SEÇÃO VI - MANEJO E CONSERVAÇÃO DO SOLO E DA ÁGUA

CROP SEQUENCES IN NO-TILLAGE SYSTEM: EFFECTS ON SOIL FERTILITY AND SOYBEAN, MAIZE AND RICE YIELD[1]

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SUMMARY

Decomposing crop residues in no-tillage system can alter soil chemical properties, which may consequently influence the productivity of succession crops. The objective of this study was to evaluate soil chemical properties and soybean, maize and rice yield, grown in the summer, after winter crops in a no-tillage system. The experiment was carried out in Jaboticabal, SP, Brazil (21 ° 15 ' 22 " S; 48 ° 18 ' 58 " W) on a Red Latosol (Oxisol), in a completely randomized block design, in strip plots with three replications. The treatments consisted of four summer crop sequences (maize monocrop, soybean monocrop, soybean/maize rotation and rice/bean/cotton rotation) combined with seven winter crops (maize, sunflower, oilseed radish, pearl millet, pigeon pea, grain sorghum and sunn hemp). The experiment began in September 2002. After the winter crops in the 2005/2006 growing season and before the sowing of summer crops in the 2006/2007 season, soil samples were collected in the layers 0–2.5; 2.5–5.0; 5–10; 10–20; and 20–30 cm. Organic matter, pH, P, K^+, Ca^{2+}, Mg^{2+}, and H + Al were determined in each soil sample. In the summer soybean/maize rotation and in maize the organic matter contents and P levels were lower, in the layers 0–10 cm and 0–20 cm, respectively. Summer rice/bean/cotton rotation increased soil K levels at 0–10 cm depth when sunn hemp and oilseed radish had previously been grown in the winter, and in the 0–2.5 cm layer for millet. Sunn hemp, millet, oilseed radish and sorghum grown in the winter increased organic matter contents in the soil down to 30 cm. Higher P levels were found at the depths 0–2.5 cm and 0–5 cm, respectively, when sunn hemp and oilseed radish were grown in the winter. Highest grain yields for soybean

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in monoculture were obtained in succession to winter oilseed radish and sunn hemp and in rotation with maize, after oilseed radish, sunn hemp and millet. Maize yields were highest in succession to winter oilseed radish, millet and pigeon pea. Rice yields were lowest when grown after sorghum.

Index terms: winter crops, crop rotation, cover crops, soil management.

RESUMO: *SEQUÊNCIAS DE CULTURAS EM SEMEADURA DIRETA: EFEITOS SOBRE A FERTILIDADE DO SOLO E A PRODUTIVIDADE DE SOJA, MILHO E ARROZ*

Os resíduos vegetais das culturas, ao se decomporem, alteram os atributos químicos do solo e, como consequência, influenciam a produtividade das culturas em sucessão. O objetivo deste trabalho foi avaliar os atributos químicos do solo e a produtividade das culturas de soja, milho e arroz, cultivadas no verão, em sucessão a culturas de inverno em semeadura direta. O experimento foi realizado em Jaboticabal-SP (48 ° 18 ' 58 " W e 21 ° 15 ' 22 " S), em um Latossolo Vermelho eutrófico. O delineamento experimental foi em blocos ao acaso, no esquema em faixas, com três repetições. Os tratamentos foram constituídos pela combinação de quatro sequências de culturas de verão (monoculturas de milho e soja e rotações soja/milho e arroz/feijão/algodão) com sete culturas de inverno (milho, girassol, nabo forrageiro, milheto, guandu, sorgo e crotalária). Os cultivos iniciaram-se em 2002. Após o manejo das culturas de inverno e antes da semeadura das culturas de verão do ano agrícola 2006/2007, foram coletadas amostras de solo nas camadas de 0–2,5; 2,5–5,0; 5–10; 10–20; e 20–30 cm. Nas amostras de solo, foram determinados: teores de matéria orgânica, pH, teores de P (resina), K, Ca e Mg trocáveis e acidez potencial (H + Al). As sequências de verão rotação soja/milho e milho em monocultura proporcionaram no solo menores teores de matéria orgânica na camada de 0–10 cm e de P do solo na camada de 0–20 cm. Na sequência de verão arroz/feijão/algodão, maiores teores de K foram proporcionados pelas culturas de inverno crotalária e nabo forrageiro, na camada de 0–10 cm, e milheto, na de 0–2,5 cm. Crotalária, milheto, nabo forrageiro e sorgo, cultivados no inverno, proporcionaram maiores teores de matéria orgânica no solo na camada de 0–30 cm. Maiores teores de P no solo foram proporcionados pela crotalária, na camada de 0–2,5 cm, e pelo nabo forrageiro, na de 0–5 cm. Maiores produtividades de soja, como monocultura de verão, foram obtidas após nabo forrageiro e crotalária e, quando em rotação com milho no verão, após nabo forrageiro, crotalária e milheto. Maiores produtividades de milho foram obtidas após nabo forrageiro, milheto e guandu, e menor produtividade de arroz foi obtida após sorgo.

Termos de indexação: culturas de inverno, rotação de culturas, plantas de cobertura, manejo do solo.

INTRODUCTION

In the no tillage system, the rotation of crops with species that increase plant residues on soil surface is fundamental to avoid erosion and to improve nutrient cycling through nutrient mobilization from deeper soil layers (Crusciol et al., 2005) to the top. Plant residues of untilled crops form a nutrient reserve (Rosolem et al., 2003) and, depending on the species, soil chemical properties may be altered during plant decomposition, which may have an influence on the following crop. Therefore, the use of species different from the main crop contributes to the soil nutrient balance, which may consequently increase soil fertility over time.

The amount and quality of plant residues are related to how long they persist on the soil surface and determine the no-tillage efficiency, which reinforces the importance of an appropriate crop rotation system (Torres et al., 2005). Climate adaptation is highly important when choosing the species for a crop system (Ceretta et al., 2002). Other desirable characteristics, such as high dry matter production, fast establishment and easy management, as well as a deep and vigorous root system are also required. It is essential that crops are not susceptible to plant diseases or prone to pest infestation. Additionally, the interest of producers in market prospects for sales must be taken into account.

