Acta Scientiarum
http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v42i1.42973

Soybean macronutrient availability and yield as affected by tillage system

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ABSTRACT. The effect of tillage system (NT-no tillage; CT-conventional tillage; MT-minimum tillage; and NT/scarification, every three years) on soybean nutrient availability and yield was evaluated on Oxisol after 12 years of cultivation. Soil samples were collected at depths of 0.00-0.05, 0.05-0.10, and 0.10-0.20 m and were analyzed for P, K, Ca, Mg, carbon (C), organic matter (OM), pH value, potential CEC, base saturation (BS%), and number of semiquinone organic radicals. The macronutrient concentration in the leaves and amount accumulated in the plants at the blooming stage were determined, as well as the yield of the two soybean crops. The soil pH value, BS% and K, Ca, and Mg concentrations were not influenced by the tillage system. The soil P and OM in the surface layer, however, were inversely proportional to the intensity of soil preparation. The P content in the soil surface layer under NT was twice as high as that of soil under CT. The P content in the soybean leaves under NT was also higher compared to that in the plants under CT and MT. The number of semiquinone radicals was low in the soil surface layer under NT, indicating a small degree of humification. However, soybean yield was not affected by the tillage system.

Keywords: no tillage; cropping systems; organic matter.

Received on May 24, 2018.
Accepted on September 11, 2018.

Introduction

Although it is recognized that a simple change of the cultivation system from conventional to NT does not increase OM throughout the soil profile, some studies have demonstrated that an increase in OM occurs in the surface layer of the soil, mainly from 0 to 0.05 m (Santiago, Quintero, & Delgado, 2008; Aziz, Mahmood, & Islam, 2013; Motschenbacher, Brye, Anders, & Gbur, 2014; Fink, Inda, Bavaresco, Barrón, & Torrent, 2016; Souza, Figueiredo, & Sousa, 2016). However, there is still a need for long-term studies relating the effect of cropping system to the degree of humification of humic substances (HS) in the surface layer of tropical soils. These data are relevant when one considers the role of more humified HS, such as humic acids and fulvic acids, in the physical-chemical properties of soils.

Martin-Neto, Rosell, and Sposito (1998), using electron paramagnetic spectroscopy (EPR or ESR, from electron spin resonance), detected an increase in the semiquinone free radical content in humic acids extracted from soils with an increase in mean annual rainfall along the temperate grassland climosequence from Argentina. They concluded that OM humification increased with increasing rainfall. In the early 2000s, Bayer, Martin-Neto, Mielniczukc, and Ernani (2002a) and Pérez et al. (2004) also used ESR to determine the semiquinone free radical content in humic substances extracted from soils under different management systems as an indicator of changes in OM characteristics.

In many cases, the adoption of NT has also resulted in an increased nutrient concentration in the surface layer, mainly from 0 to 0.05 m (Fonseca, Caires, & Barth, 2010). However, it has been rarely investigated whether increasing nutrients only in the surface layers could cause an increase in their availability to the plants. It has been reported that under NT cultivation, adsorption by soil colloids of applied phosphate is reduced as a result of fewer soil rotations and consequently reduced contact of phosphate ions with the soil particles (Rodrigues, Pavinato, Withers, Teles, & Herrera, 2016). Inorganic P is expected to increase in the soil surface because the sites of high adsorption become more saturated, reducing the bonding energy and increasing the diffusion of P to the soil solution (Rodrigues et al., 2016). In other words, the desorption of P applied as fertilizer in soils under NT will be higher than that in soils under CT (Pavinato, Dao, & Rosolem, 2010; Tiecher, Santos, Kaminski, & Calegari, 2012).

Despite the great importance of discussing the changes in soil attributes caused by the cultivation system, little information is available regarding the influence of these systems on the nutrient concentration in the leaves and nutrient accumulation in the plant. Therefore, the objective of this study was to evaluate the effect of different tillage systems on soil chemical attributes, on macronutrient concentration and accumulation in soybean plants and on crop yield.

Material and methods

The experiment was carried out at the Experimental Station of the ABC Foundation, located in the city of Ponta Grossa, Paraná State, southern Brazil. The geographic coordinates of locale are latitude of 25°0'51” S and longitude of 50°9'15” W and an altitude of 875 m. The region has a climate with fresh summer and severe and frequent frosts in the winter (climate is mesothermal humid subtropical-cfb). The average temperature of the hottest month is 22°C; the coldest, 18°C, with no dry season. According to the FAO classification system, the soil is a Rhodic Ferralsol (FAO, 1998).

