Management of rice straw in rice-soybean succession in tropical lowland

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ABSTRACT

This study aimed to analyze rice straw alternative managements to maximize the rice-soybean succession yield and to quantify their impacts on soil properties. The experiment was set up in a completely randomized design with six replicates. Nine rice straw managements were evaluated: straw burning (M1), straw harvesting (M2), straw incorporation with disc harrow and two passes (M3) or three passes (M4) of leveling disc harrow, straw incorporation with knife-roller and soybean no-tillage (M5), straw incorporation with knife-roller and two passes (M6) or three passes (M7) of leveling disc harrow, straw incorporation with two passes of knife-roller and two passes (M8) or three passes (M9) of leveling disc harrow. Straw incorporation by knife-roller provided the lowest soil organic matter (SOM) contents due to slow mineralization of fresh straw incorporated shallow into the soil, although SOM increased in the surface layer related to the initial content. Rice-soybean succession yield was more affected by the physical than by the soil chemical properties. The straw incorporation with one pass of knife-roller and two passes of leveling disc harrow (M6) can replace the straw burning, without affecting the rice-soybean succession yield and soil physical quality, with a reduction in machinery operations, allowing early soil tillage.

Keywords: *Oryza sativa* L.; knife-roller; straw burning; soil quality.

INTRODUCTION

Currently, 80% of the rice production comes from the states of Santa Catarina and Rio Grande do Sul (CONAB, 2018). However, the irrigated rice production in Tocantins is strategic for rice supply in Brazil. The rice production in Tocantins lowlands supplies the markets of the Central, North, and Northeast regions of Brazil. In the 2016/2017 crop season, the irrigated rice yield and cropped area in Tocantins were 5.9 t ha^{-1} and 105,000 ha, respectively (CONAB, 2018). In the off-season of irrigated rice (from April to September), the lowlands are cultivated with upland species, mainly soybean, under subsurface irrigation. In 2017, 57,210 ha of soybean were cultivated during the rice off-season, which represent 77% of the area cropped with rice (ADAPEC, 2018). During this period, the absence of rainfall associated with low relative air humidity and low night temperature disfavored the incidence of foliar diseases, being these areas mainly used by soybean growers for production of high sanitary quality seeds (Almeida *et al.*, 2011; Arruda *et al.*, 2016).

The increment in rice yield increases the production of straw and may hinder tillage operations and the sowing of soybean within the recommended period (Silva *et al.*, 2019). Traditionally in Tocantins lowlands, rice straw is burned. Harvesters without straw choppers or spreaders lay the straw in swaths, which facilitates burning. However, this management decrease soil organic matter levels and increase greenhouse gas emissions by releasing CO_2 and other gases into the atmosphere (Redin *et al.*, 2011; Schaller *et al.*, 2018). In addition to C and N, rice straw contains significant amounts of other nutrients such as P, K and S, which can be translocated from the original area to other areas during the combustion process (Knoblauch *et al.*, 2014), meaning financial losses and increased production costs, as the local recycling of these nutrients will no longer occur.

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An alternative to burning would be the use of disc harrow and leveling disc harrow, which can incorporate the rice straw while also correcting the soil surface roughness. However, the increment in rice yield increases the production of straw and may hinder tillage operations and the sowing of soybean within the recommended period (Silva *et al.*, 2019). Knoblauch *et al.* (2014) report that the incorporation of rice straw in the soil should be carried out at least 30 days before sowing another crop in succession. This could make this operation unfeasible due to the narrow space of time before the soybean sowing.

Soybean no-tillage may also be considered once this system reduces the soil temperature and evaporation due its coverage and promotes the microporosity in the soil layer of 0-0.10 m, which increases soil water content and water availability to the crop, may affecting positively the soybean yield in rice lowlands (Ribeiro *et al.*, 2016).

Other possibility is the incorporation of straw using a knife-roller, which consists of a mechanically towed hollow steel drum fitted with sharp knives. Theisen *et al.* (2018), in Rio Grande do Sul, Brazil, verified that soil tilling with knife-roller compared with the conventional plough-and-harrow soil preparation system resulted in similar grain yield to soybean-rice crop rotation and reduced energy consumption of soil tillage by 50%. It also reduced labor time by 29% and greenhouse gas emissions by 55% in soil tillage. In addition to these savings, the roller-based method can be performed shortly after the rice harvest, providing opportunities for upland crops in the off-season of rice crop and intensifying soil use.

Rice straw incorporation immediately after harvest can contribute to increase the yield of the subsequent crop due to the increase in nutrient contents and improvement in soil physical properties. Ou *et al.* (2016) found that rice straw incorporation increased the organic carbon stock in soil. Tanaka *et al.* (2012), Suriyagoda *et al.* (2014), and Li *et al.* (2014) reported increase in N, P, and K contents in soil due to recycling through stubble. On the other hand, Massoni *et al.* (2013) found that, regardless of the post-harvest management used for irrigated rice straw, there was no increase in the contents of mineral N and available P and K at the end of the off-season. In relation to soil physical properties, Gangwar *et al.* (2006) found that rice straw incorporation decreased soil bulk density and increased water infiltration rate, and Ou *et al.* (2016) reported increase in the proportion of macroaggregates and aggregates associated with soil organic carbon.

Therefore, it is necessary to assess whether using the knife-roller facilitates the soil tillage for the implementation of the soybean crop in Tocantins lowlands and preserves the possible benefits of rice straw incorporation, with less negative impact on the soil quality. Moreover, if the knife-roller method leads to the same agronomic results as burning and disc harrow-based tillage, the efûciency of the overall cropping system is increased, since the knife-roller demands less energy for soil preparation, reduces greenhouse gas emissions, and allows an earlier soil preparation for soybean crop than the traditional rice straw management used in the Tocantins lowlands (Theisen *et al.*, 2018; Silva *et al.*, 2019).

