



# Alternatives for handling rice (*Oryza sativa* L.) straw to favor its decomposition in direct sowing systems and their incidence on soil compaction



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## ABSTRACT

Over 85% of the worldwide area planted with rice is irrigated, mainly by flooding, because this method increases yields. Irrigation by flooding provides this crop with particular characteristics, including at harvest, when it causes difficulties for machinery traffic due to the high soil water content. In addition to this, a large amount of green material is left on the soil, which if not burned, a practice which is prohibited or in the process thereof in many countries, impedes later work to the point where over 600 to 800 kg/ha affects establishment of rice in the following season. The above is complicated by the use of direct sowing (DS), which achieves positive results, both in lowering costs and recovering soil, although there is no knowledge of how the planosol soils in Corrientes Province, Argentina, behave under these traffic conditions. The main objectives of this study were to: a) Find out how tools can be used best for improving decomposition of residue from harvesting rice grown under DS and their impact on soil compaction, and b) determine, for short periods, the amount of rice straws deposited on the surface and its decomposition time with various management techniques. A split plot with main factor arranged in a randomized complete block design with four replicates was performed. The use of harvester without spreader, harvester with rubber-flailed spreader, and harvester with metal-flailed spreader was assessed as the main factor. Additionally, three decomposition methods of rice straw were studied as split factor: passing a roller crimper over rice straw, control weed of rice straw with stubble chopper, and burning rice straw. The main results were: a) The harvester without spreader deposited more material in the center of the tail (21.680 kg/ha) decreasing toward the sides, and b) distribution done by the harvester with metal-flailed spreader was somewhat similar to the harvester with rubber-flailed spreader but with slightly less uniform deposits. The main conclusions were: 1) When planosol soil was trafficked with loads of 152.5 kN, the cone index increased in the subsoil, affecting next growing season, 2) management alternatives that left residue cover attenuated soil compaction caused by the harvester traffic, and 3) the use of a stubble chopper or roller crimper on the rice straw distributed by the harvesters with rubber-flailed or metal-flailed spreaders produced acceleration in decomposition.

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## 1. Introduction

Around 19 species of annual plants in the Gramineae family are known worldwide by the name of rice (Grist, 1975). The species *Oryza sativa* L., because of its nutritional value, is the main diet of over half of the world's population. Research by Bahgat (2004) indicates that for over 4.4 billion people it is the basis of their diet, and its demand increases 3% annually.

In South America, the main producers are Brazil, Argentina and Uruguay, which in the 2010/2012 season produced 14.81 million t, representing 2.14% of the world production. In Argentina, a 250,000 ha area, mainly in the Mesopotamia between the Paraná and Uruguay rivers, grew rice in the last season. The main producer provinces are Entre Ríos and Corrientes, which produce 705,870 and 691,748 t in areas harvested of 99,000 and 103,246 ha respectively, concentrating over 80% of the national production with an average yield of 6900 kg/ha.

Over 85% of the area is cultivated by irrigation, because this method increases yields (Kawaguchi and Kyuma, 1977). Flooding, however, implies a relatively high capital investment per unit of area which is characteristic of any intensive crop. This situation also causes the need to minimize risks, so a relatively high-technology package such as

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agrochemicals and fertilizers is necessary (Jetter, 2007). Flood irrigation gives this cropping system particular characteristics, causing difficulties for machinery traffic due to the high soil water content. When the rice is grown with flooding, a layer of water remains on the soil which causes physicochemical and biological alterations in the crop with repercussions on the normal development of the plants (Arronratana et al., 1972).

Apart from this, the soils mentioned above have large percentages of strongly adhesive, expansive montmorillonite clay, which makes them difficult to till, and thereby making direct sowing (DS) into an excellent tool for their management, due to the absence of tillage under DS (Pozzolo et al., 2001). It is known that the adoption of this type of technology involves greater dependence on agrochemicals, especially fertilizers and herbicides, while heavyweight harvesters must have powerful motors, because when they harvest they must chop and spread the chaff so it does not cause obstruction to DS of the following crop.

In Argentina, the use of the DS system in this crop is recent, starting in 1991 on an area of 14 ha, which has now increased to 35,000 ha where vertisol and planosol soils predominate. DS is done in fields where rice has been sown, conserved by Taipas (ridged terraces following the curves along a level) from previous years, and occasionally repaired as necessary. When the rice is harvested, a cover crop ryegrass (*Lolium multiflorum* L.) or oats (*Avena sativa* L.) may be sown, making use of them during the winter and early spring, or the whole-plant forage rice may be left in the field. Just before sowing, a total herbicide is applied.

In this context, it should also be mentioned that rice used in Argentina currently has a potential yield of around 9500 kg/ha, and for this production in grain, an amount of green material of approximately 22,000 kg/ha, not counting roots, is produced.

Rice straw is an important fertilizing source because it contains 70% potassium and almost all of the silicon the plant absorbs. This nutrient helps defend the plant from disease and keeps it from lodging. Potassium favors filling grains and other metabolic processes, which is in turn an essential source of carbon (Blevins et al., 1977).

Therefore, it is fundamental that it remains on the ground as protection, when the rice straw is left on the surface to decompose slowly, it releases both the potassium and silicon it contains into the soil, since it is the topsoil (200 mm) where most of the microorganisms are contained and where the plants are going to take most of the minerals. In this sense, according to Bird et al. (2002) when rice straw is incorporated, nutrients are returned to the soil. Less nitrogen can be applied to fields where the straw has been incorporated, resulting in reduced production costs and decreasing the potential for water pollution.

However, others maintain that the presence of rice straw and its slow decomposition could cause the appearance of fungi, causing diseases, such as stem rot, and an amount over 600 kg/ha has disadvantages for working with DS, because the grain planting trains are plugged by large amounts of rice straw. Hidalgo et al. (2009) mention in their studies that the establishment of rice is worse when the rice straw on the surface at time of sowing is about 800 kg/ha.

In view of this situation, most producers have burned the rice straw, according to Dobie et al. (1984), from the beginning of rice production in California and Texas in the USA, where the practice of burning the rice straws is the most commonly used and is considered an effective method of elimination, which assists in reducing the costs of preparing the soil for later crops. In Argentina, agrochemicals, controlled irrigation or burning rice straw are common practices employed by rice producers to control weeds before sowing (Hidalgo et al., 2009).