The soil was cultivated with soybeans under CT for many years (*Glycine max* L. Merr.) before starting the experiment. In the winter of 1988, the soil acidity was corrected with the application of 7,300 kg ha^{-1} of lime incorporated 0.35 m deep with a moldboard plow. The chemical and physical characteristics of the soil samples after the liming of 1988 are shown in Table 1. In the winter of 1992 and 1994, two other surface lime applications of 2,000 kg ha^{-1} each were carried out.

Table 1. Chemical and granulometric properties of the Rhodic Ferralsol (dystrophic Red Latosol) at different depths in 1989 after liming (prior to experiment installation).

Depth	pH[1]	P	OM	K	Ca	Mg	V	Sand	Silt	Clay	Classification
m	$CaCl_2$	mg dm^{-3}	g dm^{-3}	—— mmol$_c$ dm^{-3} ——			%	—— g kg^{-1} ——			
0.00-0.10	5.6	6	35	3.7	37.5	29.6	59.6	300	70	630	very clayey
0.10-0.20	4.5	3	30	1.3	13.5	9.4	28.3	340	20	640	very clayey
0.20-0.30	4.3	0	23	0.8	6.5	4.9	16.6	300	70	630	very clayey

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

The field experiment was carried out in a randomized complete block design with subdivided plots, using three blocks. The main treatments consisted of four tillage systems; the secondary, three sampling depths (0.00-0.05, 0.05-0.10, and 0.10-0.20 m). The tillage systems were no-tillage (NT); conventional tillage (CT), consisting of one plowing with a reversible disc plow with three 36-inch discs (at ≅ 0.30 m) and a harrowing with a harrow with 32 20-inch discs (at ≅ 0.10 m), before the summer and winter crops of each year; minimum tillage (MT), consisting of one harrowing with a harrow with 16 32-inch discs (at ≅ 0.17 m) and two with a leveling harrow with 32 20-inch discs (at ≅ 0.10 m), before the summer and winter crops of each year; and NT with scarification every three years (NT/ scarification) with a subsoiler, cruiser type, with 5 stems and a working depth up to 40 cm (at ≅ 0.30 m), in winter. Scarification operations occurred in the years 1990, 1992, 1995, 1999, and 2002.

The size of the plots was 8.3 x 25.0 m (207.5 m²), and each plot consisted of 20 rows of soybean plants, with a central functional area of 10 rows 4 m long. The present study refers to the cropping years of 2000/2001 and 2001/2002, i.e., 12 years after installation of the experiment in the area. The cultivation history since the beginning of the experiment in the summer of 1990 is presented by Moreira, Prochnow, Kiehl, Pauletti, and Martin-Neto (2016).

Sowing soybeans (cultivar BRS 133) in the first and second crops was performed in December (12/29/00) and November (11/1/01), respectively, with 16 seeds per linear meter and spacing of 0.40 m between rows. For both crops (2000/2001 and 2001/2002), fertilization at planting consisted of 40 kg ha^{-1} of K_2O and 40 kg ha^{-1} of P_2O_5, according to official recommendations.

The precipitation and average monthly temperatures observed during the two crop cycles are presented by Moreira et al. (2016). From the sowing to harvesting the soybeans, it rained 567 mm during the

2000/2001 crop and 702 mm during the 2001/2002 crop. Thus, rainfall met the water needs of the soybean crop, which ranges from 450 to 800 mm throughout its lifecycle according to *Empresa Brasileira de Pesquisa Agropecuária* (EMBRAPA, 2013). All management decisions, such as inoculation, seed treatment, weed management, and management of diseases and pests, are presented by Moreira et al. (2016).

The soil samples were collected at depths of 0.00–0.05, 0.05–0.10, and 0.10–0.20 m in October 2001 with a soil auger sampler. For each plot, 20 single samples were randomly collected to form a composite. The samples were oven-dried at 40°C, milled and passed through a 0.002 m sieve. In sequence, samples were subjected to determination of pH in $CaCl_2$ and OM, P, K, Ca, and Mg according to Raij et al. (1987); BS% and CEC were calculated. Total C was also determined by dry combustion via Leco CN 2000. To estimate the values of pH, OM, BS%, CEC, and the macronutrient concentration of the whole 0.00-0.20 m soil layer, a weighted average of the data from each of the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers was calculated.