Leguminous species are known for their capacity to fix atmospheric nitrogen and narrow the C/N ratio, resulting in faster residue decomposition (Aita & Giacomini, 2003) and consequent release of accumulated N and other nutrients, such as P and K, to the soil. Borkert et al. (2003) quantified nutrient accumulation in pigeon pea residues with a dry matter production of 6,165 kg ha^{-1} and found about 185.6 kg ha^{-1} N, 17.9 kg ha^{-1} P and 87.5 kg ha^{-1} K. Besides, Alcântara et al. (2000) evaluated the 0–5 cm layer, 90 days after pigeon pea cutting and observed K levels that were 3.6 and 6.3 times higher than those found after sunn hemp and *Brachiaria*, respectively. This indicates that leguminous species accumulate and increase nutrient availability, resulting in a high dry matter production reported for the following crops. Nevertheless, fast decomposition of cover crop residues may affect soil protection against erosive effects.

On the other hand, decomposition of grass residues is slow and the mulch may remain for a longer period on the soil surface, due to a higher C/N ratio, which decreases erosion and is desirable in the no-tillage system. However, the slower the residue decomposition, the lower the ratio for nutrient release to soil, resulting in microbial N immobilization (Ernani et al., 2005). Grasses are more tolerant to water stress, have a high dry matter production and have been used successfully as cover crops, particularly millet. When studying the millet cultivar ADR500 as relay crop in the Cerrado region, Boer et al. (2007) found high K accumulation in plant residues (417 kg ha^{-1}) when 10,800 kg ha^{-1} dry matter was evaluated and a cut was carried out at flowering. Braz et al. (2004) reported that millet (cultivar BN-2) with a dry matter production of 12,533 kg ha^{-1} may accumulate 348 kg ha^{-1} N and 314 kg ha^{-1} K in leaves in 52 to 55 days. As in millet, nutrient accumulation in sorghum plant residues is considerable, although a grain harvest is also possible. Oliveira et al. (2002) cut sorghum 100 days after sowing and reported 15,480 kg ha^{-1} dry matter production, in which 199 kg ha^{-1} N and 248 kg ha^{-1} K were found. These accumulated nutrients are available for the following crops and influence grain yield.

The purpose of this study was to evaluate soil chemical properties and yields of soybean, maize and rice, grown in summer, after no-tillage winter crops.

MATERIAL AND METHODS

The experiment was carried out in Jaboticabal, SP, Brazil (48 ° 18 ' 58 " W; 21 ° 15 ' 22 " S; 595 m asl). The climate is Aw, according to the Köppen classification, with a mean annual rainfall of 1,425 mm, between October and March. Mean annual temperature and relative humidity are 22 °C and 70 %, respectively.

The soil of the experimental area was a Red Latosol (Oxisol) A moderate hypoferric clay texture, and gentle slopes (Embrapa, 2006). The 0–20 cm layer contained 370 g kg^{-1} sand, 65 g kg^{-1} silt and 565 g kg^{-1} clay. Before this experiment, the area had been used for soybean and maize production in a conventional system for 20 years. Soil chemical properties of the arable layer (0–20 cm) were determined before the beginning of the experiment, according to Raij et al. (2001) as follows: pH ($CaCl_2$) = 5.0; organic matter = 19 g dm^{-3}; P (resin) = 13 mg dm^{-3}; K = 4.1; Ca = 15; Mg = 9; H + Al = 34 and CEC = 62.1, in $mmol_c$ dm^{-3}, and 45 % base saturation.

In the beginning of the experiment, soil subsoiling at a depth of 40 cm and liming to increase base saturation up to 65 % were carried out to improve the soil chemical and physical properties. Plowing and disking were used to incorporate 1.5 Mg ha^{-1} lime (ECC = 100 %). Surface liming took place in June 2005 and 1.0 Mg ha^{-1} lime (ECC = 70 %) was applied with no incorporation, to increase base saturation up to 65 %.

The experiment had a completely randomized block design, in strip plots with three replications. Every experimental block had 28 plots, which consisted of four summer crop sequences combined with seven winter crops. The summer crop sequences were the following: MM – maize monocrop (*Zea mays* L.); SS – soybean monocrop (*Glycine max* L. Merrill); SM – soybean/maize rotation, both intercropped every other year; and RBC – rice/bean/cotton rotation, with rice (*Oryza sativa* L.), bean (*Phaseolus vulgaris* L.) and cotton (*Gossypium hirsutum* L.) in rotation. Winter crops consisted of maize, sunflower (*Helianthus annuus* L.), oilseed radish (*Raphanus sativus* L.), millet (*Pennisetum americanum* (L.) Leeke), pigeon pea (*Cajanus cajan* (L.) Millsp), grain sorghum (*Sorghum bicolor* (L.) Moench) and sunn hemp (*Crotalaria juncea* L.), sown in February/March (relay crops). In each growing season, the same winter crop was sown in the same plot. The useful area of the experimental plots was 200 m^2 (20 x 10 m).

The experiment began in September 2002 and was carried out during the growing seasons of 2002/2003, 2003/2004, 2004/2005, 2005/2006 and 2006/2007. In 2004/2005, due to irregular rainfall, winter crops were not sown and fallow was considered instead. Results of this study were taken from the evaluations of 2006/2007, when summer crops consisted of soybean (SM rotation) and rice (RBC rotation). Grain yield of summer crops in succession to winter crops was evaluated from the beginning of the experiment (Table 1). Monthly accumulated rainfall and average temperatures from August 2002 to March 2007 are listed in figure 1.

During the experiment and before summer and winter crop sowing, plant residues were ground using a straw crushing-shredding device, to ensure an even distribution and soil cover. About three days after cutting, weeds were chemically desiccated through the application of 960 g ha^{-1} glyphosate.