Hill et al. (2000) suggest burning as a possible advantage for effective control of two of the severest diseases in rice, stem rot (*Sclerotium oryzae*) and aggregate sheath spot (*Rhizoctonia oryzae-sativae*). However, this methodology causes alteration of topsoil because the replacement of nutrients by rice straw decomposition is practically nil. When the rice straw is burned, the fire kills most of the microorganisms that help transform organic matter into the minerals the plants can absorb,

**Table 1**  
Typical soil profile.

Horizons	A	BA	Btss1	Btss2	Btss3
Depth range (cm)	0–13	13–30	30–60	60–116	116–170
Organic matter (%)	4.22	2.22	1.59	0.52	0.65
Organic carbon (%)	2.11	1.11	0.79	0.26	0.33
Clay (<2 μ)	51.8	60.9	64.8	58.4	60.9
Silt (2–50 μ)	38.3	33.5	28.1	26.4	31.2
Fine sand (100–250 μm)	9.9	5.6	7.1	15.0	7.9
pH in H <sub>2</sub> O (1:2.5)	4.6	4.2	4.0	4.4	4.3
Cation exchange capacity (m.e. 100 g <sup>-1</sup> )					
Ca <sup>++</sup>	22.3	27.2	–	–	–
Mg <sup>++</sup>	7.2	8.9	–	–	–
Na <sup>+</sup>	1.9	4.2	–	–	–
K <sup>+</sup>	1.2	1.1	–	–	–

and when it destroys them, the fertility of the soil decreases (Torbert and Reeves, 1995). It also causes the emission of large amounts of pollutants into the air, especially fine particles (Jenkins et al., 2000). These observations were also described by Balwinder-Singh et al. (2011), who suggest that burning rice stubble in northeast India led to air pollution, soil degradation and decreased water in the subsoil. On the contrary, leaving the rice straw was beneficial for retaining moisture in the soil and decreasing loss of organic matter.

Today, more importance is given to caring for the environment and natural resources, and therefore, the practice of burning the rice straw each time is finding more resistance in certain places in the world. A much used alternative to burning is the collection of rice straw for use in other activities. However, if no profit is to be made from the use of collected rice straw, the cost of its collection, baling, transport and storage impacts negatively on profitability (Jenkins et al., 2000). Moreover, results vary depending on the climate and the time required by soils to adapt to a new management system. Also, little is known about the effects of DS equipment traffic on soil properties and rice in the Argentinian Mesopotamia.

Finally, in view of all of the above, our main objective of this research is to determine new techniques that favor decomposition of rice straw without attacking the soil and environment. Our working hypotheses are: 1) The distribution of the rice straw is affected by type, constitution and construction material of the harvester's spreaders, and 2) the uniform distribution of rice straw favors its decomposition and attenuates topsoil compaction.

## 2. Materials and methods

### 2.1. The site and experimental design

The work was done in the Oscuro farm, located near Perogorría, Corrientes Province (35°7' South, 57°31' West) on a soil classified as Oxyaquic Hapluderts (Soil Taxonomy, 2010). The Chavarría soil series of southeastern Corrientes state are soils of relatively flat topography (0.3%) and poor internal drainage. The soil at the Oscuro farm was developed from about 1.6 m of weathered loess on level topography under a tall-grass, prairie vegetation. Typical profile characteristics are shown in Table 1. The previous soil management history of the site includes 8 years of rice crop cultivation. During this period the soil was managed under DS system.

**Table 2**  
Harvester/spreader setups and decomposition methods.

Decomposition methods (split factor)	Harvester/spreader setups (main factor)		
	Without spreader (T1WS)	Rubber-flailed spreader (T2RS)	Metal-flailed spreader (T3MS)
Stubble chopper (SC)	✓	✓	✓
Crimping (RC)	✓	✓	✓
Burning (BS)	✓	✓	✓

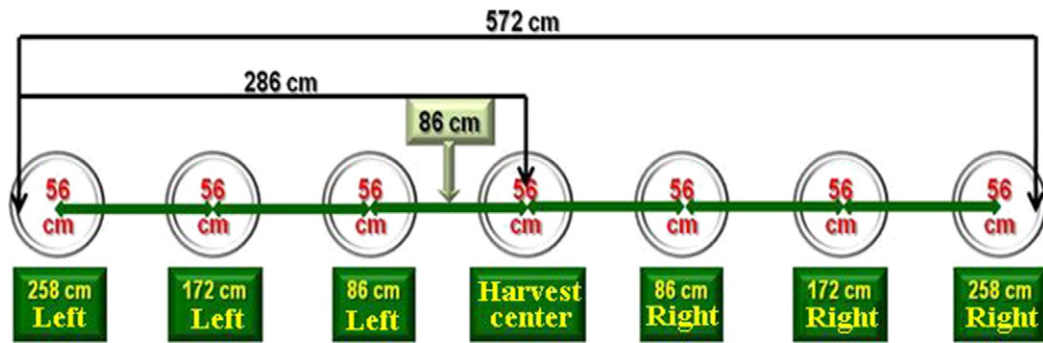


Fig. 1. Illustration of sampling points for evaluation of distribution and quality of rice straw.

Testing was done during harvesting of rice, in two consecutive years, using three different types of spreader mounted on the New Holland TC57 harvester with straw chopper which was available at Argentinean rice area. These types of spreader are commonly available across this region. The common width of the front and rear tyres are  $24.5 \times 32R1$  10 ply and  $11.25 \times 24$  8 ply, respectively. Front and rear wheel track widths were 30.5 cm and 30 cm, respectively. The ground pressures of front and rear tyre were 116.4 kPa and 228 kPa, respectively. The total weight loaded was 152.5 kN. The harvest speed was 5 km/h.

Experimental design was split plot with main factor (distribution method) arranged in a randomized complete block design with four replicates and split-plot factor (decomposition method of rice straw). As a result, each replicate plot was subdivided into three subplots ( $50 \text{ m} \times 50 \text{ m}$ ). The main factor was: harvester without spreader (T1WS), harvester with rubber-flailed spreader (T2RS) and harvester with metal-flailed spreader (T3MS), each mounted on the harvester. The split plot factors were: a) passing a roller crimper (RC) over rice straw, b) control weed of rice straw with stubble chopper (SC) and c) burning rice straw (BS) (see Table 2). The method most used by rice producers in Argentina is not using the spreader on the harvester

and burning the whole rice straw afterwards (end of the season) and near seeding the following season (T1WS + BS).

## 2.2. Experimental variables and measurement methods

### 2.2.1. Distribution and decomposition of rice straw

Rice straw decomposition was evaluated for seven months from the beginning of testing on February 27th to September 27th. It was done on the same dates so there would be no differences in data, clarifying that in the second year on June 26th it was impossible to take data due to rain and they were taken on June 28th instead. It is noteworthy that the average rice yield was 9500 kg/ha, for the two years of testing.