To evaluate the number of semiquinone free radicals in the samples, humic acid (HA) samples were extracted from the soil samples from the 0.00-0.05 and 0.05-0.10 m layers. The number of semiquinone free radicals was determined in the HA samples by electronic paramagnetic resonance (EPR) analysis at the Spectroscopy Laboratory of EMBRAPA/CNPDIA in São Carlos using a Bruker EPR Spectrometer, model EMX, X-band (≅ 9 GHz). The details are described by Moreira et al. (2016).

Leaf samples and plant shoot samples were collected in February 2001 (first crop) and January 2002 (second crop), when the soybean plants were in full bloom (R2 stage). Twenty three-leaflet samples were collected per plot, and the third leaf starting from the apex of the plant was removed. To assess the amount of nutrients accumulated in the plants, two plant shoots were collected per plot from two rows 0.5 m long. The leaf and shoot samples were washed, dried in an oven at 65°C until constant weight was reached and then ground. After drying and milling, the plant material was subjected to nitro-perchloric digestion for extraction of P, K, S, Ca, and Mg and to sulfuric digestion for extraction of N, according to the methods in Malavolta, Vitti, and Oliveira (1997).

The soybean yield was measured for the 2000/2001 and 2001/2002 cropping years. The harvests were carried out manually in the months of April 2001 and 2002. In each plot, 10 lines four-meters long were harvested. The threshing was performed mechanically using a stationary grain thresher, followed by sieving soon afterwards, weighing the grains and determining the moisture. The moisture was determined with a 'Universal Moisture Determiner'. The yield was calculated with a grain moisture of 13%.

After completing the experiment, the data were subjected to analysis of variance (ANOVA), and means were compared by Tukey's test ($p < 0.05$) whenever the F-test was significant using SISVAR software, ExpDes package (Ferreira, Cavalcanti, & Nogueira, 2014).

Results and discussion

In contrast to the results obtained by other authors, where the pH values of the surface layer were lower in soils under NT systems than in those under CT (Grove & Blevins, 1988; Tarkalson, Hergert, & Cassman, 2006; Martínez et al., 2016), pH was not modified by the tillage system in the present study (Tables 2 and 3); this observation agrees with Kibet, Blanco-Canqui, and Jasa (2016). Usually, the decrease in pH in soils under NT is caused by the application of high rates of nitrogen fertilizer in corn as a monoculture and/or under rotation with predominant grass crops (Grove & Blevins, 1988; Edwards, Wood, Thurlow, & Ruf, 1992; Reeves & Liebig, 2016).

It is known that hydrogen ions (H^+) are released during the transformation of ammonium-N (NH_4^+) by nitrifying bacteria to nitrate-N (NO_3^-), which results in lowering the pH value. Two moles of H^+ are produced per mole of NH_4^+ (Tarkalson et al., 2006). In monoculture systems with grasses, higher doses of N are applied than in systems with rotations of soybean crops, which explains the lower pH values observed in the former systems. The absence of mixing the soil could also cause the H^+ ions produced during OM mineralization to accumulate on the surface. In Brazil, soils under NT have shown higher pH values (Caires, Alleoni, Cambri, & Barth, 2005) and higher levels of Ca and Mg in the surface layer than in other layers mainly due to the application of lime without incorporation to the surface of these soils (Fonseca et al., 2010).

Table 2. Chemical properties of the Rhodic Ferralsol (dystrophic Red Latosol) at different depths after 12 years of cultivation under different tillage systems (average of three replicates).