Table 1. Soybean, maize, rice and bean grain and cotton seed yield in each summer crop sequence after the winter crops during the experiment

Winter crop	Growing seasons			
	2002/2003(1)	2003/2004	2004/2005	2005/2006
	kg ha^{-1}			
	Summer maize monocrop			
Maize	-	7,156	6,273	7,911
Sunflower	-	6,192	6,437	8,199
Oilseed radish	-	6,913	7,322	8,252
Pearl millet	-	6,983	7,459	8,707
Pigeon pea	-	6,671	7,392	7,987
Grain sorghum	-	6,133	6,139	7,315
Sunn hemp	-	6,553	7,660	7,229
Mean	6,288	6,657	6,955	7,943
	Summer soybean monocrop			
Maize	-	2,955	3,284	3,123
Sunflower	-	2,704	2,916	2,765
Oilseed radish	-	3,052	3,710	2,569
Pearl millet	-	3,038	3,403	2,801
Pigeon pea	-	2,805	3,331	3,170
Grain sorghum	-	3,007	2,303	2,500
Sunn hemp	-	3,085	4,012	2,868
Mean	3,199	2,949	3,280	2,828
	Summer soybean/maize rotation			
	(soybean)	(maize)	(soybean)	(maize)
Maize	-	6,609	3,301	8,333
Sunflower	-	6,752	3,188	8,476
Oilseed radish	-	7,210	3,446	8,655
Pearl millet	-	7,785	3,372	8,318
Pigeon pea	-	6,464	3,076	8,745
Grain sorghum	-	5,910	2,388	8,422
Sunn hemp	-	7,463	3,750	8,430
Mean	3,444	6,885	3,217	8,483
	Summer rice/bean/cotton rotation			
	(rice)	(bean)	(cotton)	(bean)
Maize	-	2,516	3,006	1,796
Sunflower	-	2,584	2,785	1,949
Oilseed radish	-	2,704	3,164	2,127
Pearl millet	-	2,512	3,034	2,088
Pigeon pea	-	2,798	2,636	2,167
Grain sorghum	-	2,674	2,479	2,154
Sunn hemp	-	2,561	3,071	2,030
Mean	1,800	2,621	2,882	2,044

(1) Beginning of the experiment with summer crops.

In all growing seasons, winter maize (cultivar 2B710) and sunflower (cultivar Catissol 01) were mechanically sown in 90 cm row spacing aiming at final populations of 55,000 and 88,000 plants ha^{-1}, respectively. The other crops were also sown mechanically, but in a 45 cm row spacing to establish final populations, in plants ha^{-1}, of 555,000 for oilseed radish (cultivar Siletina) and sunn hemp (common cultivar), 665,000 for millet (cultivar BN-2) and pigeon pea (cultivar Anão) and 175,000 for sorghum (cultivar 1G150). The amount of seeds for sowing was, in kg ha^{-1}, 10 for sunflower, 20 for maize, oilseed radish, millet and sorghum, 25 for pigeon pea and 30 for sunn hemp. Fertilization at sowing was the same for all winter crops and consisted of 200 kg ha^{-1} of the NPK fertilizer 8–20–20 + Zn 0.5 %, with no side dressing fertilization. Maize, sunflower and sorghum were grown until grain harvest. Oilseed radish, millet, pigeon pea and sunn hemp were cut at full flowering, using a shredder.

After cutting the winter crops in the growing season 2005/2006 (Table 2) and before sowing of summer crops in the growing season 2006/2007, soil samples were taken from the depths 0–2.5; 2.5–5.0; 5–10; 10–20 and 20–30 cm. In every useful plot, 20 simple samples were taken to form one composite sample for each soil layer. Sampling was performed between crop rows, diagonally across the plots. At each sampling point, a 15 cm wide x 10 cm deep trench was opened with a small shovel at the depths 0–2.5,

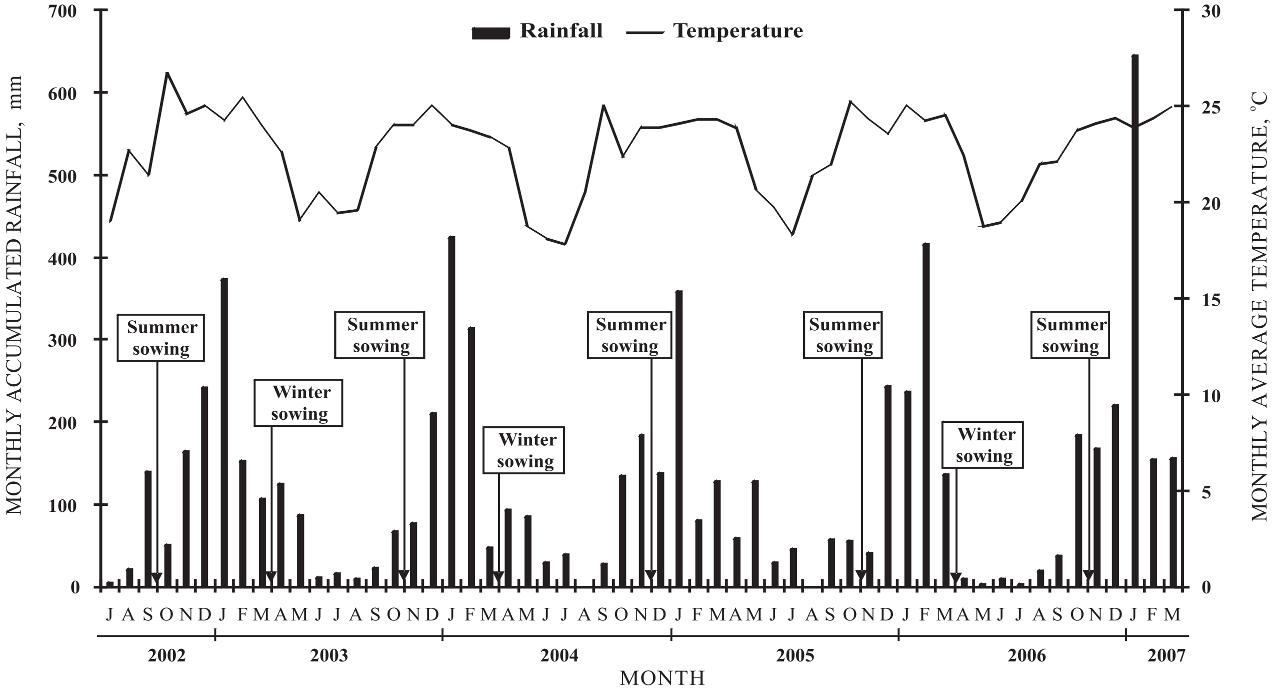

Figure 1. Data of monthly accumulated rainfall and average temperatures, from the experimental station of climatology of the Universidade Estadual Paulista (UNESP) from July 2002 until March 2007, and the sowing period of summer and winter crops during the experiment