The main analysis was the effect of each harvester/spreader setups on decomposition of rice straw. The distribution of rice straw was evaluated using  $0.56 \text{ m}$  diameter wire rings ( $0.25 \text{ m}^2$ ) for seven determinations after the harvester had passed. The rings were placed every  $0.86 \text{ m}$  starting from the center of the tail of the machine up to  $2.86 \text{ m}$  to left and right of the center ring, which covered the whole spreading width of  $5.72 \text{ m}$  (Fig. 1). After the passage of the harvesters, the rice straw deposited was quantified and its distribution was analyzed for each of the



T1WS



T2RS



T3MS

Fig. 2. State of rice straw produced by the three harvester/spreader setups.

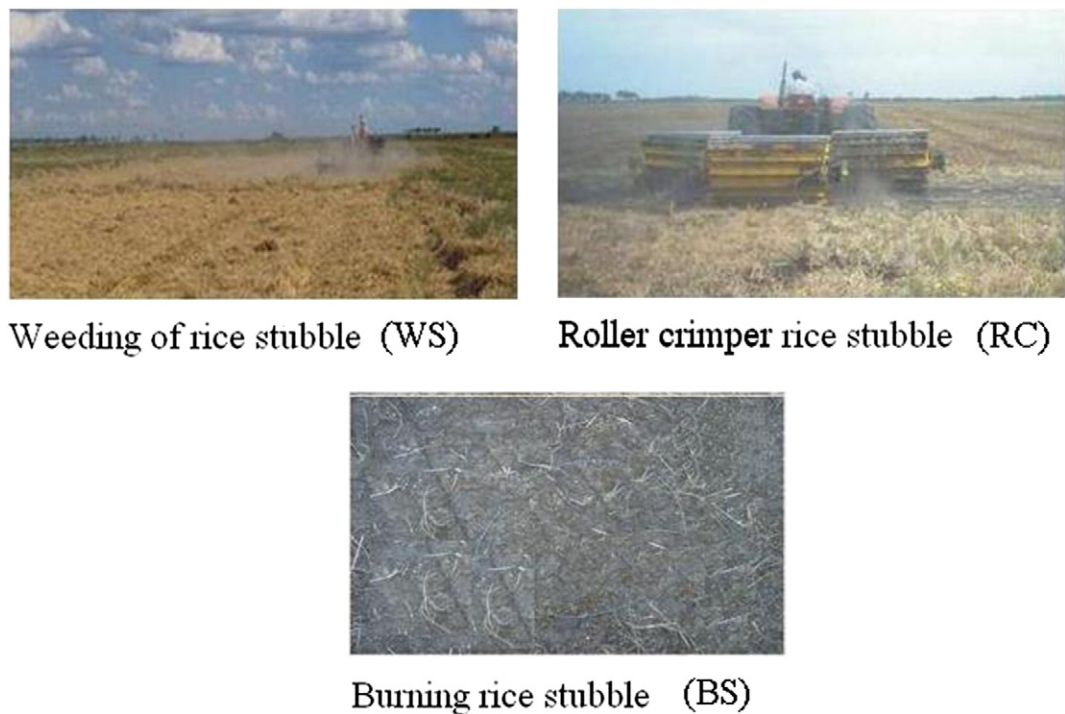


Fig. 3. Methods utilized for decomposition of rice straw.

spreaders and the decomposition methods in the study (Figs. 2 and 3). All of the rice straws inside the ring were collected to be able to measure the amount of dry matter, making three repetitions per treatment. The dry matter content was recorded for the eight months the test lasted to determine decomposition of rice straw. Because variation coefficients were not low enough with samples every 15 days during testing for blanks before the project, it was decided to take samples every 30 days, for a most effective measuring procedure. Sampling of rice straw was repeated every 30 days until the time of seeding which was done around the middle of September, so the test lasted eight months, as usually producers leave straw on the field before next crop is established.

#### 2.2.2. Determination of soil PH, organic matter, organic carbon and nutrients in soil

Analysis of the possible contribution of nutrients (P, K, Ca, Mg, Na) to the soil and the products of decomposition of rice straw using the different methods evaluated. Soil samples were taken on three dates: 27/02, 22/06 and 27/09 (dates 1, 2 and 3). The decision to leave four months between the first and second dates and three months between the second and third was due to the assumption that there would be more decomposition in those periods. The range of depth analyzed was 0 to 250 mm.

Soil pH was determined with a potentiometer equipped with a glass electrode that was inserted in the soil, as proposed by Pozzolo (2007). Organic matter was measured by the Walkley and Black method (1934). Granulometric fractioning was done by wet screening before dispersion by agitation (Galantini and Rosell, 1997).

For the fine (FF < 100  $\mu\text{m}$ ) and coarse (CF: 100  $\mu\text{m}$ –2000  $\mu\text{m}$ ) fractions and original (0–2000  $\mu\text{m}$ ) samples, the oxidizable carbon (OXC) content was determined in duplicate by wet combustion. To determine the organic carbon (OC) from OXC, oxidation factors of 0.79, 1.00 and 0.90 were used for the FF, CF and original sample, in that order as proposed by Galantini and Rosell (1997). The enrichment index of each sample (Ie), defined as the quotient of OC in each fraction and total organic carbon (TOC) was calculated to compare OC in FF and CF with OC in the original sample (TOC). Humified organic carbon (HOC) and

particulated organic carbon (PCO) contents were found referring CO in the FF and CF to the total sample analyzed.

Determination of phosphorous and potassium, bases and minor elements (Ca, Mg and Na) in the soil was analyzed by simultaneous extraction using a sodium chloride and citric acid reagent. This reagent has the virtue of extracting exchangeable bases by the sodium, the soluble phosphorus in water plus what is soluble in citrate (assimilable phosphorus), and the chelatable minor elements by the citric acid. All these determinations were done at the beginning of testing and every three months thereafter (Mandolesi et al., 2002).

#### 2.2.3. Variables linked to soil compaction

The experimental variable responses linked to the attenuation of soil compaction were: Infiltration (I), soil water content (SWC) and cone index (CI). Infiltration values were determined with a ring infiltrometer. To determine the SWC variable, four sample points per subplot per treatment were taken, finding SWC every 100 mm down to a depth of 600 mm. SWC was found by a neutron probe. Five repetitions were done every 100 mm for each average in each of the crop main factor plots as proposed by Botta (2000) and Pozzolo (2007).

