with the increasing surface lime rate in the 0-0.05 m layer. According to Fonseca et al. (2010), an increase in the soil pH as a consequence of liming can enhance microbial activity, increasing the amount of dissolved organic matter and, consequently, improving the solubility of Mn bound to the low molecular-weight organic compounds.

Table 5. Extractable soil Fe at different depths of a Red Latosol after three, six and nine years of soybean cultivation under no tillage as a function of lime rates.

Soil depth	Lime rate [1]				
	100 I	100 S	67 S	33 S	0
1m m	mg dm^{-3}				
	No tillage for three years				
0-0.05	23.8 abA[2]	23.6 aA	20.7 aA	20.8 bA	24.9 aA
0.05-0.10	23.0 bA	24.0 aA	26.4 aA	25.3 abA	27.2 aA
0.10-0.20	26.6 bA	27.6 aA	27.0 aA	29.1 aA	30.3 aA
0.20-0.30	30.4 aA	28.0 aA	27.1 aA	27.6 abA	30.8 aA
	No tillage for six years				
0-0.05	46.6 aA	41.0 bAB	38.4 bB	40.6 bAB	40.0 cAB
0.05-0.10	47.7 aB	52.3 aAB	57.1 aA	53.3 aAB	53.7 abAB
0.10-0.20	48.5 aA	54.3 aA	54.8 aA	53.6 aA	55.2 aA
0.20-0.30	45.3 aA	47.4 abA	44.2 bA	41.9 bA	45.0 bcA
	No tillage for nine years				
0-0.05	37.0 aAB	31.8 aB	30.9 bB	31.4 aB	43.1 aA
0.05-0.10	38.0 aA	36.8 aA	40.8 aA	37.5 aA	43.0 aA
0.10-0.20	34.5 aA	31.0 aA	34.2 abA	36.0 aA	36.6 abA
0.20-0.30	34.8 aA	30.3 aA	29.5 bA	31.4 aA	35.0 bA
C.V.	11.0%				

[1]Percentage of the rate necessary to raise the base saturation to 70%; I = broadcast with incorporation in the 0-0.20 m layer; S = broadcast on the surface. [2]Lower case letters compare soil depths within each lime rate and each period of time under no tillage (NT); upper case letters compare lime rates within each period of time under NT and each soil depth using the Tukey test at a significance level of 5%.

Table 6. Extractable soil Mn at different depths of a Red Latosol cultivated with soybeans for three, six and nine years under no tillage as a function of lime rates.

Soil depth	Lime rate [1]				
	100 I	100 S	67 S	33 S	0
mm	mg dm^{-3}				
	No tillage for three years				
0-0.05	4.6 aB[2]	6.2 aA	4.8 aB	4.9 aAB	5.6 aAB
0.05-0.10	3.7 abA	3.2 bA	4.1 aA	4.0 aA	3.8 bA
0.10-0.20	2.9 bA	2.2 bcA	2.0 bcA	2.4 bA	2.2 cA
0.20-0.30	1.6 bA	1.1 cA	0.8 cA	0.9 cA	1.0 cA
	No tillage for six years				
0-0.05	4.2 aB	6.8 aA	5.7 aA	6.6 aA	6.5 aA
0.05-0.10	3.4 aB	4.1 bAB	4.4 aA	4.9 bA	4.3 bAB
0.10-0.20	3.1 abA	2.9 bcA	2.9 bA	3.4 cA	3.0 bA
0.20-0.30	1.8 bA	1.4 cA	1.2 cA	1.2 dA	1.2 cA
	No tillage for nine years				
0-0.05	3.3 aB	4.3 aAB	4.8 aA	4.5 aAB	5.6 aA
0.05-0.10	2.5 aA	2.5 bA	3.3 bA	2.8 bA	2.8 bA
0.10-0.20	2.0 abA	1.6 bA	1.8 cA	1.9 bcA	1.7 bcA
0.20-0.30	1.1 bA	1.4 bA	1.1 cA	1.3 cA	1.3 cA
C.V.	25.8%				

[1]Percentage of the rate necessary to raise the base saturation to 70%; I = broadcast with incorporation in the 0-0.20 m layer; S = broadcast on the surface. [2] Lower case letters compare soil depths within each lime rate and each number of years under no tillage (NT); upper case letters compare lime rates within each number of years under NT and each soil depth using the Tukey test at a significance level of 5%.