Tillage system	pH	P	OM	C[2]	K	Ca	Mg	CEC	BS
	$CaCl_2$	mg dm^{-3}	— g dm^{-3} —		— mmol$_c$ dm^{-3} —				%
				0.00-0.05 m					
NT[1]	5.6 Aa[3]	83 Aa	58 Aa	37.2 Aa	4.4 Aa	71.3 Aa	28.3 Aa	136.7 Aa	75 Aa
CT	5.9 Aa	39 Ab	46 Ac	26.9 Ab	4.1 Aa	45.0 Aa	19.0 Aa	104.1 Aa	65 Aa
MT	6.0 Aa	42 Aab	51 Abc	30.3 Ab	4.4 Aa	48.7 Aa	20.0 Aa	106.4 Aa	69 Aa
NT/scarif.	5.5 Aa	60 Aab	56 Aab	36.2 Aa	4.0 Aa	50.0 Aa	22.3 Aa	115.0 Aa	66 Aa
				0.05-0.10 m					
NT	5.5 Aa	78 Aa	44 Ba	26.5 Ba	3.2 Aa	54.7 Aa	21.7 Aa	114.2 Aa	70 Aa
CT	5.6 Aa	32 Ab	45 Aa	26.5 Aa	2.8 Aa	41.7 Aa	17.3 Aa	99.2 Aa	62 Aa
MT	6.0 Aa	40 ABab	49 Aa	28.9 Aa	3.0 Aa	45.7 Aa	19.3 Aa	102.3 Aa	66 Aa
NT/scarif.	5.5 Aa	44 Aab	43 Ba	27.9 Ba	2.6 Aa	46.7 Aa	19.0 Aa	102.9 Aa	66 Aa
				0.10-0.20 m					
NT	5.9 Aa	37 Ba	40 Ba	22.7 Ca	2.9 Aa	40.7 Aa	18.7 Aa	100.6 Aa	62 Aa
CT	5.8 Aa	29 Aa	44 Aa	24.2 Aa	2.7 Aa	43.7 Aa	17.7 Aa	100.4 Aa	63 Aa
MT	5.9 Aa	22 Ba	39 Ba	22.9 Ba	2.7 Aa	40.0 Aa	18.0 Aa	94.4 Aa	64 Aa
NT/scarif.	5.4 Aa	41 Aa	41 Ba	23.2 Ca	2.0 Aa	41.3 Aa	14.7 Aa	97.3 Aa	58 Aa
C.V	6.7%	20.3%	6.2%	4.9%	7.7%	18.2%	12.6%	9.6%	7.6%

[(1)]NT: no tillage; CT: conventional tillage; MT: minimum tillage and NT/scarif.: scarification (≅ 0.30 m) every three years. [(2)]Carbon determined by dry combustion. [(3)]Lowercase letters compare tillage systems within each soil depth, and uppercase letters compare soil depths within each tillage system via Tukey's test at 5%.

The absence of variation in the pH value due to the cropping system (Tables 2 and 3) can be largely attributed to the small amount of N applied to the soil compared to the rates used in North America. In the present study, soybean is the main crop in the rotation without N application. Another fact is that the amount of N applied to maize and wheat crops was much lower than that used in the USA. In the present study, for the last three years (1999 to 2001), 162.5 kg ha^{-1} of N was applied (97.5 and 65 kg ha^{-1} to maize crops in 1999 and wheat in 2001, respectively), i.e., approximately 54 kg ha^{-1} year^{-1} of N (Moreira et al., 2016). In one year, Edwards et al. (1992) applied a total of 280 kg ha^{-1} of N to the wheat and corn crops. Motschenbacher et al. (2014) applied 337 kg ha^{-1} of N to only a single corn crop. It is worth noting that Grove and Blevins (1988) did not observe a reduction in the pH value with annual doses of up to 168 kg ha^{-1} of N applied to corn.

Table 3. Chemical properties of the dystrophic Red Latosol in the 0.00-0.20 m layer (weighted averages of data from the 0.00-0.05, 0.05-0.10 and 0.10-0.20 m layers) after 12 years of cultivation under different tillage systems (average of three replicates).

Tillage system[1]	pH	P	OM	C[2]	K	Ca	Mg	CEC	BS
	$CaCl_2$	mg dm^{-3}	— g dm^{-3} —		— mmol$_c$ dm^{-3} —				%
NT	5.8 a	59 a	46 a	27 a	3.4 a	52 a	22 a	113 a	67 a
CT	5.8 a	32 b	45 a	25 a	3.1 a	44 a	17 b	101 a	64 a
MT	5.9 a	31 b	44 a	26 a	3.2 a	44 a	19 ab	99 a	66 a
NT/scarif.	5.4 a	47 ab	45 a	28 a	2.7 a	45 a	19 ab	103 a	52 a

[(1)]NT: no tillage; CT: conventional tillage; MT: minimum tillage and NT/scarif.: scarification (≅ 0.30 m) every three years. [(2)]Carbon determined by dry combustion. [(3)]Lowercase letters compare tillage systems via Tukey's test at 5%.