Cone index was determined with a Rimick CP20 recording penetrometer S 313 (ASAE Standards S 313.2, 1992). Data for studying the

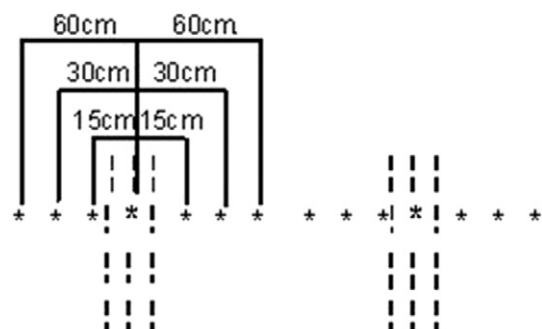


Fig. 4. Cone index sampling points in the harvester tracks.

impact of harvester passes on the CI during the time the test lasted were taken at the beginning and at the end, and averaged for the two years of study, and were taken on two dates, 27/02 and 27/09. They were taken on the tracks of harvester at seven places: center of the track, 0.15, 0.30 and 0.60 m on both sides, left and right (Fig. 4) and in three depth ranges, 0–200, 200–400 and 400–600 mm, taking readings every 50 mm from the surface to a maximum depth of 600 mm, and then were averaged by depth range. Each datum was the mean of thirty soil samples for each of the subplots per treatment, as proposed by Botta (2000) and Pozzolo (2007).

CI data were taken at the beginning of testing and before starting the testing. Soil at the test site was characterized for correct diagnosis of the original situation and to detect any a posteriori changes from the test proposed.

Conditions when data were taken made it possible to track evolution of compaction over time and to evaluate any natural soil restructuring, as proposed by Botta (2000). The harvest and rice straw distributions were measured at the start and end of the harvest period with SWC compatible with penetration resistance measurements, thus evaluating the effect of working harvester traffic, as proposed by Pozzolo (2007). For CI parameter, the control plot was a soil without traffic.

The statistical analysis of the possible contribution of nutrients was done by averaging the two years of testing. The statistical analysis of the variables was done by split-plot ANOVA (split-plot design), with the Statgraf 7.1 program. The criterion employed to express the results of the comparison of means tests was Duncan.

### 3. Results and discussion

#### 3.1. Soil water content, cone index and infiltration

At the beginning (27/02) and at the end (27/09) of the test, SWC did not show statistical differences in the whole study profile (0 to 600 mm depth range and both sides of the harvester track), although there was a small increase in absolute values with sampling depth (Table 3). Accordingly, CI can be regarded as a good representative parameter for assessing the degree of soil compaction produced by harvester traffic, and no adjustments to the penetrometer data were therefore considered necessary.

In the analysis of impact of decomposition methods of rice straw on the CI (Fig. 5), data observed were similar at the beginning and at the end of the test. It should be mentioned that there were no changes in this variable over time. However, as in the analysis of spreaders, there were significant ( $p < 0.01$ ) differences in each decomposition method of rice straw between depths. In the first depth range (0–200 mm) there were strong differences in the data from the sampling points with maximum CI in the center of the harvester tracks and diminishing toward the sides, but always higher than the control plot, up to 0.15 m to the left and right of the center of the tread. Nevertheless, all the CI values measured in soil with abundant rice straw on the surface were lower than the ones measured where the BS decomposition method of rice straw was applied.

In all harvester/spreader setups and decomposition methods of rice straw the CI values at 0.6 m to the left and right of the center of the track did not differ from the control plot, indicating that the harvester passage impacted on the CI only in the width of the tread of the track (Fig. 5).

For the BS decomposition method of rice straw, the CI values at the center of the track were higher than 2.7 MPa between depths of 200 to 600 mm. The CI values indicate that over-compaction occurred in the subsoil; these values must overcome 2.0 MPa to avoid yield decreases, as suggested by Terminiello et al. (2000) and Botta et al. (2004, 2006, 2008, 2009). In this decomposition method of rice straw, CI values measured at 0.15, 0.30 and 0.60 m, left and right of the center of the track are lower toward the center of the track. For the BS decomposition method of rice straw, a higher CI percentage increase in the center of the track was observed in the 0 to 200 mm interval than in the others decomposition methods of rice straw (RC and SC). This may be due to lower organic matter in the first centimeters of the profile (Table 8) because of the lack of plant cover as a result of the practice of burning. Cover could reduce water loss by keeping the sun's rays and wind away from the soil surface.

Examination of the soil response to harvest traffic in deeper layers revealed that soil compaction, as indicated by CI, had increased in the depth range 200–600 mm for all harvester/spreader setups and decomposition methods of rice straw. It is more likely that this higher CI in the deeper horizons is due to the passage of heavyweight machinery during planting (tractors and machine planters are heavier than the harvester) causing densification in the subsurface strata, than to the qualities of the ground itself, coinciding with studies by Smith and Dickson (1992), Håkansson and Reeder (1994), Alakukku (1998) and Botta et al. (2007). In all harvester/spreader setups, starting from the 400 mm depth range, CI exceeded the 2.00 MPa limit indicated by Terminiello et al. (2000) and Botta et al. (2004, 2006, 2008, 2009) as harmful for root growth in most widespread crops. This coincides with studies done by several authors (Vomocil et al., 1958; Ayers and Perumpral, 1982; Draghi et al., 1989; Jorajuria et al., 1997).

Infiltration did not differ statistically ( $p < 0.01$ ) between harvester/spreader setups and decomposition methods of rice straw regarding control plot (Fig. 6), and was low and characteristic of planosol soils, which according to Ligier (2007), are weedy and susceptible to puddling, suitable for grazing, rice production, and in certain places, forestation. It is also likely, as suggested by Bonne et al. (1976), Pidgeon and Soane (1977), Gantzer and Blake (1978) and Lindstrom et al. (1984) that low infiltration in the surface horizon is because in soils under direct seeding, the volume of large or transmission pores is smaller in the surface horizons.

#### 3.2. Distribution, decomposition and nutrient contribution of rice straw

The harvester without spreader (T1WS), as was to be expected, left more material deposited in the center of the tail (21,680 kg/ha) and less toward the sides (Table 4). This trend is significant, recording nearly 750 and 900 kg/ha at 258 cm on the left and right, respectively. The high concentration of rice straw in the tail could be prejudicial to its

**Table 3**  
Soil water content (SWC) (w/w) measured for all harvester/spreader setups and decomposition methods of rice straw at the start and end of testing.

T1WS	Depth range (mm)	27-feb	27-sep	T2RS	27-feb	27-sep	T3MS	27-feb	27-sep
+ RC	0–200	21.3 a	20.0 a	+ RC	21.3 a	20.0 a	+ RC	21.3 a	19.0 a
	200–400	22.0 a	19.7 a		22.0 a	21.4 a		22.0 a	21.7 a
	400–600	22.6 a	21.0 a		22.6 a	21.5 a		22.6 a	22.0 a
+ SC	0–200	20.6 a	19.6 a	+ SC	20.6 a	19.6 a	+ SC	20.6 a	19.6 a
	200–400	21.4 a	19.5 a		21.4 a	20.5 a		21.4 a	21.5 a
	400–600	21.0 a	20.5 a		21.5 a	21.5 a		21.0 a	21.5 a
+ BS	0–200	18.2 a	18.0 a	+ BS	18.2 a	18.0 a	+ BS	18.2 a	18.0 a
	200–400	20.0 a	20.4 a		20.0 a	19.4 a		19.0 a	19.4 a
	400–600	21.3 a	21.0 a		20.3 a	20.0 a		20.3 a	20.0 a

SWC values with different letters (vertically) are significantly different at each depth ( $p < 0.01$  Duncan's multiple range test).