Table 2. Number of days from winter crops sowing until cutting/harvest, and from the winter crops cutting/ harvest (2005/2006 growing season) until the soil sampling procedure

Winter crop	Sowing – cutting/harvest Growing seasons(1)			Winter crops cutting/harvest (2005/2006) – soil sampling (2)
	2002/2003	2003/2004	2005/2006	
Maize	150	151	160	29
Sunflower	122	128	125	61
Oilseed radish	63	59	60	127
Pearl millet	69	72	70	117
Pigeon pea	90	88	104	83
Grain sorghum	150	149	159	29
Sunn hemp	75	73	85	102

(1) Growing season 2004/2005 without winter crops. (2) Soil sampling was realized in the first week of October 2006.

2.5–5.0 and 5.0–10 cm and a Dutch auger for the layers 10–20 and 20–30 cm. For each soil sample, pH (0.01 mol L^{-1} CaCl$_2$), P level (resin), organic matter, K$^+$, Ca^{2+}, Mg^{2+} and H + Al were evaluated, according to Raij et al. (2001).

Base fertilization for the summer crops was calculated according to soil chemical analysis based on evaluations of the previous growing season, aiming at high yields (Raij et al., 1997). Table 3 shows the amount of fertilizer applied to the summer crops during the experiment. For the summer crops of 2006/ 2007, no-tillage soybean, maize and rice were mechanically sown on October 10, 2006. An early maturity soybean, cv Coodetec 216, was sown for the summer crop SS and SM rotation, in 45 cm row spacing, aiming at a final population of 480,000 plants ha^{-1}. Soybean seeds were inoculated with *Bradyrhisobium japonicum*. An early single-cross maize, hybrid AG-9010, was sown in the summer as monocrop (MM), in 90 cm row spacing, aiming at a final population of 66,000 plants ha^{-1}. Side dressing fertilization was applied to maize when the plants had grown six completely outspread leaves (Cantarella et al., 1997). Cv IAC 202 was sown as medium maturity rice in the summer RBC rotation, in 45 cm row spacing, aiming at a population of 2 million plants ha^{-1}. Side dressing fertilization was applied at panicle differentiation (Cantarella et al., 1997).

Table 3. Amounts of fertilizers applied to summer crops during the experiment

Summer crop sequence⁽¹⁾	Fertilizing time	Growing seasons				
		2002/2003	2003/2004	2004/2005	2005/2006	2006/2007
MM	Sowing	(maize) 350 kg ha^{-1} 8–28–16+Zn 0.5 %	(maize) 350 kg ha^{-1} 8–28–16+Zn 0.5 %	(maize) 350 kg ha^{-1} 8–28–16+Zn 0.5 %	(maize) 350 kg ha$^{-1\}}$ 8–20–20+Zn 0.5 %	(maize) 100 kg ha^{-1} 8–28–16+Zn 0.5 %
	Side dressing	300 kg ha^{-1} 30–0–10	300 kg ha^{-1} 30–0–10	300 kg ha^{-1} 30–0–10	480 kg ha^{-1} Ammonium sulphate	200 kg ha^{-1} 20–0–20
SS	Sowing	(soybean) 300 kg ha^{-1} 0–20–20	(soybean) 300 kg ha^{-1} 0–20–20	(soybean) 300 kg ha^{-1} 0–20–20	(soybean) 330 kg ha^{-1} 0–20–20	(soybean) 200 kg ha^{-1} 0–20–20
	Side dressing	–	–	–	–	–
SM	Sowing	(soybean) 300 kg ha^{-1} 0–20–20	(maize) 350 kg ha^{-1} 8–28-16+Zn 0.5%	(soybean) 300 kg ha^{-1} 0–20–20	(maize) 350 kg ha^{-1} 8–20–20+Zn 0.5 %	(soybean) 200 kg ha^{-1} 0–20–20
	Side dressing	–	300 kg ha^{-1} 30–0–10	–	480 kg ha^{-1} Ammonium sulphate	–
RBC	Sowing	(rice) 300 kg ha^{-1} 8–28–16+Zn 0.5 %	(bean) 300 kg ha^{-1} 0–20–20	(cotton) 450 kg ha^{-1} 8–28-16+Zn 0.5%	(bean) 370 kg ha^{-1} 0–20–20	(rice) 150 kg ha^{-1} 8–28–16+Zn 0.5%
	Side dressing	250 kg ha^{-1} 30–0–10	–	250 kg ha^{-1} Ammonium sulphate	–	150 kg ha^{-1} Ammonium sulphate

(1) MM: maize monocrop; SS: soybean monocrop; SM: soybean/maize rotation; RBC: rice/bean/cotton rotation.

Nine rows, 15 m long totaling 60.75 m² per plot were mechanically harvested 117 and 128 days after soybean and rice sowing, respectively. For maize, four 15 m long rows, totaling 54 m², were manually harvested and mechanically threshed 118 days after sowing. Final grain weight was calculated considering 13 % moisture.

Variance analysis for soil chemical properties was considered for statistical procedures. The experimental design was completely randomized block with strip and subdivided plots, which consisted of sampled soil layers. For grain yield, variance analysis was applied considering the completely randomized block design for each summer crop sequence. Whenever significant results were observed ($p < 0.05$), means were submitted to the Scott-Knott cluster analysis procedure ($p < 0.05$).