The P level of the surface layer, which doubled in the NT system after 12 years of cultivation compared to that in the CT system, was inversely proportional to the intensity of soil preparation (Table 2). This is extremely important since the amount of phosphate fertilizer added over the years was the same in all systems. When considering the entire 0.00-0.20 m soil layer, the calculated average P concentration was also higher in NT than in CT (59 and 32 mg dm^{-3}, respectively) (Table 3). In Brazil, P-resin levels in the range of 16-40 mg dm^{-3} in the 0.00-0.20 m soil layer are considered "medium" for fertilization recommendation purposes, while levels in the 40-80 mg dm^{-3} range are considered "high" (Raij, Cantarella, Quaggio, & Furlani, 1997). Thus, based on the results of this study, it can be said that the NT system increased the soil P status from medium to high, which would, in practice, result in a significant reduction in the need of P from fertilizer for the crop. Currently, the recommendations for phosphate fertilizers in Brazil are based on the expectation of productivity and soil content. In this way, the P application rate is reduced as the nutrient content of the 0.00 to 0.20 m layer of the soil is increased (EMBRAPA, 2013).

A higher P content in surface soil under NT, compared to CT, was also observed by other authors (Rodrigues et al., 2016). As the soil tillage intensity increases, the P applied as fertilizer comes into contact more often with the soil particles. In NT, the absence of soil rotations decreases the contact between the applied P and the soil colloids and, therefore, reduces the adsorption of Fe and Al oxides (Rodrigues et al., 2016), increasing their desorption and availability (Pavinato et al., 2010; Tiecher et al., 2012).

In addition, in the NT system, there is an increase in organic P due to the increase in OM (Rodrigues et al., 2016), which is mainly due to the accumulation of crop residues on the soil surface. The slow decomposition of these residues helps maximize the use of organic P as a source of P for plants via the synchronization of nutrient availability and plant growth. Since soil losses due to runoff and erosion are not a major problem in soils under NT (Triplett & Dick, 2008), even if the NT impact is small and restricted to the topsoil, NT contributes to the increase of organic P.

The C and OM content of the surface layer, which was higher in the NT system than that in CT, was inversely proportional to the intensity of the soil preparation (Table 2); this result was also found by several other authors (Santiago et al., 2008; Aziz et al., 2013; Motschenbacher et al., 2014; Souza et al., 2016; Fink et al., 2016). Under CT, soil disturbance accelerates the decomposition of OM because it increases soil aeration and the activity of microorganisms.

The higher OM content in the soil surface under the NT system compared to that under the CT system has been attributed to the lower decomposition rate of the plant residues on the surface; the lower decomposition rate is due to the lower temperature and aeration of the soil, since in the NT system, the soil is not rotated (Motschenbacher et al., 2014), and the amount of fresh plants introduced is the same in both systems. The accumulation of C and OM in the soil surface under NT increases over the years as indicated by the vertical stratification of the OM content of soils under NT.

It is believed that the increase in the OM content at the surface is faster if rotations with a predominance of grasses that produce high amounts of residues are used (Souza et al., 2016). This fact is more relevant, especially for soils under Cerrado, where the decomposition process is faster due to higher moisture and temperature conditions (Silva, Bonetti, Souza, Paulino, & Carneiro, 2016). This is why, in some cases, increases in the OM content of soils under Cerrado cultivated under NT occur only after long periods. Silva et al. (2016) did not observe a recovery of the OM content back to the original value existing in the native Cerrado areas after 10 years of cultivation.

The K content was not modified by the tillage system (Tables 2 and 3), and there was no increase in the concentration of this nutrient in the surface layer (Table 3), as observed in other studies (Motta, Reeves, & Touchton, 2002; Sainju, Allen, Caesa-Tonthat, & Lenssen, 2015; Martínez et al., 2016). However, a number of researchers have documented higher levels of K in the surface layer of soils under CT than under NT (Edwards et al., 1992; Tarkalson et al., 2006; Sainju et al., 2015). These divergent results may be due to variations in the quantity of K exported by the crops used in the experiments, as well as variations in the application rates of the fertilizers and leaching conditions at the different experimental sites (Motta et al., 2002). The differences in clay content and composition among the soils of the experimental sites can also explain the divergent results. It is known that potassium is not part of the organic constituents of plant residues. Thus, K salts in the residues are readily washed out by rainfall and subsequently leach downward in the soil profile, as observed by Tarkalson et al. (2006) in the soil under NT and CT. Thus, no relationship would be expected between residue inputs with NT and K levels in the surface soil.

The Ca content was not influenced by the tillage system, while the Mg level, which was larger in the NT than in the CT system, was altered only when the average content of the whole 0.00-0.20 m layer was considered (Tables 2 and 3). Usually, it has been observed that these nutrients occur at higher concentrations in the surface layer of soils under NT than under CT (Motta et al., 2002; Martínez et al., 2016). In Brazil, soils under NT have shown higher levels of Ca and Mg in the first centimeters of the soil layer, mainly due to lime application practices (Caires et al., 2005; Fonseca et al., 2010). Over time, there has been a vertical stratification of these nutrients, with higher contents in the surface layer under NT.