The highest extractable soil Mn was found in the surface layers, in agreement with the results reported by other authors (Martin-Rueda et al., 2007; Vukasinovic et al., 2015). However, this portion of the soil showed the highest pH (Moreira et al., 2001). These results agree with those obtained by Teixeira et al. (2003), Moreira et al. (2006), and Moreira et al. (2016), and disagree with what has been long known about the effect of pH on Mn availability (Gupta et al., 2008, Rutkowska et al., 2014). In this manner, the highest extractable Mn in the surface of NT soil was related to a higher content of OM, which would be a source of this nutrient (Martin-Rueda et al., 2007; Santiago et al., 2008). There were correlations between OM and extractable soil Mn (values of 0.4, 0.5, 0.7, and 0.5 at the depths of 0.0-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.30, respectively), in agreement with results obtained by Teixeira et al. (2003), Moreira et al. (2006)

and Moreira et al. (2016) for NT soils. However, it must be stressed that OM may also decrease the Mn availability due to the formation of non-soluble chelates with the element (Tisdale et al., 1985; Moreira et al., 2006; Moreira et al., 2016).

In the case of extractable soil Zn, the most pronounced effect of lime application occurred in the site with three years under NT, where the extractable soil Zn decreased with all application rates on the surface (Table 7). The stronger effect on this soil may be due to its higher initial pH (Table 1). According to Tisdale et al. (1985), at a pH above 6.0, the soluble forms of Zn^{2+} are decreased because they are transformed into not very soluble compounds, such as $Zn(OH)_2$ and $ZnCO_3$. Alleoni et al. (2005) also observed that extractable soil Zn at a 0.10 m depth under NT decreased after surface liming as a consequence of the increase in pH. However, in NT

soils, Shuman and McCracken (1999a) concluded that the extractable soil Zn content was not affected by liming and Fonseca et al. (2010) observed that in the 0-0.05 m layer, soil extractable Zn concentrations were not influenced by the lime rates.

The extractable soil Zn in the six-year NT soil did not vary with depth, thus disagreeing with previous results obtained (Castro, Camargo, Cantarella, Vieira, & Dechen, 1992; Edwards et al., 1992; Teixeira et al., 2003; Vukasinovic et al., 2015). In contrast, the extractable soil Zn in the site with three years under NT was almost always lower in the deepest layer evaluated.

The concentrations of B, Cu, Fe, and Zn in the soybean leaves were not changed by lime rates (data not shown), which reflects the weak effect of liming on the extractable soil micronutrients. Fonseca et al. (2010) also did not observe a decrease in Cu, Fe, and Zn concentrations in wheat leaves due to surface liming in NT fields, but they did find that Mn concentrations decreased. In contrast, Soratto and Crusciol (2008) reported a lower concentration of Fe due to surface liming in NT in black oat plants during the first year of cultivation, but surface liming did not affect the Cu, Mn, and Zn concentrations. In the second year of cultivation, they found that only the Mn concentrations decreased with surface liming.

At the first sampling, the correlation coefficients between the concentrations of B, Cu, and Mn in the leaves and the extractable nutrients in the soil were positive (Table 8). At the R2 stage (time indicated for leaf diagnosis), the correlation coefficients between the B, Cu in the leaves and soil content were low and not significant. The correlation coefficients between the concentrations of Fe in the leaves and the extractable Fe in the soil were negative. Shuman and McCracken (1999b) found negative correlations between Mn and

Zn concentrations in corn leaves and extractable Mn and Zn in the soil under NT.

It appears that differences in micronutrient behaviour in soils under NT compared to soil under CT are mainly due to its higher OM content. It is possible that the extractors used in the present study, hot water for B and DPTA for Cu, Fe, Mn and Zn, were not as effective for soils under NT as they would be for CT soils in Brazil, as previously reported by Fonseca et al. (2010), in the case of cationic micronutrients and by Moreira et al. (2006) for Mn. Such soils usually have a high content of OM, which may form insoluble complexes with Cu, Fe, Mn, and Zn, thus decreasing the availability of such elements. Moreira et al. (2006) applied Mn doses of up to 48 kg ha^{-1} in soils under NT and observed minor variations in Mn accumulation in soybean. However, the amount of Mn in the soil organic portion changed from 15.5 to 51.9% of the Mn in soil, demonstrating that most of the applied Mn was retained in the OM. Based on these results and studies by electron paramagnetic resonance, Moreira et al. (2006) concluded that much of the Mn applied to the soil under NT is retained in the organic fraction in more stable forms and is therefore not available to plants.

There was an effect of lime rates and of the years under NT on the concentrations of Mn in soybean leaves only at the first sampling (Table 9). In the sites with six and nine years under NT, the lowest Mn concentration occurred both when the highest rate was broadcast with incorporation in the 0-0.20 m layer in the soil and in the plots with the shortest time under NT, when this rate was applied on the surface. In all locations, leaf Mn concentrations were adequate for soybean, according to Malavolta et al. (1997).