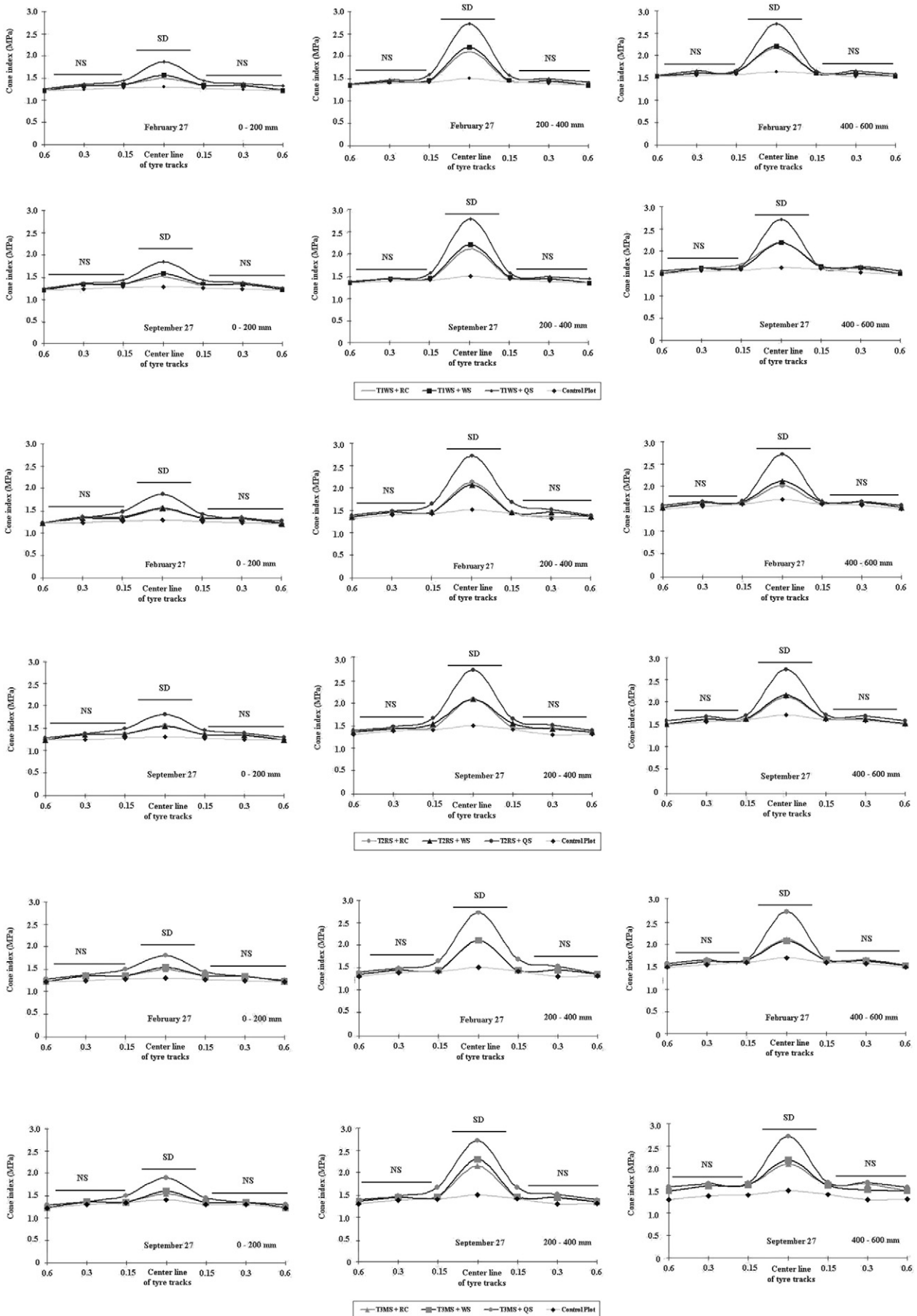


Fig. 5. Cone index (CI) (MPa) measured for all harvester/spreader setups and decomposition methods of rice straw at the start and end of testing.

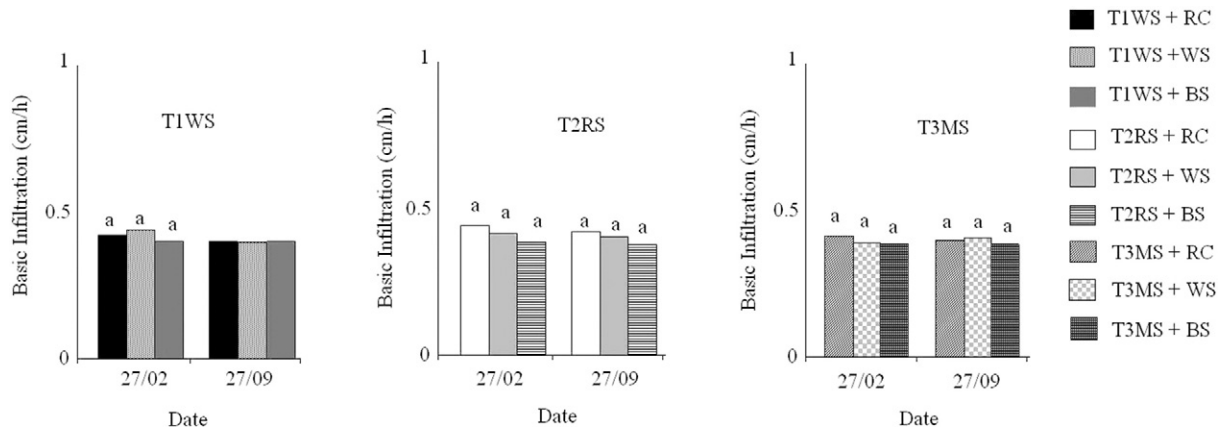


Fig. 6. Basic infiltration in the 0–200 mm depth range for all harvester/spreader setups and decomposition methods (mm/h).

decomposition, significantly affecting sowing and establishment of the following crop, which coincides with studies by Hidalgo et al. (2009).

The amount of crop residues concentrated at the harvester tail by the machine without spreading and chopping strongly reduced decomposition as a result of not distributing the crop residues, finding over 600–800 kg/ha of material over the working width after seven months, which would interfere with later sowing of rice and impact negatively on yields, and thus also profitability. The maximum of 7280 kg/ha was found in the center of the harvester tail, decreasing toward the sides, and recording 160 and 200 kg/ha at 258 cm on the left and the right of the center of the tail respectively.