The objective of this study was to analyze rice straw alternative managements in tropical lowland for maximizing rice-soybean succession yield and to quantify their impacts on soil properties.

MATERIAL AND METHODS

The study was carried out in a grain production area, Sementes Talismã Farm, located at Formoso do Araguaia, TO, between the coordinates 11°49’38.11" S and 49°38’02.07" W, 192 m altitude. The soil is classified as Plintossolo, according to Santos *et al.* (2018), and Plinthosol, according to the IUSS Working Group WRB (2015), with a clay loam texture. The climate is classified as “Aw”, according to Köppen’s classification (Alvares *et al.*, 2013).

From 2015 to 2017, three soybean and two rice crops were carried out during off-seasons and rainfed seasons. In May 2015, soil samples were collected from the 0-0.10 m and 0.10-0.20 m layers. The chemical and physical soil properties are presented in Table 1.

Nine treatments (Table 2) consisting of a combination of rice straw management (burning, harvesting and incorporation with disc harrow, leveling disc harrow, and knife-roller) with soybean sowing (no-tillage and conventional) were evaluated in a completely randomized design, with six replications. The disc harrow operated at 0.20-0.25 m, the leveling disc harrow at 0.10 m, and the knife-roller at 0.13 m depth. The total plot area was 600 m^2 (10 m wide and 60 m long).

In this study, because the grain to straw yield ratio is 1:1, about 7500 kg ha^{-1} of straw was incorporated into the soil in each season, before the soybean sowing. The rice straw composition was as follows: 35.7 g kg^{-1} C, 0.9 g kg^{-1} N, 1.5 g kg^{-1} P, 24.6 g kg^{-1} K, 3.9 g kg^{-1} Ca, 1.7 g kg^{-1} Mg, 1.6 g kg^{-1} S, 9.6 g kg^{-1} B.

Soil tillage for rice sowing was performed with disc harrow and two passes of leveling disc harrow. Rice was sown in October 2015 and 2016, with spacing between rows of 0.17 m, density of 80 seeds per meter of cultivar IRGA 424. At sowing, 10 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, and 60 kg ha^{-1} K_2O were applied to soil based on fertility analysis. Nitrogen topdressing was carried out at the vegetative growth stage V3-V4 (pre or early tillering) and at the V7-V8 (effective tillering), according to the scale of Counce *et al.* (2000), using 30 kg ha^{-1} of N (formula 20-00-20) and 45 kg ha^{-1} of N (urea). Irrigation started right after the first nitrogen topdressing and a uniform water depth of about 0.12 m was maintained. The suppression of irrigation occurred in the R8-R9 stage (complete grain maturity).

The soybean cultivar M-8644 was sown in May 2015, 2016 and 2017, with spacing between rows of 0.40 m, density of 15 seeds per meter, under subsurface irrigation. Seeds were inoculated with Rhizobium and treated with fungicides. Fertilizer of the formula 5-20-20 was applied at sowing (400 kg ha^{-1}).

In July 2017, at soybean flowering, soil samples with undisturbed and disturbed structure were collected in the 0-0.10 m and 0.10-0.20 m layers, with six replicates, to analyze the soil physical and chemical properties, respectively. The physical properties were bulk density, total porosity, microporosity, macroporosity, available water capacity, according to Teixeira *et al.* (2017), *S* index, according to Dexter (2004), and air capacity (AC), according to Reynolds *et al.* (2002). The chemical properties were: soil pH and the contents of Ca^{2+}, Mg^{2+}, $H^+ + Al^{3+}$, P, K^+, Cu^{2+}, Zn^{2+}, Fe^{3+}, Mn^{2+}, and organic matter. The pH was determined in water. Ca^{2+} and Mg^{2+} were extracted in 1 mol L^{-1} KCl solution and determined by atomic absorption spectroscopy. The potential acidity ($H^+ + Al^{3+}$) was determined by titration using 0.5 mol L^{-1} calcium acetate solution at pH 7 for extraction. These analyses were performed according to Teixeira *et al.* (2017). Phosphorus, potassium, and micronutrients were extracted with Mehlich 1 solution (HCl at 0.5 N + H_2SO_4 at 0.025 N) and determined by inductively coupled plasma atomic emission spectroscopy (Soltanpour *et al.*, 1996). Soil organic matter (SOM) was calculated by multiplying the total soil organic carbon content by 1.724, according to the chromic acid titration method (Teixeira *et al.*, 2017).

At harvest, sampling of rice and soybean plants was carried out in areas of 2.55 m² and 4.00 m², respectively, to determine grain yield (kg ha^{-1}) in each plot, after adjusting moisture to 13%. Rice and soybean grain yields were determined annually and the cumulative yields of these crops were calculated.

The data were submitted to variance analysis, and the means were compared by the Scott-Knott's test, at 5% probability. Correlation analyses were performed between each major component and the variables analyzed by principal component analysis (PCA). The ordination diagram was constructed using variables with correlations higher than 80% in the first or second PCA. The hierarchical cluster method, using the squared Euclidean distance as a measure of dissimilarity and the increase in sum of

Table 1: Results of initial chemical and granulometric analyses according to soil layers, in Formoso do Araguaia, TO, 2015[(1)]

Layer	pH	Ca	Mg	Al	H+Al	P	K	Cu
m		mmol$_c$ dm^{-3}				mg dm^{-3}		
0-0.10	5.6	21.9	6.9	1.0	32.8	32.3	81.0	1.5
0.10-0.20	5.7	23.5	6.1	0.9	35.1	30.1	60.3	1.6
	Zn	Mn	Fe	SOM	Clay	Silt	Sand	
	mg dm^{-3}			g kg^{-1}				
0-0.10	5.4	12.2	68.1	49.3	289.6	267.4	443.0	
0.10-0.20	5.6	13.2	74.1	51.2	310.3	258.6	431.1	

[(1)]H+Al, potential acidity; SOM, soil organic matter.