The absence of variation in the Ca and K levels and small variation of soil Mg found in the present study explains why the tillage system did not modify the CEC and BS% of the soil (Tables 2 and 3), since these two parameters are a function of the content of those nutrients. A higher BS% with more Ca, Mg, or K would be linked to a higher soil pH, which would increase the pH-dependent colloidal charge and thus CEC, but this effect was not observed. Specifically, it was expected that CEC would be modified by the tillage system at least in the 0.00-0.05 cm layer of NT soil due to the higher amount of OM in this layer (Table 2), as observed by Lal, Mahboubi, and Fausey (1994). In turn, Tarkalson et al. (2006) observed an increase in CEC but a reduction in Ca, K, and BS% in the soil under NT. They explained this result by the greater removal of nutrients from the soil due to the higher yields under NT compared to that from soils under CT.

For Brazilian soils, the contents of Ca and Mg observed at all depths are considered high, while the content of K varied from medium to high, according to the levels established by Raij et al. (1997). High Ca, Mg, and K contents are usually found in soils with adequate or elevated pH. High pH values could also increase the pH-dependent colloidal charge and thus CEC.

The number of semiquinone organic radicals of the HA extracted from the surface layer increased with the intensity of soil preparation (Figure 1). There is a consensus in the literature that the larger the amount of semiquinone free radicals obtained by electronic paramagnetic resonance (EPR), the higher the degree of humification of the HS is (Bayer, Martin-Neto, Mielniczukc, & Ceretta, 2000; Martin-Neto et al., 1998). Thus, it can be said that the HA extracted from the 0.00-0.05 m layer of the soil under CT was more humified than the HA of the soil under NT. In contrast, Pérez et al. (2004) did not find a significant effect of tillage system on the quality of soil OM after five years of cultivation. The authors attributed this fact to the high clay content of the soil, which would protect the clay–Fe–OM complex against strong structural alterations.

The results obtained in the present study are similar to other results obtained with soils from the state of Rio Grande do Sul (Bayer et al., 2000; Bayer, Martin-Neto, Mielniczukc, & Ernani, 2002a and b), where the climatic conditions (rain, air humidity and temperature) are similar to those in the current study location (central-southern region of Paraná). In places where the soil is constantly rotated, increased aeration accelerates the decomposition of the crop residues, leading to the formation of a more humified OM (Bayer et al., 2002b). The result of the lower decomposition rate of OM in the NT system is that the newly added OM has a lower degree of humification. Bayer et al. (2000) studied the effect of 12 years of cultivation under NT on the amount of semiquinone free radicals in HA with different crops; they found that higher amounts of crop residues on the surface resulted in a lower number of free radicals because the newly added OM has a low degree of humification compared to the native OM of the soil (Bayer et al., 2002 a and b).

The rapid decomposition of crop residues on the surface of soils under CT leads to the synthesis of high-molecular-weight stable polymers in the soil. In contrast, the decomposition of OM in the NT system is slower, leading to the coexistence of HS of various molecular sizes (or molecular weights) and chemical compositions (Evangelou and Marsi, 2001). In the present study, there was a tendency for soils under NT to have a lower amount semiquinone free radicals (Figure 1) and, therefore, lower synthesis of stable polymers in the soil. Thus, the OM content was lower in the surface layer of the soil conventionally tilled (Tables 2 and 3) but showed a higher degree of humification, as reflected by the greater number of semiquinone free radicals.

The leaf concentrations of N, K, Ca, Mg, and S were not influenced by the tillage system (Table 4). This can be explained, with the exception of Mg, by the fact that the levels of Ca and K in the soil were also not modified by the tillage system (Table 3). In addition, these levels were within or above the range considered adequate by Raij et al. (1997) independent of the tillage system. It is also noted that the leaf concentrations of K, Ca and Mg were within the sufficiency range described as suitable for soybean by Malavolta et al. (1997), which are 17 to 25, 4.1 to 10.0, and 3.1 to 10.0 for K, Ca, and Mg, respectively. However, the N concentration in the soybean leaves cultivated under the systems with the highest soil turnover (CT and MT) and the concentration of S in the leaves of plants grown under MT were slightly below the levels considered suitable by Malavolta et al. (1997), which are N = 45 to 55 g kg^{-1} and S = 2.5 g kg^{-1}.