Statistical differences were recorded for each sampling point and for dates, showing rice straw decomposition on the one hand and on the other deficient distribution over the machine's working width (Table 4).

The combination of T1WS plus the roller crimper (RC) produced more uniform distribution with fewer differences among sampling points and impacted positively on decomposition of rice straw (Table 4). However, at the end of the test near rice seeding for the following season,

amounts over 1000 kg/ha were recorded at 86 cm on the left and the right of the center of the tail respectively, which would cause problems for the establishment of the following crop. The maximum and minimum were 2920 and 1340 kg/ha, more than observed in this type of spreader without the use of RC, indicating that this implement does not increase rice straw decomposition, at least under the test conditions.

When T1WS was used with a stubble chopper (SC), strong differences were found between maximums of 7280 kg/ha for T1WS vs. 1230 kg/ha for T1WS + SC, and minimums 160 kg/ha for T1WS vs. 989 kg/ha for T1WS + SC. Compared to data for T1WS + RC differences in distribution are also observed, mainly because the rotational movement of the weeder cuts and spreads the material all over the ground, while the RC, as explained below, smashes the rice straw as it passes without depositing it more uniformly, and observing more material (2920 kg/ha) left in the center of the tail by the harvester without spreader (Table 4).

When the distribution of rice straw from the harvester with rubber spreader (T2RS) was evaluated, although the statistical analysis showed

Table 4

Statistical analysis of the degree of decomposition of rice straw over time and as scattered by T1WS (scaled up yields from 0.25 m<sup>2</sup> sampling area, kg/ha).

	Sampling date	Sampling sites														
		285 cm left		172 cm left		86 cm left		Harvest tail (center)		86 cm right		172 cm right		258 cm right		
+ BS	27/02	880	vF	1970	sE	14790	dB	21680	aA	13560	eC	1600	tD	747	vF	
	21/03	440	wD	1150	uC	11780	gB	20800	bA	11420	gB	1190	uC	400	wD	
	2404	320	wE	932	vD	10200	iC	17830	cA	11000	hB	452	wE	293	wE	
	28/05	360	wE	800	vD	8500	kC	14920	dA	8000	lB	880	vD	240	xE	
	26/06	240	xC	400	wC	6230	oB	12500	fA	6600	nB	364	wC	230	xC	
	22/07	280	wxC	280	wxC	4600	pB	10300	iA	4560	pB	240	xC	260	xC	
	25/08	240	wxC	240	wxC	3810	qB	9400	jA	3640	qB	280	wxC	230	wxC	
	27/09	160	xC	200	xC	3280	rB	7280	mA	3120	rB	200	xC	200	xC	
	+ RC	27/02	750	jE	1600	ijD	11000	cdB	16500	aA	10760	cdB	2100	hiC	720	jE
		21/03	520	kE	1200	ijD	10800	cdC	14600	bA	10200	cdeB	1420	iD	560	kE
2404		300	kE	876	jD	9400	defC	13100	bA	8760	efB	800	jkD	460	kE	
28/05		290	klD	900	jC	7800	fB	11400	cA	8100	fB	630	jkC	370	kCD	
26/06		210	lDE	600	ijD	5000	gC	10000	dA	6000	gB	420	kD	180	lE	
22/07		200	lD	200	lD	3000	hC	7200	fgA	2540	hiB	310	kD	160	lD	
25/08		150	lD	140	lD	2800	hiB	4100	ghA	2680	hiB	180	lD	130	lD	
27/09		100	lC	100	lC	1612	iB	2920	hA	1340	iB	130	lC	125	lC	
+ SC		27/02	14050	aCD	14250	aC	14970	aB	15420	aA	14100	aC	14430	aC	13950	aD
		21/03	10300	bB	10900	bA	10950	bA	10700	bA	10812	bA	10200	bB	10000	bB
	2404	7670	deA	7810	cdA	7800	cdA	8100	cA	7920	cdA	7000	cdeB	7000	cdeB	
	28/05	5810	dA	5970	cdA	6000	cdA	6000	cdA	5840	dA	5280	deB	5320	deB	
	26/06	4600	defAB	4000	efgC	4850	defA	4350	defgB	4720	defB	4470	defgB	4980	deA	
	22/07	3000	gB	3150	fgB	3000	gB	3780	efgA	3000	gB	3000	gB	3120	gB	
	25/08	2000	hBC	2200	hB	2410	hB	2000	hiB	2950	gA	2310	hB	1986	hiBC	
	27/09	1100	iA	1000	iA	1230	iA	989	iA	1120	iA	1000	iA	990	iA	

Means with different lowercase letters show significant differences between sampling date (vertically, within decomposition method) and capital letters show significant difference between sampling site (horizontally) ( $p < .01$ ).

**Table 5**  
Statistical analysis of the degree of decomposition of rice straw over time and as scattered by T2RS (scaled up yields from 0.25 m<sup>2</sup> sampling area, kg/ha).

	Date	Sampling sites													
		285 cm Left		172 cm Left		86 cm Left		Harvest tail (Center)		86 cm Right		172 cm Right		258 cm Right	
+ BS	27/02	880	vE	1970	sD	14790	dB	21680	aA	13560	eC	1600	tD	747	vE
	21/03	440	wD	1150	uC	11750	gB	20800	bA	11420	gB	1190	uC	400	WD
	2404	320	wE	932	vD	10200	iC	17830	cA	11000	hB	452	wE	293	wF
	28/05	360	wE	800	vD	8500	kC	14920	dA	8000	lB	880	vD	240	xE
	26/06	240	xD	400	wD	6230	oC	12500	fA	6600	nB	364	wD	230	xD
	22/07	280	wxC	280	wxC	4600	pB	10300	iA	4560	pB	240	xC	260	xC
	25/08	240	xC	240	xC	3810	qB	9400	jA	3640	qB	280	wxC	230	xC
	27/09	160	xC	200	xC	3280	rB	7280	mA	3120	rB	200	xC	200	xC
	+ RC	27/02	15000	aA	14000	aB	14710	aA	13520	bBC	15050	aA	12830	cC	13680
21/03		12000	dA	10430	efD	9120	hE	9800	fgF	11600	dB	10140	efg	11000	deC
2404		6650	kB	6410	klBC	7200	jA	7510	iA	6350	lBC	6000	mC	6300	lC
28/05		4120	oB	3760	pBC	3400	qC	3000	rD	4610	nA	3890	opB	4000	oB
26/06		2000	tC	2600	rsA	2960	rA	2000	tC	2310	sB	2710	rA	1960	tC
22/07		1250	uvB	1430	uA	1110	vB	1530	uA	1470	uA	1500	uA	1120	vB
25/08		960	vA	1120	vA	876	vwA	1000	vA	964	vA	1170	uvA	997	vA
27/09		500	wA	460	wA	610	wA	580	wA	400	wA	560	wA	600	wA
+ SC		27/02	15000	aA	14500	bB	14300	bBC	14000	cC	15100	aA	13980	cC	14970
	21/03	10480	eC	9760	qD	11300	dA	9000	qE	11470	dA	10000	fCD	9510	qD
	2404	7280	ijAB	6400	ikB	6000	klC	7300	ijA	7000	ijAB	6500	jkB	7460	iA
	28/05	3920	nC	4200	mnC	5100	lmA	4000	nC	4600	mnB	4730	mnB	4000	nC
	26/06	2360	pqC	3100	oA	3000	oA	2700	pAB	2300	qC	2840	opB	2560	pC
	22/07	1760	rsA	1450	sB	1600	rsAB	1720	rsA	1880	rA	1500	sB	1200	tC
	25/08	720	uA	980	tuA	1000	tuA	860	uA	720	uA	1000	tuA	700	uA
	27/09	440	vA	520	vA	588	uvA	480	vA	400	vA	360	vwA	520	vA