Table 2: Treatments applied to rice straw management and soybean sowing, in Formoso do Araguaia, TO, 2015

Treatment	Rice straw management					Soybean sowing	
	Burning	Harvesting[(1)]	Disc harrow	Leveling disc harrow	Knife- roller	No-tillage	Conventional
			nº of passes				
M1	Yes	No	1	3	0	No	Yes
M2	No	Yes	1	3	0	No	Yes
M3	No	No	1	2	0	No	Yes
M4	No	No	1	3	0	No	Yes
M5	No	No	0	0	1	Yes	No
M6	No	No	0	2	1	No	Yes
M7	No	No	0	3	1	No	Yes
M8	No	No	0	2	2	No	Yes
M9	No	No	0	3	2	No	Yes

[(1)]Straw harvesting for various uses, such as fencing or watermelon packaging squares as the fusion criterion (Ward's method), was applied to the treatments (straw managements). The number of clusters was based on two criteria: a) sum of squares within the groups, and b) inertia gain, based on the Huygens's theorem, which allows the decomposition of the total variance between and within the groups (Husson *et al.*, 2015). The Pearson's analysis among the rice, soybean and rice-soybean succession cumulative yields and some soil properties was also performed. The software program used to analyze the data was R version 3.5.0 (R Development Core Team, 2018).

RESULTS AND DISCUSSION

The rice straw managements did not significantly affect the soil physical properties (Table 3). It was expected that different tillage depths and harrowing intensities would have caused changes in variables sensitive to structural change. However, changes in the structure of lowland soils may not occur significantly after several years of irrigated rice cultivation (Mentges *et al.*, 2013).

In rice crops, despite the flooded irrigation being capable of degrading the soil physical quality by dispersing soil aggregates and increasing bulk density, according to Ribeiro *et al.* (2016), conventional tillage operations promote the reorganization of the natural structure of the soil that can be reconstituted during the growing period. Nevertheless, cropping systems with intense tillage operations in lowland soils, over time, can damage the soil physical quality (Bamberg *et al.*, 2009). Despite that, considering $S = 0.035$ as a limit between soil with good structural quality and soil with a tendency to become degraded and $S \leq 0.020$ as indicative of fully physically degraded soils (Dexter, 2004), all the straw managements maintained the soil surface layer with adequate physical quality, except M5 and M9. Probably, the lack of soil tillage for soybean sowing in M5 management and the large number of machinery operations before soybean sowing in M9 management may have contributed to increase soil compaction (higher absolute value of bulk density) and

Table 3: Mean values of bulk density, porosity relationships, *S* index, air capacity (AC), and available water capacity (AWC) according to rice straw management and soil layer, in Formoso do Araguaia, TO, 2017(1)

Straw management	Soil layer (m)							
	0-0.10	0.10-0.20	0-0.10	0.10-0.20	0-0.10	0.10-0.20	0-0.10	0.10-0.20
	Bulk density		Total porosity		Microporosity		Macroporosity	
	Mg m^{-3}		m^3 m^{-3}					
M1	1.16a	1.22a	0.564a	0.540a	0.455a	0.473a	0.109a	0.067a
M2	1.12a	1.22a	0.578a	0.523a	0.456a	0.448a	0.122a	0.075a
M3	1.16a	1.26a	0.561a	0.523a	0.440a	0.423a	0.121a	0.100a
M4	1.17a	1.27a	0.563a	0.520a	0.450a	0.443a	0.113a	0.077a
M5	1.28a	1.27a	0.518a	0.531a	0.466a	0.458a	0.052a	0.073a
M6	1.19a	1.16a	0.553a	0.560a	0.450a	0.446a	0.103a	0.114a
M7	1.20a	1.23a	0.546a	0.536a	0.437a	0.414a	0.109a	0.122a
M8	1.21a	1.22a	0.543a	0.538a	0.448a	0.434a	0.095a	0.104a
M9	1.28a	1.31a	0.517a	0.507a	0.452a	0.426a	0.065a	0.081a

	S		AC		AWC (mm)	
M1	0.044a	0.036a	0.20a	0.13a	11.4a	12.8a
M2	0.044a	0.037a	0.22a	0.15a	12.4a	11.8a
M3	0.036a	0.034a	0.23a	0.20a	10.0a	10.5a
M4	0.042a	0.032a	0.20a	0.17a	11.4a	12.4a
M5	0.025a	0.034a	0.12a	0.14a	10.6a	12.1a
M6	0.038a	0.043a	0.20a	0.21a	11.2a	11.8a
M7	0.035a	0.044a	0.21a	0.24a	10.5a	11.2a
M8	0.038a	0.038a	0.20a	0.21a	12.7a	11.2a
M9	0.029a	0.030a	0.14a	0.18a	11.1a	10.2a

(1)Means followed by the same letters in the columns are not significantly different at 5% probability by the Scott-Knott's test. M1, straw burning and soil tillage with one pass of disc harrow and three passes of leveling disc harrow; M2, straw harvesting for various uses such as fencing or watermelon packaging, and soil tillage with one pass of disc harrow pass and three passes of leveling disc harrow; M3, straw incorporation with one pass of disc harrow and two passes of leveling disc harrow; M4, straw incorporation with one pass of disc harrow and three passes of leveling disc harrow; M5, straw incorporation with one pass of knife-roller and no-tillage for soybean sowing; M6, straw incorporation with one pass of knife-roller and two of leveling disc harrow; M7, straw incorporation with one pass of knife-roller and three passes of leveling disc harrow; M8, straw incorporation with two passes of knife-roller and two passes of leveling disc harrow; M9, straw incorporation with two passes of knife-roller and three passes of leveling disc harrow.

negatively affect the soil physical quality. In the 0.10-0.20 m layer, the straw managements M1, M2, M6, M7, and M8 also presented *S* index values higher than 0.035.