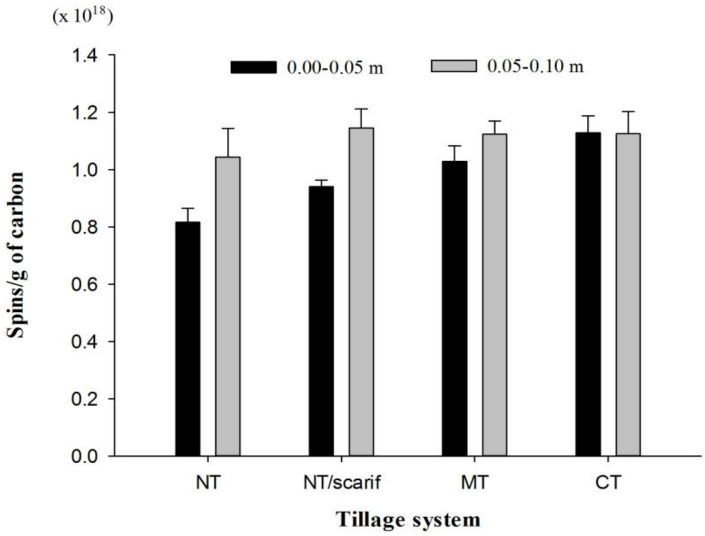

Figure 1. Number of semiquinone radicals in HA samples extracted from the 0.00-0.05 and 0.05-0.10 m layers of Red Latosol cultivated under different tillage systems (NT: no tillage; CT: conventional tillage; MT: minimum tillage; and NT/scarif.: scarification with a subsoiler (≅ 0.30 m) every three years. Error bars represent the standard error of the mean (n = 2).

Table 4. Macronutrient concentrations in the soybean leaves as a function of tillage system (average of three replicates).

Tillage system[1]	N	P	K	Ca	Mg	S
			$g\ kg^{-1}$			
NT	40.5 a[2]	3.3 a	27.3 a	7.9 a	3.7 a	2.4 a
CT	39.9 a	2.5 b	29.9 a	8.6 a	3.6 a	2.4 a
MT	36.6 a	2.4 b	26.2 a	9.1 a	3.5 a	2.0 a
NT/scarif.	42.4 a	3.0 ab	26.3 a	6.9 a	3.3 a	2.5 a

(1)NT: no tillage; CT: conventional tillage; MT: minimum tillage; and NT/scarif.: scarification (≅ 0.30 m) every three years. (2)Numbers followed by the same letter in each column do not differ by Tukey's test at 5%.

As in the present work, Nielsen and Woodard (2015) also did not observe differences in the foliar concentration of N and K in plants grown under NT and CT. Lavado, Porcelli, and Alvarez (2001) did not observe an effect of these cropping systems on the concentration of K and S in soybean leaves.

The concentrations of P in the analyzed leaves of plants grown under the NT system were higher than those of plants under the systems with the highest turnover (CT and MT) (Table 4). It should be noted that in these two cases, P concentrations were below the levels suggested as adequate by Malavolta et al. (1997) (2.6 to 5.0 g kg^{-1}). Soils under NT have a higher moisture content in the surface layer than soils under CT, which favors the diffusion of P to the plant roots. Contrary to what was found in the present study, Nielsen and Woodard (2015) did not observe differences in leaf concentration of P in plants grown under NT and CT. According to the authors, these results could have been much different in a warmer season where growth could have been stimulated to a greater extent. Cooler than normal soil conditions in the early part of the growing season probably slowed the diffusion rate of nutrients.

The higher concentration of P in the leaves of the plants grown under NT (Table 4) can be explained by the higher level of P in the soil under this tillage system (Tables 2 and 3). In the soil under CT, P levels at depths of 0-0.05 m, 0.05-0.10 m and 0-0.20 m were within the range of levels considered "medium" (16 to 40 mg dm^{-3}) according to Raij et al. (1997), while in the soil under NT for the same depths, the P levels were in the "high" range (41 to 80 mg dm^{-3}). Thus, it is possible to say that changing the cultivation system from CT to NT would promote the P status of the soil, promoting P absorption by the plants. This fact is extremely important since the amount of P added to the soil under the different tillage systems was the same over time. Thus, it can be inferred that the adoption of NT in tropical soils with low initial levels of P improves nutrient utilization, contributing to a reduction in costs over the years. This fact can be confirmed by the low response of soybeans to applied P in soils that have adequate levels of P and have been cultivated under NT for a long time (Lacerda, Resende, Furtini-Neto, Hickmann, & Conceição, 2015).