Means with different lowercase letters show significant differences between sampling date (vertically, within decomposition method) and capital letters show significant difference between sampling site (horizontally) ( $p < 0.01$ ).

significant differences over the working width, deposit was more uniform, and data found at seven months were lower than for other treatments (Table 5). However, in the last month of testing before the following seeding, over 600–800 kg/ha of crop residues was recorded over the working width of the harvester, considered limiting values for good establishment of the following crop. This table shows

the maximum taken on 27/09 as 1341 kg/ha and the minimum of 960 kg/ha.

In terms of overall decomposition, the passage of the RC over the rice straw distributed by the harvester with rubber spreader had a strong impact. Over the span of the working width at the end of the test and near seeding of rice for the following season, less than the 600–800 kg/ha

**Table 6**  
Statistical analysis of the degree of decomposition of rice straw over time and as scattered by T3MS (scaled up yields from 0.25 m<sup>2</sup> sampling area, kg/ha).

	Date	Sampling sites													
		285 cm left		172 cm left		86 cm left		Harvest tail (center)		86 cm right		172 cm right		258 cm right	
+ BS	27/02	15230	bB	16000	aA	14480	cC	15000	bB	12800	f	14600	cC	14300	dC
	21/03	13000	fC	14600	cA	11780	h	13400	eB	13000	fC	12400	gD	12980	fC
	2404	11100	iB	10960	iB	11000	iB	12300	gA	9460	lD	9870	kD	10540	iC
	28/05	9000	mA	7520	pC	8600	nAB	8950	mA	7210	pqC	8000	oB	6470	rD
	26/06	7000	qB	8000	oA	6800	qB	5960	rsC	6200	rsC	5420	sD	6700	qB
	22/07	4000	tuB	4120	tuB	5200	sA	5000	stA	5000	stA	3960	tuB	3820	tuB
	25/08	2000	vB	2000	vB	1750	vwB	2520	uvA	1460	wC	2000	vB	1120	xC
	27/09	1410	wB	1200	xC	2000	vwA	1000	xC	962	zC	1000	xC	1390	vB
	+ RC	27/02	16200	abA	15870	bcA	16100	abcA	14800	dB	16300	aA	15800	cA	14000
21/03		12800	gB	13120	fgB	14000	eA	12890	gB	13400	fB	13000	gB	11700	iC
2404		10200	jB	9970	jkB	12100	hA	9870	jkB	9600	kB	8750	lC	9870	jkB
28/05		8460	lA	8000	mB	7850	mBC	8000	mB	7000	nC	8460	lA	6000	opD
26/06		6210	oB	7200	nA	6000	opB	5800	pqB	5420	qC	6000	opB	5720	pqC
22/07		3200	sB	3000	sB	4200	rA	4000	rA	3850	rA	3000	sB	2870	sB
25/08		1980	tA	1000	uB	1900	tA	1900	tA	2100	tA	1860	tA	2000	tA
27/09		613	vA	620	vA	540	vA	560	vA	590	vA	580	vA	592	vA
+ SC		27/02	16660	aA	16000	cC	15980	cB	16420	B	15000	dD	16700	abA	16940
	21/03	13000	fgB	14120	eA	13210	fgB	13500	fB	12780	gBC	14200	eA	14000	eA
	2404	9820	jB	10100	iB	9780	jB	10420	hA	9000	kC	8620	lD	9120	kC
	28/05	7200	noA	7560	mA	7000	noAB	6890	oB	5990	qD	6420	pC	7310	mnA
	26/06	5210	sAB	5420	rA	5000	sB	5600	rA	5600	rA	4870	tB	4200	tC
	22/07	2880	vB	2500	wC	3100	vB	3560	uA	2760BC	vw	2900	vB	2989	vB
	25/08	1300	yA	1200	yA	1207	yA	1120	yA	1150	yA	1260	yA	1000	yA
	27/09	587	zA	600	zA	563	zA	489	zA	592	zA	498	zA	563	zA

Means with different lowercase letters show significant differences between sampling date (vertically, within decomposition method) and capital letters show significant difference between sampling site (horizontally) ( $p < 0.01$ ).

**Table 7**  
Effect of burning rice straw on dry matter residues for all harvester/spreader setups. Analysis of values from the last sampling date (kg/ha).

	Date	Sampling sites						
		258 cm left	172 cm left	86 cm left	Center	86 cm right	172 cm right	86 cm right
T1WS	27/09	12 abcd	8 ef	10 bcdef	10 bcdef	12 abcd	11 abcd	9 def
T2RS	27/09	10 bcdef	9 def	8.2 ef	10 bcdef	12 abcd	11abcd	8ef
T3MS	27/09	6.8 ef	7.5 ef	8.4 ef	12 abcd	6.8 f	10 bcdef	7.8 ef

Different letters between columns and files indicate a significant difference ( $p < 0.01$ ).

considered critical for establishment by Hidalgo et al. (2009) remained. In the last month of sampling there were 1341 kg/ha for T2RS and 610 kg/ha for T2RS + RC (731 kg/ha less), and a difference of 560 kg/ha between the minimums of 960 for T2RS and 400 kg/ha T2RS + RC.

These results show that the T2RS + RC treatment should be kept in mind for adequate decomposition of rice straw, and at the time of the following seeding, the volume of material on the soil is not the cause of inefficient establishment (Table 6). Finally, the statistical analysis showed differences among dates, when decomposition of rice straw was also different at different sampling points, but decreasing over time, to minimums on 22/07 and 25/08, and no differences on the last date (27/09).

As may be seen in Table 5 when the stubble chopper was passed over the rice straw distributed by the harvester with rubber spreader T2RS + SC, there was an increase in decomposition, possibly due to better distribution of the material, corroborated by statistical analysis, which did not show significant differences ( $p < 0.01$ ) among sampling points on the last sampling dates 25/08 and 27/09.