Table 7. Extractable soil Zn at different depths of a Red Latosol cultivated for three, six and nine years under no tillage as a function of lime rates.

Soil depth	Lime rate[1]				
	100 I	100 S	67 S	33 S	0
m			mg dm^{-3}		
			No tillage for three years		
0-0.05	4.7 aAB[2]	2.5 aB	2.3 aB	2.0 aB	9.8 aA
0.05-0.10	4.4 aB	1.8 aBC	1.6 abC	2.3 aBC	10.4 aA
0.10-0.20	3.7 aA	0.8 abB	1.3 abB	1.1 abB	4.1 bA
0.20-0.30	1.3 bA	0.4 bA	0.4 bA	0.3 bA	1.0 cA
			No tillage for six years		
0-0.05	1.5 aA	0.8 aA	0.7 aA	0.8 aA	1.3 aA
0.05-0.10	1.0 aA	0.6 aA	0.7 aA	0.6 aA	0.9 aA
0.10-0.20	1.4 aA	1.5 aA	0.7 aA	0.9 aA	1.5 aA
0.20-0.30	0.6 aA	0.8 aA	0.2 aA	0.3 aA	0.4 aA
			No tillage for nine years		
0-0.05	2.5 aA	1.3 aA	2.1 bA	2.1 abA	1.8 aA
0.05-0.10	2.4 aB	1.0 aB	5.0 aA	1.7 abB	2.7 aB
0.10-0.20	1.2 abAB	0.6 aB	2.8 abA	2.5 aA	1.1 aAB
0.20-0.30	0.5 bA	0.7 aA	0.5 cA	0.5 bA	0.5 aA
C.V.	34.0%				

[1]Percentage of the rate necessary to raise the base saturation to 70%; I = broadcast with incorporation in the 0-0.20 m layer; S = broadcast on the surface. [2]Lower case letters compare soil depths within each lime rate and each number of years under NT; upper case letters compare rates within each number of years under NT and each soil depth using the Tukey test at a significance level of 5%.

Table 8. Coefficients of linear correlation (r) between extractable soil micronutrients and concentrations in leaves in treatments with lime broadcast without incorporation at different times and soil depths.

Soil depth	B	Cu	Fe	Mn	Zn
m			Soybean V4 stage		
0-0.05	0.39 **	0.48 **	0.17 ns	0.53 **	-0.12 ns
0.05-0.10	0.52 **	0.43 **	-0.10 ns	0.50 **	0.33 *
0.10-0.20	0.57 **	0.37 **	-0.20 ns	0.37 **	0.48 **
0.20-0.30	0.45 **	0.36 *	-0.10 ns	0.36 *	0.09 ns
			Soybean R2 stage		
0-0.05	0.08 ns	0.14 ns	-0.40 **	0.34 *	0.57 **
0.05-0.10	0.11 ns	0.12 ns	-0.50 **	0.36 *	0.44 **
0.10-0.20	0.25 ns	0.12 ns	-0.50 **	0.30 *	0.18 ns
0.20-0.30	0.16 ns	0.22 ns	-0.40 **	-0.20 ns	0.20 ns

ns = non-significant, *significant at 5%, **significant at 1%.

Table 9. Concentration of Mn in leaves of soybean cultivated in a Red Latosol for different numbers of years under no tillage as a function of lime rates at two sampling times.

Years under no tillage	Lime rate[1]				
	100 I	100 S	67 S	33 S	0
			mg kg^{-1}		
			Soybean V4 Stage		
Three	35 abAB[2]	30 bB	33 bAB	40 bAB	43 bA
Six	44 aB	55 aAB	57 aA	52 aAB	57 aA
Nine	29 bB	31 bAB	33 bAB	36 bAB	41 bA
			Soybean R2 Stage		
Three	27 aA	31 aA	29 aA	30 aA	35 aA
Six	35 aA	29 aA	30 aA	29 aA	37 aA
Nine	24 aA	22 aA	24 aA	24 aA	29 aA
C.V.	13.1%				

[1]Percentage of the rate necessary to raise the base saturation to 70%; I = broadcast with incorporation in the 0-0.20 m layer; S = broadcast on the surface. [2]Lower case letters compare the number of years under NT within each lime rate and sampling time using Tukey's test at a significance level of 5%.

Conclusion

Results indicate that, in general, there were no differences in the extractable soil micronutrients and nutrient concentrations in the leaves of soybean as a function of years under no tillage, rates of lime applied and lime incorporation. These data suggest that current rates of lime applied to the soil surface in areas using no tillage do not necessarily lead to micronutrient deficiencies.

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