Although soybeans cultivated under the NT system showed a higher foliar concentration of P (Table 4), the accumulation of this nutrient in the plants was similar under the different systems (Table 5). With the exception of Ca, which was higher in CT compared to NT/scarif., the accumulated amount of macronutrients was not influenced by the cropping system; a fact that was expected considering the small differences in leaf concentrations and the uniformity of plant growth.

It is worth mentioning that the plants were collected for analysis during full bloom (R2 stage). At that time, soybean plants are still absorbing nutrients, and uptake is the most intense during grain filling (from the R5.1 stage), as observed by Zobiole et al. (2012) and Pedrinho-Junior, Bianco, and Pitelli (2004). Thus, differences in nutrient accumulation could likely occur if the analysis had been performed at the end of the grain filling stage of the crop.

Table 5. Macronutrients accumulated in the top of the soybean plant as influenced by tillage system (average of three replicates).

Tillage system	N	P	K	Ca	Mg	S
				gram[2]		
NT	4.9 a[3]	0.5 a	5.4 a	1.6 ab	0.8 a	0.3 a
CT	5.5 a	0.4 a	5.5 a	1.8 a	0.8 a	0.4 a
MT	5.7 a	0.5 a	6.0 a	1.8 ab	0.8 a	0.4 a
NT/scarif.	4.8 a	0.4 a	5.3 a	1.5 b	0.7 a	0.3 a

(1)NT: no tillage; CT: conventional tillage; MT: minimum tillage; and NT/scarif.: scarification (≅ 0.30 m) every three years. (2)Nutrients accumulated in the dry matter of plants collected in 1.0 linear meter. (3)Numbers followed by the same letter in each column do not differ by Tukey's test at 5%.

The cultivation system did not influence soybean yield in either of the two cropping years. In the 2000/01 cropping year, the average yield of soybeans under NT, CT, MT, and CT/scarification was 3,872, 3,939, 3,855, and 3,828 kg ha^{-1}, respectively. In the 2001/02 harvest, the average was 3,207, 3,094, 3,214, and 2,907 kg ha^{-1}

under NT, CT, MT, and CT/scarification, respectively. Similar results were observed by Nielsen and Woodard (2015) in North American soils. On the other hand, other authors found higher grain yields of soybeans cultivated under NT than under CT (Edwards, Thurlow, & Eason, 1988), and the same has been true for other crops under NT (Tarkalson et al., 2006).

The grain yields obtained under CT can be higher than those under NT in specific situations, as was observed by Dick, McCox, Edwards, and Lal (1991) in poorly drained organic soils in the USA or in places with low temperatures during plant growth (Triplett Jr. & Dick, 2008; Nielsen & Woodard, 2015, Cook & Trlica, 2016). In this situation, the presence of crop residues on the surface increases water availability, decreases soil temperature, impairs seed germination, and favors the loss of nitrate via denitrification due to an increase in the redox potential of the soil. Wilhelm and Wortmann (2004) observed higher yields of soybean grains in NT soils in warmer and wetter years, as well as in extremely hot and dry years, than in other years. No-tillage tended to have greater yields than conventional tillage in the southern and western regions of the United States, similar yields in the central region, and lower yields in the northern United States and Canada (Triplett & Dick, 2008). Under stress conditions, the retention of soil moisture as a result of increased residue cover under NT likely contributed to higher NT yields (Tarkalson et al., 2006). In summary, based on several studies found in the literature, Nielsen and Woodard (2015) affirmed that crop residue cover not disturbed by tillage resulted in retention of greater soil moisture and reductions in temperature fluctuation compared to that of soils under NT. It can also be concluded that during years of extreme heat and drought, the increased surface residue from no-till may benefit the growing environment by moderating temperature and maintaining moisture levels throughout the growing season.

Conclusion

The soil pH value, BS (%) and K, Ca, and Mg concentrations were not influenced by the tillage system. The P and OM levels were higher in NT soils compared to those in soils under minimal and conventional cultivation. The P concentration in the soybean leaves under NT was also higher compared to that in the plants under CT and MT. The number of semiquinone radicals of the humic acid extracted from the surface layer increased with the intensity of soil preparation, which indicates a higher degree of humification. Soybean yield was not affected by the tillage system.

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