RESULTS AND DISCUSSION

Results of comparison showed differences among P levels for summer crop sequences down to a depth of 20 cm (Table 4). Considering the previous summer crop, lower P levels were observed to 20 cm depth for the crop sequences for SM rotation and MM. Both summer crop sequences included the maize crop, which is a highly nutrient demanding crop, compared to bean grown in the RBC rotation and soybean as monoculture. Consequently, the P export through maize grain harvest is higher. According to Guimarães et al. (2006), for 7,729 kg ha^{-1} grain yield, maize exports about 32 kg ha^{-1} P, which is higher than the 16 kg ha^{-1} P exported by 3,494 kg ha^{-1} of soybean grain (Francisco et al., 2007), and 6 kg ha^{-1} P exported with bean, with a grain yield of 1,758 kg ha^{-1} (Andrade et al., 2004). Additionally, the results may also have been influenced by slower decomposition of grass residues with higher C/N ratio, reducing decomposition rate and P release, compared to leguminous species. Wisniewski & Holtz (1997) evaluated P mineralization rates of black oat residues (C/N = 24:1) and maize (C/N = 43:1). The authors observed a P release of 85 % from black oat residues, which is higher than 77 % from maize residues, indicating that P release is greatly influenced by the C/N ratio. Down to 10 cm depth, higher P levels in the soil were observed for the crop sequence RBC rotation, compared to SM. This may be due to the higher amount of P applied via fertilization in this summer crop sequence during the experiment (Table 3), together with the higher P export through soybean grain compared to bean.

Comparing P levels among winter crops in each soil layer (Table 5), differences were observed in the

Table 4. Phosphorus, organic matter, exchangeable calcium and magnesium levels, potential acidity (H + Al) and pH ($CaCl_2$) values in the soil layers under summer crop sequences

Soil layer	Summer crop sequence(1)			
	MM	SS	SM	RBC
cm	P (mg dm^{-3})			
0–2.5	31 Ac	46 Ab	34 Ac	58 Aa
2.5–5	24 Bc	29 Bb	24 Bc	42 Ba
5–10	23 Bb	23 Cb	25 Bb	34 Ca
10–20	17 Ca	14 Da	10 Cb	13 Da
20–30	13 D	10 E	7 C	11 D
	Organic matter (g dm^{-3})			
0–2.5	27 Ab	30 Aa	30 Aa	31 Aa
2.5–5	24 Bc	26 Bb	24 Bc	28 Ba
5–10	22 Cb	24 Ca	21 Cb	24 Ca
10–20	19 Da	20 Da	19 Da	17 Db
20–30	17 Ea	16 Ea	17 Ea	15 Eb
	Ca^{2+} ($mmol_c\,dm^{-3}$)(2)			
0–2.5	7.3 Ac	6.9 Ac	8.4 Aa	7.9 Ab
2.5–5	6.1 Bb	6.6 Bb	6.6 Bb	7.2 Ba
5–10	5.6 Cb	5.7 Cb	5.4 Cb	6.4 Ca
10–20	4.8 Da	4.3 Db	4.2 Db	4.2 Eb
20–30	4.8 Da	4.3 Db	4.1 Db	4.5 Da
	Mg^{2+} ($mmol_c\,dm^{-3}$)			
0–2.5	28 Ac	20 Ad	42 Aa	35 Ab
2.5–5	18 Bb	20 Ab	24 Ba	27 Ba
5–10	12 Cc	17 Bb	17 Cb	22 Ca
10–20	10 D	9 C	10 D	12 D
20–30	11 D	10 C	10 D	14 D
	H + Al ($mmol_c\,dm^{-3}$)			
0–2.5	17 Da	13 Eb	15 Eb	17 Ca
2.5–5	18 D	18 D	20 D	19 B
5–10	23 Ca	23 Ca	25 Ca	20 Bb
10–20	35 Aa	32 Ab	35 Ab	37 Aa
20–30	29 Bb	27 Bb	30 Bb	35 Aa
	pH			
0–2.5	6.1 Ac	6.3 Ab	6.5 Aa	6.3 Ab
2.5–5	5.8 Bb	6.2 Aa	5.9 Bb	6.1 Ba
5–10	5.5 Cb	5.7 Ba	5.4 Cb	5.8 Ca
10–20	4.9 D	5.0 C	4.9 D	4.8 D
20–30	5.1 D	5.1 C	5.0 D	4.9 D

(1) MM: maize monocrop; SS: soybean monocrop; SM: soybean/maize rotation; RBC: rice/bean/cotton rotation. (2) Data transformed (√x). Means followed by the same letter, capital letter in a column and lowercase letter in a row, are not significantly different, by the Scott-Knott test ($p < 0.05$).

0–5 cm layer, which may be due to the high P levels accumulated by sunn hemp and oilseed radish. Besides, the faster the decomposition of plant residues, the faster is P release in soil surface layers. Crusciol et al. (2005) also found that oilseed radish requires high P levels; it accumulates 15.3 kg ha^{-1} in shoot and has a high dry matter production, up to 2,938 kg ha^{-1}, in the winter. The authors concluded that residue decomposition of oilseed radish is fast; dry matter decreased by 72.5 % within 53 days after cutting, consequently releasing 71.4 % P to the soil. Collier et al. (2006) evaluated the effects of cover crop decomposition on a Typic Haplustox, in the Cerrado region, and observed that P levels increased by about 7 mg dm^{-3} in the 0–15 cm layer after sunn hemp cultivation.

For all summer crop sequences and winter crops, it was observed that the deeper the soil layer, the lower was the P level (Tables 4 and 5). The reason is that soil mobilization is restricted to plant rows and also due to fertilizer application and residue accumulation on the soil surface, as typical feature of the no-tillage system (Santos et al., 2003). According to Raij (1991), P mobility in the soil profile is low, resulting in higher accumulation in surface layers. In this study, P levels were classified as medium and high (15–40 and 40–80 mg dm^{-3}, respectively) down to 10 cm and low (7–15 mg dm^{-3}) in the 10 - 30 cm layer (Raij et al., 1997).