The effect of rice straw managements on soil chemical properties varied according to soil attribute and soil layer (Table 4). In the 0-0.10 m layer, the contents of P, Cu, Zn, and Fe and, in the 0.10-0.20 m layer, the contents of Ca and Mg were not significantly different as a function of the straw management.

Rice straw application to paddy soils strongly increases nutrient availability for rice plants (Schaller *et al.*, 2018), therefore it was expected that straw burning or straw harvesting could decrease SOM contents (Villegas-Pangga *et al.*, 2000). However, no differences were observed between these treatments and straw incorpora-

Table 4: Mean values of macro and micronutrients and soil organic matter according to rice straw management and soil layer, in Formoso do Araguaia, TO, 2017[(1)]

Straw management	Soil layer (m)							
	0-0.10	0.10-0.20	0-0.10	0.10-0.20	0-0.10	0.10-0.20	0-0.10	0.10-0.20
	pH in water		Calcium		Magnesium		Potential acidity	
			mmol$_c$ dm^{-3}					
M1	5.8b	6.1b	26.0a	24.6a	12.0a	10.3a	26.5a	21.0a
M2	5.9a	5.9b	25.4a	24.3a	13.4a	10.8a	24.8a	23.0a
M3	5.7b	6.0b	23.0b	21.2a	9.7b	8.4a	27.0a	18.8a
M4	6.0a	6.2a	22.6b	20.5a	10.6a	9.2a	22.5b	12.8b
M5	5.7b	5.9b	22.9b	21.6a	9.2b	9.1a	26.5a	18.5a
M6	6.0a	6.3a	24.4a	18.9a	13.1a	7.7a	22.2b	9.2b
M7	5.9a	6.2a	21.3b	19.8a	8.9b	7.5a	23.5b	12.8b
M8	5.8b	6.2a	22.8b	18.3a	9.2b	6.7a	25.5a	12.0b
M9	6.0a	6.2a	25.6a	18.2a	12.7a	8.4a	20.5b	13.8b
	Phosphorus		Potassium		Copper		Zinc	
			mg dm^{-3}					
M1	41.2a	22.0b	256.0a	137.8a	1.4a	1.1b	6.0a	3.4b
M2	47.0a	33.2a	136.5b	99.5a	1.5a	1.4a	6.4a	5.1a
M3	40.4a	21.8b	205.2a	95.2a	1.4a	1.3a	6.8a	3.4b
M4	37.5a	16.2c	139.0b	89.5a	1.5a	1.3a	6.0a	2.4c
M5	70.5a	21.3b	205.2a	93.8a	1.4a	1.1b	6.1a	2.3c
M6	31.5a	6.8c	83.0b	27.8b	1.2a	0.9b	5.1a	1.1c
M7	40.9a	12.0c	109.5b	62.0b	1.4a	0.9b	6.2a	2.0c
M8	38.1a	10.9c	90.8b	36.2b	1.3a	1.0b	5.3a	1.8c
M9	41.8a	13.2c	103.2b	61.5b	1.6a	1.2a	6.2a	2.2c

Straw management	Manganese		Iron		Organic matter	
	mg dm^{-3}				g kg^{-1}	
M1	13.0a	10.6a	92.52a	66.5a	61.92a	60.9a
M2	9.9b	10.0a	89.10a	72.0a	63.88a	63.3a
M3	12.0a	11.4a	88.60a	66.3a	65.10a	55.0a
M4	12.3a	8.8b	89.72a	61.4a	63.28a	54.4a
M5	10.6b	8.4b	76.28a	57.7a	59.08b	53.7a
M6	11.0b	7.0b	72.98a	47.6b	58.18b	46.1b
M7	11.3b	7.6b	87.62a	44.6b	55.95b	47.9b
M8	10.2b	7.0b	78.60a	44.8b	54.88b	45.6b
M9	11.3b	7.2b	86.42a	56.4a	58.10b	50.4b

[(1)]Means followed by the same letters in the columns are not significantly different at 5% probability by the Scott-Knott's test. M1, straw burning and soil tillage with one pass of disc harrow and three passes of leveling disc harrow; M2, straw harvesting for various uses such as fencing or watermelon packaging, and soil tillage with one pass of disc harrow pass and three passes of leveling disc harrow; M3, straw incorporation with one pass of disc harrow and two passes of leveling disc harrow; M4, straw incorporation with one pass of disc harrow and three passes of leveling disc harrow; M5, straw incorporation with one pass of knife-roller and no-tillage for soybean sowing; M6, straw incorporation with one pass of knife-roller and two of leveling disc harrow; M7, straw incorporation with one pass of knife-roller and three passes of leveling disc harrow; M8, straw incorporation with two passes of knife-roller and two passes of leveling disc harrow; M9, straw incorporation with two passes of knife-roller and three passes of leveling disc harrow.

tion with disc harrow, which promoted fast mineralization, especially in tropical climate with high temperatures. Root biomass also may have contributed to this result. Ou *et al.* (2016) found no difference in the organic carbon content in the superficial layer of the soil tilled with moldboard plow, with or without rice straw incorporation.

On the other hand, the soil organic matter content was lower in rice straw managements where knife-roller was used (M5, M6, M7, M8, and M9), in both layers evaluated, although SOM has increased in the surface layer in relation to the initial content, indicating the possibility of growing up over time, albeit more slowly. This could be attributed to the shallow incorporation and high straw C:N ratio together with uncut pieces of straw (only crushed), which promotes slower mineralization than straw incorporation with disc harrow (cut straw). This affected the contents of P, K, and micronutrients, which, in general, showed lower values in the 0.10-0.20 m layer with knife-roller managements. The straw mineralization increases the P and K contents, as reported by Suriyagoda *et al.* (2014) and Li *et al.* (2014). The positive correlations between SOM and P and K contents in the 0.10-0.20 m layer (Table 5) support this hypothesis. In addition to P and K, in this layer, SOM correlated positively with Ca, Mg, and micronutrient contents (Table 5).