On the last date, amounts of rice straw found for T2RS + SC were under the critical values for seeding and crop establishment similar to the T2RS + RC but relatively lower, with a minimal difference between maximums and minimums of 610 kg/ha for T2RS + RC vs. 588 kg/ha for T2RS + SC and a difference of 40 kg/ha between the minimums of 400 for T2RS + SC and 360 kg/ha T2RS + RC. These results suggest that the use of RC or SC on rice straw distributed by a harvester with rubber spreader is a valid method for increasing decomposition of rice straw, achieving after seven months amounts below those considered critical for seeding and development of rice in the following season.

Distribution by the harvester with the metal spreader (T3MS) (Table 6) was similar to a certain extent to the treatment described above, but achieving a less uniform deposit than that one, which could cause partial decomposition of the rice straw, mainly in those sectors with the most material, impacting negatively on establishment of the following crop. Just as in the T2RS, after seven months and before seeding with rice, values observed over the entire working width of the harvester were higher than those considered critical for good seeding and establishment of the following crop (600–800 kg/ha). The

maximum recorded was 2000 kg/ha, while the minimum observed was 962 kg/ha.

When the RC was used on rice straw distributed by harvester T3MS + RC (Table 6) the result was similar to T2RS + RC, impacting noticeably on decomposition. Much less material remained on the ground at the last sampling date (27/09) by harvester T3MS + RC than by T3MS. The difference in maximums and minimums was 1410 vs. 820 kg/ha and 620 vs. 540 kg/ha for T3MS and T3MS + RC, respectively. Over the working width of the machine, values recorded were below those considered critical for seeding and establishment of rice in the following season.

The results of T3MS + SC show that decomposition increased, similar to what happened in the other harvester/spreader setups, and in the statistical analysis, significant differences between sampling dates support decomposition of harvest residue. In the last month of testing, values were below those considered critical for seeding and development of rice in the following season, which is very different from the decomposition of material distributed by T3MS where values detected could negative impair establishment of the following crop.

### 3.3. Burning residue

After burning rice straw there were no differences between values on the different sampling dates, and so it was decided to analyze the amounts determined at the end of the test and near seeding the following season (Table 7). This management alternative left an extremely small amount of material that would not affect establishment of the following crop, but the effect of fire on the ground and contribution of nutrients to it would be affected.

When the results were analyzed, statistically significant differences were found in pH, varying from 4.61 to 6.20, coinciding with assessments by Escobar et al. (1996), who found acid pH in the type of soil where the tests were done. The statistical analysis did not record significant differences ( $p < 0.01$ ) between treatments with respect to increase in nutrients, except for potassium in one case and sodium in two. Considering that potassium is one of the nutrients with the most presence in rice residue, the fact that there was no significant difference ( $p < 0.01$ ) either between treatments or sampling dates indicates

**Table 8**  
Analysis of nutrients contribution to soil by decomposition of rice straw for all treatments.

	Date	Depth range (mm)	pH	OM (%)	OC (%)	TN (%)	P ppm	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>
								(m.e. 100 g <sup>-1</sup> )			
T1WS	27/02	0–250	5.9 c	4.4 b	2.5 b	0.21 b	10.7 b	1.6 b	21 b	5.3 b	2.2 b
	22/06	0–250	6.2 c	4.3 b	2.5 b	0.29 b	11.4 b	1.5 b	21 b	5.4 b	2.4 b
	27/09	0–250	6.0 c	4.0 b	2.3 b	0.28 b	11.3 b	1.6 b	21 b	5.5 b	2.5 b
T2RS	27/02	0–250	5.1 b	5.1 c	2.9 c	0.30 b	10.4 b	1.4 b	21 b	4.9 b	2.5 b
	22/06	0–250	5.0 b	5.0 c	2.9 c	0.30 b	11.5 b	1.5 b	21 b	5.0 b	2.5 b
	27/09	0–250	4.9 b	5.1 c	2.9 c	0.30 b	11.6 b	1.6 b	21 b	5.3 b	2.5 b
T3MS	27/02	0–250	5.9 c	4.3 b	2.3 b	0.28 b	10.6 b	1.6 b	21 b	5.6 b	2.6 b
	22/06	0–250	5.8 c	3.9 b	2.2 b	0.20 b	11.4 b	1.6 b	21 b	4.9 b	2.4 b
	27/09	0–250	5.7 c	4.0 b	2.3 b	0.28 b	11.3 b	1.5 b	21 b	5.2 b	2.4 b
Burning	27/02	0–250	4.1 a	2.1 a	1.2 a	0.21 a	9.7 a	0.4 a	17 a	4.1 a	1.8 a
	22/06	0–250	4.2 a	2.4 a	1.3 a	0.22 a	9.8 a	0.4 a	17 a	4.1 a	1.8 a
	27/09	0–250	4.2 a	2.7 a	1.4 a	0.25 a	9.8 a	0.3 a	17 a	41 a	1.8 a

Different letters (vertically) indicate a significant difference at ( $p < 0.01$ ).

Key table: organic matter (OM), organic carbon (OC), total nitrogen (TN), phosphorus (P), potassium (K), magnesium (Mg), sodium (Na).

absence of any contribution of this element from decomposition of rice straw during the test period (Table 8). The same table shows that the alternative of burning rice straw impacted, as was expected, negatively on any possible contribution of nutrients, and there were no significant differences recorded between sampling dates in any of the nutrients evaluated.

Finally, it was demonstrated that some spreaders distributed the rice straw better than others, and the constitution and type of spreader used had a strong impact on distribution and decomposition of it, and the presence of cover attenuated compaction caused by harvester traffic. Hence, the data support both hypotheses.

#### 4. Conclusions

Within the limits of our experimental conditions, we can arrive at the following conclusions:

1. Based on CI values obtained in this study, which are higher than 2.5 MPa between 200 and 600 mm depth range, we can say that rice yield of the next growing season will be affected.
2. The highest values of CI (>1.8 MPa) at topsoil (0 to 200 mm depth range) were observed for BS decomposition methods of rice straw. The opposite was observed in the other two decomposition methods of rice straw (SC and RC), where plant cover, SWC and organic matter, attenuated the impact of heavyweight harvester traffic.
3. The lowest values of CI (<1.52 MPa at the center of the track) at topsoil (0 to 200 mm depth range) were observed for the use of roller crimper (RC) as decomposition method of rice straw. In addition, lower values than 1.52 MPa were observed at 0.60 m, left and right, of the center of the track. However, when planosol soil was trafficked with loads of 152.5 kN, the CI increased (>2.5 MPa) in the subsoil (between 200 and 600 mm depth range) in all decomposition methods.

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