The explanation for the low organic matter (OM) levels of the summer crop sequences, observed to a depth of 10 cm and where maize had been sown

Table 5. Phosphorus and organic matter soil levels after winter crops in soil layers

Soil layer	Winter crop						
	Maize	Sunflower	Oilseed radish	Pearl millet	Pigeon pea	Grain sorghum	Sunn hemp
cm				P (mg dm^{-3})			
0–2.5	38 Ab	41 Ab	50 Aa	38 Ab	42 Ab	41 Ab	45 Aa
2.5–5	26 Bb	28 Bb	36 Ba	30 Bb	32 Bb	32 Bb	30 Bb
5–10	24 B	26 B	32 C	26 C	27 B	27 C	23 C
10–20	14 C	15 C	13 D	14 D	15 C	12 D	14 D
20–30	10 D	10 D	10 D	10 D	11 C	9 D	11 D
				Organic matter (g dm^{-3})			
0–2.5	30	28	33	32	30	31	34
2.5–5	24	25	26	27	25	27	26
5–10	22	22	23	23	22	23	23
10–20	17	18	19	19	18	20	20
20–30	15	15	16	17	15	16	16
0–30(1)	19 b	19 b	20 a	21 a	19 b	21 a	21 a

(1) Soil layer 0–30 cm (weighted mean). Means followed by the same letter, capital letter in a column and lowercase letter in a row, are not significantly different, by the Scott-Knott test ($p < 0.05$).

previously (SM rotation and MM) (Table 4), may be related to a low decomposition rate of maize residues, compared to soybean and bean. The reason is the higher C/N ratio (Wisniewski & Holtz, 1997), which slows down OM incorporation. In the SM rotation organic matter levels in the layer 0–2.5 cm were not low, probably because soybean was sown in this summer crop sequence. In this situation, N storage was higher than in the summer crop sequence MM, reducing C/N ratio and increasing the plant decomposition rate and OM formation, which increased N soil levels. Wisniewski & Holtz (1997) observed that the N content of plant residues increased by 25 % and the C/N ratio decreased by 17 % when soybean leaves were added to maize and black oat residues.

Independently of the soil layer, winter crops influenced the soil OM levels differently (Table 5). Low OM levels were found after winter maize and this may be associated to slower decomposition of plant residues due to high C/N ratio. Therefore, OM was slowly incorporated into the soil, compared to the other winter crops. The shredding of crops cut before maize harvest are another aspect to be considered (Table 2). Crops that had been had more time for residue decomposition until sampling time. In comparison to harvested winter crops, a longer period is required for an increase of the soil OM levels.

Lowest OM levels were observed after sunflower and pigeon pea (Table 5), which may be related to the poor soil cover of these residues. Before sowing, Corá (2006) evaluated the soil cover before the summer crops of 2003/2004 and observed a soil cover of 65 % and 75 % for sunflower and pigeon pea, respectively, and over 90 % for the other winter crops. The lower value found for pigeon pea may be due to a reduced growth of this crop in the winter (Amabile et al., 2000), when flowering occurs earlier because of the low photoperiod. For sunflower, the structure of the residues, consisting of stems, mainly (Sodré Filho et al., 2004), also contributed to a poorer soil cover. Besides, considering pigeon pea and sunflower leaves, the C/N ratio of the residues was low (Sodré Filho et al., 2004), which accelerates decomposition and exposes the soil to climate variations. The result is an increase in temperature amplitude, favoring OM oxidation (Eltz & Rovedder, 2005). It is also possible that the fallow in 2004/2005 may have influenced this result, reducing the accumulative effects of winter crops during the experiment.

Although it was observed that the deeper the soil layer, the lower were the OM levels (Table 4), root systems of winter crops influenced OM levels, mainly oilseed radish, millet, grain sorghum and sunn hemp, because modifications were found regardless of the soil layer (Table 5). In no-tillage system, even when crops are harvested or cut, the root systems remain in the soil for decomposition, which contributes to higher OM levels in deeper layers. Studying pigeon pea and velvet bean, Souza & Melo (2003) observed root contribution in organic C levels down to 10 cm. This effect is mainly found when more drought-resistant species are grown that can develop considerably under dry condition. This ensures the shoot dry matter production and a deep root system of crops. Several studies observed satisfactory development of oilseed radish (Crusciol et al., 2005), millet (Boer et al., 2007), sorghum (Oliveira et al., 2002) and sunn hemp (Sodré Filho et al., 2004; Collier et al., 2006) as cover crops.

Winter crops did not differently influence exchangeable Ca and Mg levels, potential acidity

(H + Al) or pH in the soil. Nevertheless, modifications in these chemical properties were observed considering the interaction between summer crop sequences and sampled soil layers (Table 4). Comparing Ca^{2+}, Mg^{2+}, H + Al levels, and pH values among summer crop sequences, it was not possible to identify any causes for the interactions, because randomized behavior was found for each soil layer. According to Almeida et al. (2005), Ca^{2+} and Mg^{2+} levels in the soil are changeable and seem to be environmentally influenced, for example, by soil texture, crop rotation, climate and nutrient mobility in the soil profile. On the other hand, in this study, the levels were considered high (Raij et al., 1997), probably due to a surface liming without incorporation, in 2005. Therefore, the values were higher mainly in the soil surface layers. This indicates that the applied lime was still active to some degree in the soil even 15 months after acidity correction, especially when low reactivity (ECC = 70 %) is reported. Lower Ca^{2+} and Mg^{2+} levels and pH values and higher H + Al levels were observed for deeper soil layers (Table 4). Considering all chemical properties evaluated here, the nutrient decrease observed in the deeper soil layers is typical of no-tillage system, as reported by Santos et al. (2003).