Ou *et al.* (2016) found that the C accumulation in the soil is related to the depth of rice straw incorporation. The authors reported that the straw mainly concentrated on the soil surface under the no-tillage system but was relatively evenly distributed within the plough layer under the moldboard plow system. Consequently, C accumulation was significantly concentrated in the 0.00-0.05 m soil layer under the no-tillage system and in the 0.00-0.20 m layer under the moldboard plow system.

With the exceptions of P and K contents in the 0.10-0.20 m layer, which were classified as low, all chemical properties were at an adequate level according to Freire (2003). This is probably the reason why, even with differences in chemical properties among the straw managements, their effects on the yield of rice-soybean succession was less evident that the physical properties, as discussed below.

The cumulative yield of two rice crops was higher in the M1, M2, M6, M7, and M8 managements (Table 6). These managements provided, in absolute values, lower densities in the 0.10-0.20 m layer and *S* index higher than 0.035 (Table 3), which may have contributed to a greater root depth development in rice plants. A negative correlation between cumulative rice yield and bulk density in the 0.10-0.20 m layer was observed (Table 5). According

Table 5: Coefficients of Pearson's linear correlation (r) between rice, soybean, and rice-soybean succession cumulative yields and some soil properties in 0-0.10 m and 0.10-0.20 m layers

Variable		Correlation r	Probability (p)
	0-0.10 m layer		
Soybean yield (kg ha^{-1})	Bulk density (Mg^3 m^{-3})	-0.75	< 0.05
	Total porosity (m^3 m^{-3})	0.77	< 0.05
	Macroporosity (m^3 m^{-3})	0.78	< 0.05
	Air capacity	0.70	< 0.05
	Soil organic matter (g kg^{-1})	0.70	< 0.05
Rice-soybean yield (kg ha^{-1})	Bulk density (Mg^3 m^{-3})	-0.96	< 0.05
	Total porosity (m^3 m^{-3})	0.96	< 0.01
	Macroporosity (m^3 m^{-3})	0.89	< 0.01
	S index	0.91	< 0.01
	Air capacity	0.85	< 0.01
	0.10-0.20 m layer		
Rice yield (kg ha^{-1})	Bulk density (Mg^3 m^{-3})	-0.68	< 0.05
Rice-soybean yield (kg ha^{-1})	Bulk density (Mg^3 m^{-3})	-0.67	< 0.05
Soil organic matter (g kg^{-1})	Phosphorus (mg^3 dm^{-3})	0.93	< 0.01
	Potassium (mg^3 dm^{-3})	0.89	< 0.01
	Calcium (mmol$_c$ dm^{-3})	0.93	< 0.01
	Magnesium (mmol$_c$ dm^{-3})	0.95	< 0.01
	Copper (mg^3 dm^{-3})	0.74	< 0.05
	Zinc (mg^3 dm^{-3})	0.91	< 0.01
	Manganese (mg^3 dm^{-3})	0.82	< 0.01
	Iron (mg^3 dm^{-3})	0.95	< 0.01

to Bamberg (2009), the bulk density in the zone of root development affects rice crop considerably. However, burning (M1) causes significant air pollution, losses of nutrients, death of beneficial soil insects and microorganisms, and, as well as the straw harvesting (M2), can reduce soil organic matter over time.

The cumulative yield of three soybean crops conducted in succession to rice was the highest with straw incorporation with one pass of disc harrow and two (M3) or three (M4) passes of leveling disc harrow. The lowest yields were obtained with the managements using the knife-roller, except for M6 (Table 6). The soybean was conducted under subirrigation and, therefore, the root system was concentrated in the soil superficial layer (0-0.10 m), where fresh straw residues are most concentrated. According to Sousa & Bortolon (2002), fresh rice straw residues incorporated into flooded soil can lead to the production of organic acids, which are harmful to seedling growth. This is likely the case of soybean after rice, considering the subirrigation system used in Tocantins, which is based on raising the water table and maintaining the soil with high moisture (or saturation) conditions (Farencena, 2011), decreasing soybean yield when the knife-roller was used.

In addition, the managements that maintained the physical quality of this layer resulted in greater soybean yields. The cumulative soybean yield correlated positively with total porosity, macroporosity, and aeration capacity and negatively with bulk density in the 0-0.10 m layer (Table 5). It also correlated positively with the soil organic matter content in this layer. Andreotti *et al.* (2010) also observed a positive correlation between soybean yield and soil macroporosity in the 0-0.10 m layer, and Chioderoli *et al.* (2012) found that soybean yield was favored by higher soil porosity.

The cumulative yield of the rice-soybean succession was lowest in the managements with rice straw incorporated with one pass of knife-roller and soybean under no-tillage (M5) or straw incorporated with two passes of knife-roller and three passes of leveling disc harrow (M9). These managements contributed to the lowest yields of both rice and soybean (Table 6), possibly for resulting in the highest absolute values of bulk density (Table 3). The cumulative yield of the rice-soybean succession was negatively correlated with bulk density and positively with total porosity, macroporosity, *S* index and air capacity in the 0-0.10 m layer (Table 5). Flooded irrigation is capable of degrading the soil physical quality by dispersing soil aggregates and increasing bulk density, what can be reversed by soil tillage. Since no-tillage does not disturb the soil, the soil compaction may cause lower values of soybean yield. Gangwar *et al.* (2006) reported lower yield of no-tillage wheat grown after rice in a paddy soil. In the same way, the large number of machinery operations before soybean sowing in M9 management may have contributed to increase soil compaction.