Variance analysis showed a significant effect of triple interaction (summer crop sequence x winter crop x soil layer) on K levels (Table 6), indicating effects of one factor in particular on each of the other combinations. Through triple interaction partitioning, K levels were compared among winter crops and differences were found for the RBC rotation only, in the layers 0–2.5, 2.5–5.0 and 5.0–10 cm. Similarly to the discussion about P soil levels, it is possible to state that some winter crops accumulate higher K levels in plant residues. Higher values were therefore observed in soil surface layers and in plots where sunn hemp, millet and oilseed radish were sown. These crops were considered K-recycling by many authors when managed at flowering. Alcântara et al. (2000) found that sunn hemp accumulates 30.8 kg ha^{-1} K in 6,500 kg ha^{-1} dry matter. For oilseed radish, Crusciol et al. (2005) observed 85.7 kg ha^{-1} K accumulated in 2,938 kg ha^{-1} dry matter. Braz et al. (2004) and Boer et al. (2007), respectively, reported 314 kg ha^{-1} and 416.9 kg ha^{-1} K accumulated by millet in 12,553 and 10,800 kg ha^{-1} dry matter. The authors found that K was the most accumulated nutrient and was released fastest, which may be due to its ionic form and because it does not form any stable organic compounds (Mengel & Kirkby, 2001). A fast release of K by plant residues

Table 6. Potassium soil levels in the summer crop sequences, winter crops and soil layers

Summer crop sequence[1]	Winter crop						
	Maize	Sunflower	Oilseed radish	Pearl millet	Pigeon pea	Grain sorghum	Sunn hemp
	mmol$_c$ dm^{-3}						
	0–2.5 cm						
MM	5.9 (a)	6.1 (a)	5.6 (a)	5.6 (a)B	5.8 (a)	5.6 (a)	6.1 (a)B
SS	5.2 (a)	6.1 (a)	5.6 (a)	4.4 (a)B	4.2 (a)	4.9 (a)	5.9 (a)B
SM	5.2 (a)	5.7 (a)	6.1 (a)	4.8 (a)B	5.7 (a)	5.7 (a)	5.5 (a)B
RBC	5.6 (a)c	6.1 (a)c	7.0 (a)c	8.9 (a)Ab	6.5 (a)c	7.3 (a)c	14.4 (a)Aa
	2.5–5 cm						
MM	4.3 (b)	4.7 (b)	4.4 (b)	5.0 (a)	4.7 (a)	5.1 (a)	5.5 (a)
SS	3.7 (b)	5.4 (a)	4.6 (a)	3.9 (a)	3.6 (a)	4.1 (a)	4.6 (b)
SM	3.9 (b)	4.7 (a)	4.6 (b)	3.6 (b)	4.2 (b)	5.3 (a)	5.1 (a)
RBC	5.4 (a)b	5.0 (a)b	6.0 (a)b	6.0 (b)b	5.0 (b)b	5.6 (b)b	7.4 (b)a
	5–10 cm						
MM	3.6 (c)	3.7 (c)	4.4 (b)	4.5 (a)	4.7 (a)	4.4 (a)	4.8 (a)
SS	3.9 (b)	5.5 (a)	5.1 (a)	3.7 (a)	3.5 (a)	4.0 (a)	4.4 (b)
SM	3.2 (c)	3.5 (b)	3.8 (c)	2.7 (b)	3.9 (b)	4.9 (a)	4.3 (a)
RBC	4.4 (a)b	4.9 (a)b	6.2 (a)a	5.3 (b)b	4.7 (b)b	5.4 (b)b	6.5 (b)a
	10–20 cm						
MM	2.7 (c)	3.0 (c)	3.3 (c)	3.8 (b)	3.9 (b)	3.8 (b)	3.2 (b)
SS	2.9 (c)	4.4 (b)	3.7 (b)	2.8 (b)	2.9 (b)	2.8 (b)	3.3 (c)
SM	2.6 (c)	3.9 (b)	3.4 (c)	3.7 (b)	3.6 (b)	3.6 (b)	3.5 (b)
RBC	2.9 (b)	2.5 (b)	3.0 (b)	3.2 (c)	3.4 (c)	3.4 (c)	3.5 (c)
	20–30 cm						
MM	1.7 (d)	1.8 (d)	2.3 (c)	2.8 (b)	3.0 (b)	2.6 (b)	2.6 (b)
SS	2.1 (c)	3.3 (b)	2.8 (b)	2.4 (b)	2.3 (b)	2.4 (b)	2.7 (c)
SM	2.2 (c)	2.5 (c)	2.7 (c)	2.7 (b)	2.7 (b)	2.6 (b)	2.8 (b)
RBC	2.9 (b)	3.3 (b)	3.6 (b)	3.2 (c)	3.3 (c)	3.7 (c)	3.8 (c)

(1) MM: maize monocrop; SS: soybean monocrop; SM: soybean/maize rotation; RBC: rice/bean/cotton rotation. Means followed by the same letter, capital letter in the column (summer crop sequences), lowercase letter in the line (winter crops) and lowercase letters in brackets (soil depth layers for each sequence combination of summer and winter crop) are not significantly different by the Scott-Knott test ($p < 0.05$).

was also observed in other studies on sunn hemp (Calonego et al., 2005) and millet (Rosolem et al., 2003), in greenhouse with simulated rainfall, and on oilseed radish (Crusciol et al., 2005), under field conditions, in the Southern region of Brazil. Considering K levels of the summer crop sequences, differences related to the winter crops were only observed for the RBC rotation. This summer crop sequence had the highest variety of species in the summer, which may have influenced the result.

Comparing K levels in the 0–2.5 cm depth and summer crop sequences (Table 6), higher values were observed for RBC rotation and for plots with winter sunn hemp and millet. Possibly, the explanation could be the use of bean as a summer crop in the previous growing season (2005/2006). According to Andrade et al. (2004), this crop exports 20 kg ha^{-1} K through grain harvest, which is low compared to maize and soybean, with 45 kg ha^{-1} (Guimarães et al., 2006) and 56 kg ha^{-1} (Francisco et al., 2007), respectively. Due to the low K export, a great amount is traken up by plants and remains in the leaves, stems and roots. During decomposition, plants release the element into soil solution, increasing the nutrient levels, which explains the high amount of soil K found here.