The principal components analysis (PCA) showed that the first two components accounted for 69.3% of the variance, the first component explained 42.8% of the total variance and the second component explained 26.5% (Figures 1a and 1b). Three clusters were formed according to the criteria used in this study. The managements were clustered as follows: 1) M1, M2, M3, and M4; 2) M5 and M9; and 3) M6, M7, and M8.

Table 6: Cumulative mean yields of two rice and three soybean crops and the rice-soybean succession as a function of rice straw management, in Formoso do Araguaia, TO, 2017[1]

Straw management	Cumulative yield (kg ha^{-1})		
	Rice	Soybean	Rice-soybean succession
M1	15729a	10056b	25785a
M2	16303a	9838b	26141a
M3	14691b	10575a	25266a
M4	14648b	10724a	25372a
M5	15019b	9194c	24213b
M6	15484a	9929b	25412a
M7	15558a	9674c	25232a
M8	15746a	9390c	25136a
M9	14738b	9038c	23776b

[1]Means followed by the same letters in the columns are not significantly different at 5% probability by the Scott-Knott's test. M1, straw burning and soil tillage with one pass of disc harrow and three passes of leveling disc harrow; M2, straw harvesting for various uses such as fencing or watermelon packaging, and soil tillage with one pass of disc harrow pass and three passes of leveling disc harrow; M3, straw incorporation with one pass of disc harrow and two passes of leveling disc harrow; M4, straw incorporation with one pass of disc harrow and three passes of leveling disc harrow; M5, straw incorporation with one pass of knife-roller and no-tillage for soybean sowing; M6, straw incorporation with one pass of knife-roller and two of leveling disc harrow; M7, straw incorporation with one pass of knife-roller and three passes of leveling disc harrow; M8, straw incorporation with two passes of knife-roller and two passes of leveling disc harrow; M9, straw incorporation with two passes of knife-roller and three passes of leveling disc harrow.

The cluster formed by the M1, M2, M3, and M4 managements is mainly associated to the contents of Ca, Zn, Mn, Fe, and SOM in the 0.10-0.20 m layer (Figures 1a and 1b). In these managements, soil tillage was carried out with a disc harrow, which revolves the soil in greater depth than the knife-roller and promotes faster straw mineralization, resulting in higher organic matter content in depth, in agreement with the results of Ou *et al.* (2016).

The cluster formed by the M5 and M9 managements is mainly associated with the bulk density in the superficial layer (Figures 1a and 1b), which presented the highest absolute value in these managements (Table 3). These managements are characterized by the incorporation of rice straw with one pass of knife-roller and no-tillage soybean (M5) or with two passes of knife-roller and three passes of leveling disc harrow before soybean sowing (M9). As discussed earlier, the lack of soil tillage for soybean sowing (M5) or a large number of machinery operations before soybean sowing (M9) may have contributed to the increase in bulk density, adversely affecting soybean yield and, therefore, the yield of rice-soybean succession.

The cluster formed by the M6, M7, and M8 managements is mainly associated with the macroporosity and *S* index in the 0.10-0.20 m layer (Figures 1a and 1b), which presented the highest absolute values under these managements (Table 3). In these three managements, the soil was tilled with a knife-roller.

The cumulative rice-soybean yield (Figure 1b) was positively associated with the better soil physical condition in the superficial layer (total porosity, macroporosity, *S* index, and air capacity) and negatively with bulk density (opposite vector), as discussed before. Cumulative soybean yield showed the same trend as the cumulative rice-soybean yield, but with lower intensity.

Although a long-term study can provide better answers about the best alternatives for managing rice straw, the straw managements based on knife-roller methods (M6, M7, and M8) showed equivalent agronomic performance compared to disc harrow-based tillage (M1, M2, M3, and M4). However, the higher sustainability performance makes the knife-roller methods appealing to seedbed preparation after irrigated rice in lowland production systems. Besides preserving the possible benefits of the rice straw

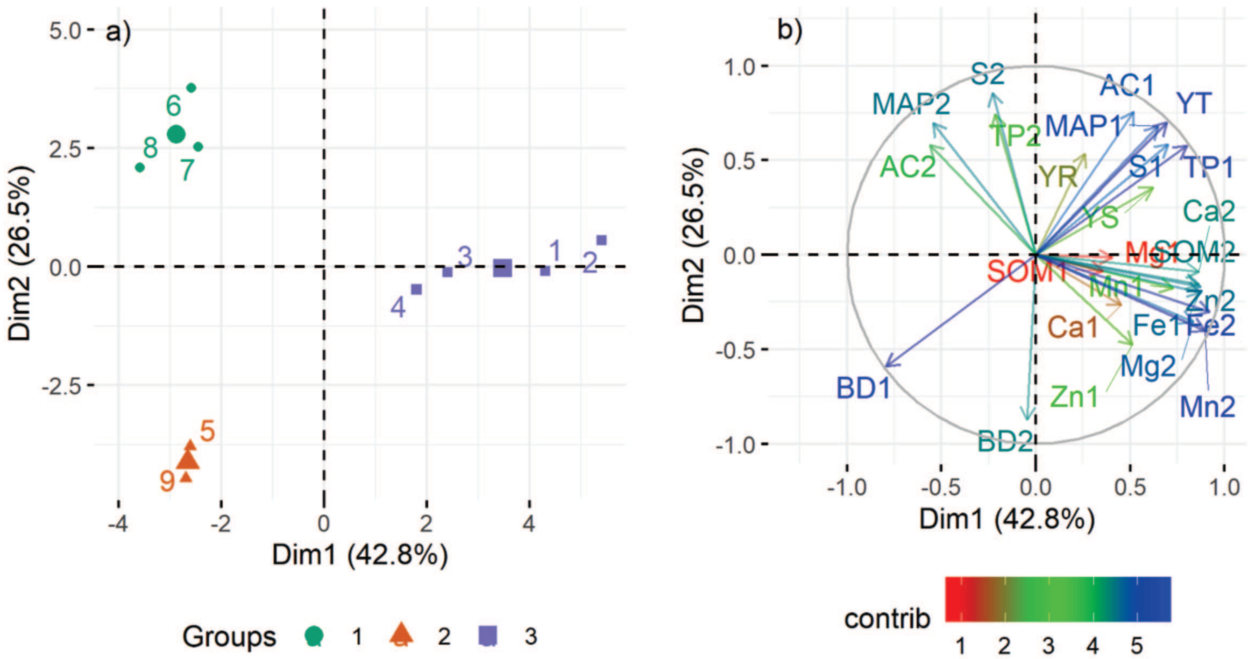

Figure 1: Ordination diagram (a) and eigenvectors (b) of cumulative yields of rice, soybean and rice-soybean succession and physical and chemical properties in the 0-0.10 m and 0.10-0.20 m layers of soil subjected to different rice straw managements in Formoso do Araguaia, TO, 2017. 1, straw burning and soil tillage with one pass of disc harrow and three passes of leveling disc harrow; 2, straw harvesting for various uses such as fencing or watermelon packaging, and soil tillage with one pass of disc harrow pass and three passes of leveling disc harrow; 3, straw incorporation with one pass of disc harrow and two passes of leveling disc harrow; 4, straw incorporation with one pass of disc harrow and three passes of leveling disc harrow; 5, straw incorporation with one pass of knife-roller and no-tillage for soybean sowing; 6, straw incorporation with one pass of knife-roller and two of leveling disc harrow; 7, straw incorporation with one pass of knife-roller and three passes of leveling disc harrow; 8, straw incorporation with two passes of knife-roller and two passes of leveling disc harrow; 9, straw incorporation with two passes of knife-roller and three passes of leveling disc harrow. BD, bulk density; TP, total porosity; MAP, macroporosity; S, *S* index; AC, air capacity; Ca, calcium; Mg, magnesium; Zn, zinc; Mn, manganese; Fe, iron; SOM, soil organic matter; YR, rice cumulative yield; YS, soybean cumulative yield; YT, rice-soybean succession cumulative yield. The number 1 or 2 after each soil attribute refers to the 0-0.10 and 0.10-0.20 m layers, respectively.

incorporation unlike straw burning (M1) or harvesting (M2), they maintained the soil physical quality, as evaluated by *S* index and macroporosity, in an adequate level. Moreover, a knife-roller can incorporate rice stubbles near to the soil surface, which, compared to deep incorporation, as in the M3 and M4 managements, reduces the amount of methane from residue decomposition (Alberto *et al.*, 2015) and demands less energy to prepare the soil (Theisen *et al.*, 2018). In addition, the knife-roller operation allows early soil tillage, soon after the rice harvest, because it requires standing water, unlike the disc harrow operations, which demand drier soil. Among the knife-roller methods, straw incorporation with one pass of knife-roller and two passes of leveling disc harrow (M6) stands out. This management method employs a smaller number of machinery operations than the managements M7 and M8. These results corroborate those of Theisen *et al.* (2018) and Silva *et al.* (2019).

CONCLUSIONS

Rice straw incorporation by knife-roller provides lower soil organic matter contents regarding to disc harrow treatments due to slow mineralization of fresh straw incorporated shallow into the soil, although organic matter increases in the surface layer related to the initial content.

The yield of rice-soybean succession is more affected by the physical than by the chemical properties of the soil.

Straw incorporation with one pass of knife-roller and two passes of leveling disc harrow can substitute the rice straw burning, without affecting rice-soybean succession yield and soil physical quality, with a reduction in machinery operations, allowing early soil tillage.

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REFERENCES

ADAPEC - Agência de Defesa Agropecuária do Estado do Tocantins (2018) Notícias. Available at: <https://adapec.to.gov.br/noticia/2018/4/20/comeca-o-periodo-do-plantio-de-soja-nas-varzeas-tropicais-/>. Accessed on: June 25th, 2018.

Alberto MCR, Wassmann R, Gummert M, Buresh RJ, Quilty JR, Correa Jr TQ, Centeno CAR & Oca GM (2015) Straw incorporated after mechanized harvesting of irrigated rice affects net emissions of CH_4 and CO_2 based on eddy covariance measurements. Field Crops Research, 184:162-175.

Almeida RD de, Peluzio JM & Afférri FS (2011) Divergência genética entre cultivares de soja, sob condições de várzea irrigada, no sul do Estado Tocantins. Revista Ciência Agronômica, 42:108-115.

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JL de M & Sparovek G (2013) Köppen´s climate classification map of Brazil. Meteorologische Zeitschrift, 22:711-728.

Andreotti M, Carvalho M de P, Basso FC, Pariz CM, Vercese F, Montanari R & Azenha MV (2010) Produtividade da soja correlacionada com a porosidade e a densidade de um Latossolo Vermelho do cerrado brasileiro. Ciência Rural, 40:520-526.

Arruda MHM, Meneghello GE, Vieira JF & Gadotti GI (2016) Qualidade fisiológica de lotes de sementes de soja com diferentes percentuais de sementes esverdeadas. Magistra, 28:194-200.

Bamberg AL, Pauletto EA, Gomes A da S, Timm LC, Pinto LFS, Lima ACR de & Silva TR da (2009) Densidade de um planossolo sob sistemas de cultivo avaliada por meio da tomografia computadorizada de raios gama. Revista Brasileira de Ciência do Solo, 33:1079-1086.

Chioderoli CA, Mello LMM de, Grigolli PJ, Furlani CEA, Silva JOR & Cesarin AL (2012) Atributos físicos do solo e produtividade de soja em sistema de consórcio milho e braquiária. Revista Brasileira de Engenharia Agrícola e Ambiental, 16:37-43.