Analyzing different K levels and soil depths for each winter crop and summer crop sequences (Table 6), K accumulation in soil surface layers and a gradual decrease in the deeper soil layers was observed. This was found for all crop combinations but was not very pronounced, probably due to K mobility in the soil profile (Raij et al., 1991). In no-tillage systems, the K behavior is usually changeable but the accumulation of this nutrient occurs mostly in soil surface layers (Santos et al., 2003; Almeida et al., 2005). In this experiment and according to Raij et al. (1997), K levels were within ranges considered high and very high (3.1–6.0 and > 6.0 mmol$_c$ dm^{-3}, respectively), down to a depth of 20 cm and medium below 20 cm (1.6–3.0 mmol$_c$ dm^{-3}), in most of the cases.

Higher soybean yields were found in succession to sunn hemp and oilseed radish in the summer SS, and after sunn hemp, millet and oilseed radish in the summer SM rotation (Table 7). This may be explained by higher P levels found after oilseed radish and sunn hemp grown in the winter (Table 5), indicating direct influence of P levels on soybean yield. However, it must be emphasized that the critical level of the element in the soil is 15 mg dm^{-3} (Raij et al., 1997). In this research, all treatments resulted in P levels which were higher than the values found in the literature, mainly in the first 10 cm. Studying similar soil and climate conditions, Tanaka et al. (1992) observed increases of up to 30 % in soybean yield after sunn hemp residues were incorporated in the soil, compared to soybean monoculture. The authors explained that sunn hemp cropping could have decreased the occurrence of phytopathogenic nematodes in the soil, favoring soybean in succession. Higher soybean yields obtained after millet may be related to the capacity of this crop to recycle nutrients, especially N and K (Boer et al., 2007) and to the higher number of species sown in the SM rotation, compared to SS. As a consequence, the microbial diversity in the soil is higher, intensifying the decomposition process of plant residues (Tauk, 1990) and increasing nutrient release. Nevertheless, soybean yields were similar among the summer crop sequences SM and SS.

The values of rice the yield, was negatively influenced by previous sorghum, were lowest yield among summer crops (Table 7). Although only rice yield after sorghum was clearly differentiated based on the means, it is worth emphasizing the high grain yields obtained after sunn hemp, oilseed radish and millet. The answer was similar to the results for soybean, in the summer crop sequences SM and SS, and the explanations may be related. Similarly as discussed for soybean, considering P levels and the same reasons, K levels were also above the critical range for the element in the soil, i.e., 1.5 mmol$_c$ dm^{-3} (Raij et al., 1997), hardly influencing rice yield by the different winter crops. In similar conditions, Bordin et al. (2003) evaluated rice yield in different crop rotations and obtained higher and lower values after sunn hemp (2,177 kg ha^{-1}) and sorghum (1,750 kg ha^{-1}),

Table 7. Summer crop yields after winter crops in growing season 2006/2007

Winter crop	Summer crop sequence(1)			
	MM (maize)	SS (soybean)	SM (soybean)	RBC (rice)
	kg ha^{-1}			
Maize	6,649 b	2,754 b	2,943 b	3,682 a
Sunflower	6,594 b	2,613 b	3,009 b	4,077 a
Oilseed radish	7,060 a	2,949 a	3,281 a	4,238 a
Pearl millet	7,420 a	2,678 b	3,181 a	4,364 a
Pigeon pea	7,018 a	2,643 b	2,757 b	3,548 a
Grain sorghum	6,797 b	2,790 b	2,914 b	2,423 b
Sunn hemp	6,790 b	3,206 a	3,214 a	4,726 a

(1) MM: maize monocrop; SS: soybean monocrop; SM: soybean/maize rotation; RBC: rice/bean/cotton rotation. Means in each column followed by the same letter are not significantly different by the Scott-Knott test ($p < 0.05$).

respectively, possibly due to N supply by leguminous species. Additionally, there are also allelopathic effects to be considered. Several components can be released by sorghum residues during decomposition, such as tannin and some fatty acids (Olibone et al., 2006), negatively affecting seed germination and development of the following crop. Sorghum has many desirable characteristics as relay crop, such as tolerance to unfavorable soil moisture conditions, high dry matter production, high C/N ratio, and good soil cover during the second growing season. On the other hand, sorghum residues may negatively affect the crop in succession. Nunes et al. (2003) emphasized the importance of these facts during crop rotation planning.

Higher maize yields were observed after oilseed radish, millet and pigeon pea grown in the winter (Table 7). Although oilseed radish is not a legume but a *Brassica*, the decomposition rate of plant residues of this crop is also high, compared to grasses. However, oilseed radish is very similar to grasses, which have a considerable capacity of nutrient uptake, including N inorganic forms. According to Crusciol et al. (2005), a high dry matter production is also reported for this crop, but with faster decomposition, which may have contributed to increase maize yields.

Both in the previous and current growing seasons evaluated here (Table 1), soybean and maize yields in summer were always lower when sown in succession to harvested winter crops (maize, sunflower and sorghum), which indicates that nutrient export results in lower nutrient availability for the following crop (Corá, 2006). Nutrient concentration in plant tissues is affected by both crop cutting and harvesting. In this study, crop cutting (oilseed radish, millet, pigeon pea and sunn hemp) was performed at full flowering, when a higher nutrient accumulation is reported (Mengel & Kirkby, 2001). Higher nutrient levels were therefore found, compared to plant residues of the harvested crops (maize, sorghum and sunflower), where nutrient levels were lower, due to the element export by grains.

CONCLUSIONS

1. Summer soybean/maize rotation and maize monoculture resulted in lower organic matter contents and P levels in the layers 0–10 cm and 0–20 cm, respectively.

2. Summer rice/bean/cotton rotation increased soil K levels at depth 0–10 cm when sunn hemp and oilseed radish were previously grown in the winter, and at 0–2.5 cm for millet cropping.

3. Sunn hemp, millet, oilseed radish and sorghum grown in the winter increased organic matter contents in the soil down to 30 cm. Higher P levels were found in the layers 0–2.5 and 0–5 cm, respectively, when sunn hemp and oilseed radish were grown in the winter.

4. Grain yields of soybean grown as monoculture were higher in succession to oilseed radish and sunn hemp in the winter and in rotation with maize, after oilseed radish, sunn hemp and millet. Higher maize yields were observed in succession to oilseed radish, millet and pigeon pea grown in the winter. For rice, yields were lower when grown after sorghum.

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