CONAB - Companhia Nacional de Abastecimento (2018) Acompanhamento da safra brasileira [de] grãos: safra 2017/18: décimo levantamento. Brasília, CONAB. 178p.

Counce PA, Keisling TC & Mitchell AJA (2000) Uniform, objective, and adaptive system for expressing rice development. Crop Science, 40:436-443.

Dexter AR (2004) Soil physical quality. Part 1. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma, 120:201-214.

Farencena JC (2011) Análise da subirrigação em várzeas tropicais. Dissertação de Mestrado. Universidade Federal do Rio Grande do Sul, Porto Alegre. 95p.

Freire FM (2003) Interpretação de resultados de análise de solo. Sete Lagoas, Embrapa Milho e Sorgo. 4p. (Comunicado Técnico, 82).

Gangwar KS, Singh KK, Sharma SK & Tomar OK (2006) Alternative tillage and crop residue management in wheat after rice in sandy loam soils of Indo-Gangetic plains. Soil & Tillage Research, 88:242-252.

Husson F, Lê S & Pagès J (2015) Exploratory multivariate analysis by example using R. Boca Raton, CRC Press. 240p.

IUSS Working Group WRB (2015) World reference base for soil resources 2014 - International soil classification system for naming soils and creating legends for soil maps. Rome, FAO. 203p. (World Soil Resources Reports, 106).

Knoblauch R, Ernani PR, Deschamps FC, Gatiboni LC, Walker TW, Lourenço KS, Martins AA & Pegoraro A (2014) Rice straw incorporated just before soil flooding increases acetic acid formation and decreases available nitrogen. Revista Brasileira de Ciência do Solo, 38:177-184.

Li J, Jianwei L, Li X, Ren T, Cong R & Zhou L (2014) Dynamics of potassium release and adsorption on rice straw. Plos One, 9:e90440.

Massoni PFS, Marchesan E, Grohs M, Silva LS da & Roso R (2013) Nutrientes do solo influenciados por diferentes manejos da palha após a colheita do arroz irrigado. Revista Ciência Agronômica, 44:205-214.

Mentges MI, Reichert JM, Gubiani PI, Reinert DJ & Xavier A (2013) alterações estruturais e mecânicas de solo de várzea cultivado com arroz irrigado por inundação. Revista Brasileira de Ciência do Solo, 37:221-231.

Ou HP, Liu XH, Chen QS, Huang YF, He MJ, Tan HW, Xu FL, Li YR & Gu MH (2016) Water-stable aggregates and associated carbon in a subtropical rice soil under variable tillage. Revista Brasileira de Ciência do Solo, 40:e0150145.

R Development Core Team (2018) R: A language and environment for statistical computing. Available at: http://www.R-project.org. Accessed on: May 25th, 2018.

Redin M, Santos GF, Miguel P, Denega GL, Lupatini M, Doneda A & Souza EL (2011) Impactos da queima sobre atributos químicos, físicos e biológicos do solo. Ciência Florestal, 21:381-392.

Reynolds WD, Bowman BT, Drury CF, Tan CS & Lu X (2002) Indicators of good soil physical quality: density and storage parameters. Geoderma, 110:131-146.

Ribeiro PL, Bamberg AL, Reis DA & Oliveira ACB (2016) Condições físico-hídricas de Planossolo cultivado com soja em plantio direto e preparo convencional. Pesquisa Agropecuária Brasileira, 51:1484-1491.

Santos HG dos, Jacomine PKT, Anjos LHC dos, Oliveira VA de, Lumbreras JF, Coelho MR, Almeida JÁ de, Araujo Filho JC de, Oliveira JB de & Cunha TJF (2018) Sistema brasileiro de classificação de solos. 5ª ed. Brasília, Embrapa. 356p.

Schaller J, Wang J, Islam MR & Planer-Friedrich B (2018) Black carbon yields highest nutrient and lowest arsenic release when using rice residuals in paddy soils. Scientific Reports, 8:01-11.

Silva JG da, Nascente AS & Silveira PM da (2019) Equipments to manage soil and irrigated rice straw for the sequential sowing of soybean in tropical floodplains. Pesquisa Agropecuária Brasileira, 49:e54879.

Soltanpour PN, Johnson GW, Workman SM, Jones JB & Miller RO (1996) Inductively coupled plasma emission spectrometry and inductively coupled plasma-mass spectrometry. In: Sparks SL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabaitabai MA, Johnston CT & Sumner ME (Eds.) Methods of Soil Analysis Part 3 - Chemical Methods. Madison, Soil Science Society of America. p.91-139.

Sousa RO de & Bortolon L (2002) Crescimento radicular e da parte aérea do arroz (*Oryza sativa* L.) e absorção de nutrientes, em solução nutritiva com diferentes concentrações de ácido acético. Revista Brasileira de Agrociência, 8:231-235.

Suriyagoda L, Costa WAJM de & Lambers H (2014) Growth and phosphorus nutrition of rice when inorganic fertiliser application is partly replaced by straw under varying moisture availability in sandy and clay soils. Plant and Soil, 384:53-68.

Tanaka A, Toriyama K & Kobayashi K (2012) Nitrogen supply via internal nutrient cycling of residues and weeds in lowland rice farming. Field Crops Research, 137:251-260.

Teixeira PC, Donagemma GK, Fontana A & Teixeira WG (2017) Manual de métodos de análise de solo. 3ª ed. Brasília, Embrapa. 574p.

Theisen G, Silva JCC & Bastiaans L (2018) A knife-roller effectively substitutes soil preparation by plough-and-harrow in lowland production systems. Experimental Agriculture, 54:901-914.

Villegas-Pangga G, Blair G & Lefroy R (2000) Measurement of decomposition and associated nutrient release from straw (*Oryza sativa* L.) of different rice varieties using a perfusion system. Plant and Soil, 223:01-11.