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https://doi.org/10.5109/2339106

出版情報：九州大学大学院農学研究院紀要. 64 (2), pp.213-218, 2019-09-02. Faculty of Agriculture, Kyushu University
バージョン：
権利関係：

J. Fac. Agr., Kyushu Univ., **64** (2), 213–218 (2019)

Effects of Straw Incorporation Time on Rice Yield and Methane Emissions from Sandy Loam Paddy Fields

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(*Received May 8, 2019 and accepted May 8, 2019*)

Rice paddy fields are a significant source of anthropogenic methane emitted into the atmosphere with several studies reporting heightened emissions after rice straw incorporation into the paddy soils. These emissions may differ owing to the time of straw incorporation into the field, i.e. either during the fallow or growing seasons. In the current study, we evaluated the emissions from straw incorporated during both the rice growing and fallow seasons over a three–year period. Additionally, effects on soil chemical properties and rice yields were assessed. The treatments involved incorporating straw a few days before the main rice growing season (spring straw), incorporation of straw during the fallow season, i.e. immediately after the autumn harvest (autumn straw) and the control with no straw incorporated at all. The weekly emissions from both spring and autumn straw applications decreased with the progression of the experiment, i.e. the emissions went on reducing season after season until the end of the experiment. The emissions from the control remained mostly constant throughout the experiment. Of the two straw application times, autumn application resulted in the lowest methane emissions. The effects of all the treatments on soil chemical properties were mostly adverse while the total rice yields slightly increased over time in the straw amended soils. The adverse effects on soil chemical properties might have been caused by the incomplete decomposition of rice straw given that a single rice growing season may not be enough for its complete dissolution.

Key words: Autumn straw incorporation, Methane emissions, Sandy loam soil, Spring straw incorporation

INTRODUCTION

Rice paddies are a crucial source of atmospheric methane (Liou *et al*., 2003; Jacobson 2005) contributing approximately 20–40 Tg of CH_4 year^{-1} which accounts for about 20% of the anthropogenic CH4 emitted globally (Tariq *et al*., 2017). The rapidly increasing global population requires similar increases in rice production which is one of the three important kinds of cereal that account for more than 50% of the global food calories, the others being maize and wheat (Fischer *et al*., 2009; Calabi–Floody *et al*., 2017). This increased rice production will automatically heighten the methane emission problem especially if the existing farming practices continue. (Neue *et al*., 1996; Liou *et al*., 2003).

Management of straw after rice harvests poses an enormous challenge to all rice farmers around the globe (Tariq *et al*., 2017). In many countries, farmers burn these crop residues openly in the rice fields (Gadde *et al*., 2009) as the quickest and inexpensive way of disposing of them and preparing for the next crop growing season (NDEP, 2003; Gadde *et al*., 2009; Webb *et al*., 2009). However, open burning of crop residues is associated with a miscellany of environmental issues for example emissions of heavy metals and dioxins (Webb *et al*., 2009), large quantities of CO, CO_2, particulate matter and volatile hydrocarbons into the air (EIA, 2008). That is in addition to the loss of valuable crop nutrients in gaseous forms (Haider, 2013). Due to these environmental effects, rice straw burning is currently outlawed in many countries.

Incorporating rice straw into the soil is, therefore, becoming a common agronomic practice among rice farmers although several studies for example by Kim e*et al*. (2018a), Wang *et al*. (2015) and others have reported methane emission increases from paddy fields due to this style of straw management. The current study thus aimed to quantify methane emissions resulting from rice straw incorporated into the sandy loam paddy soil in different seasons of the year, i.e. autumn and spring and to assess how these incorporation time variations affect both the rice yield and soil chemical properties.

MATERIALS AND METHODS

Field Experimental Set–Up

The experiments were conducted for three years (2016–2018) in the paddy fields of Noeun–dong (36°22’ 23.7”N, 127°19’39.5”E), Yuseong–Gu, Daejeon, South Korea. The straw was incorporated into the soil at different times of the year, i.e. autumn (immediately after

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harvesting) and spring (straw left on the soil surface during the winter season and incorporated in the soil in the spring season). The straw was incorporated at a rate of 8 Mg ha^{-1}. The chemical fertiliser of NPK was added uniformly to all plots at rates of 90, 45 and 57 kg ha^{-1} respectively. The control was made of plots that only received chemical fertilisation, i.e. with no straw added. The variety of rice cultivated was the medium to late maturing Sindong–jinbyeo. Twenty–one days (old) seedling were transplanted into the flooded paddies with harvesting coming 132 days later. The paddies were only flooded during the rice growing season after which they were drained to dry. It's important to note that the Korean rice growing season usually starts in late May or early June and ends in October.

Gas Sampling and Analysis

Methane gas emitted during the rice growing seasons was estimated by a closed–chamber method (Rolston, 1986; Ali *et al.*, 2009). The chambers were made from acrylic glass with a base of 60 cm × 60 cm and a height of 120 cm for each of them. Methane was sampled once every week throughout the rice–growing season; however additional samplings were done owing to the prevailing weather conditions. The gas samples were collected in 60 ml polypropylene syringes 30 min after closing the chamber between 11:00 am and 12:00 pm as stipulated by Pramanik and Kim (2013). Methane concentrations in the collected gas samples were measured by gas chromatography using an Agilent 6890N system equipped with fused silica capillary column (30 m × 0.53 mm) and a flame ionisation detector (FID). The oven and detector temperatures were adjusted to 100°C and 250°C, respectively. Hydrogen (H_2) and nitrogen (N_2) were used as the burning and carrier gases, respectively. Emission rates from the sandy loam soils were calculated basing on the increase in methane concentration per unit surface area of the chamber within a specific time interval. A closed–chamber equation described by Rolston (1986) was applied for the methane flux estimations as follows.

$$F = \rho \times \left({}^{b}\!/_{a} \right) \times \left({}^{\Delta c}\!/_{\Delta t} \right) \times \left({}^{273}\!/_{T} \right)$$

Where F represents the CH_4 flux (mg m^{-2} h^{-1}), ρ is the gas density which stands at 0.714 mg cm^{-3}, b is the chamber's volume (m^3), a is the chamber's surface area (m^2), $\Delta c/\Delta t$ is the rate of increase of CH_4 concentration in the chamber (mg m^{-3} h^{-1}), and T is the absolute temperature. T is the Kelvin temperature obtained by adding the mean temperature (°C) of the chamber to 273. The total CH_4 flux for each of the full growing season was computed from the equation proposed by Singh *et al.* (1999) as indicated below;

$$TF = \sum_{i}^{n} (F_i \times D_i)$$

TF stands for Total methane gas flux; F_i is the CH_4 emission flux (gm^{-2} d^{-1}) in the i^{th} sampling interval, D_i represents the number of days in the i^{th} sampling interval, while n represents the number of sampling intervals.

Soil Analysis

The soil was sampled using a zigzag pattern, with the soil cores picked up to a depth of 15 cm. Air–dried samples were sieved through a 2 mm strainer and then analysed following the Soil and Plant Analysis Methods (NIAST, 2000) established by the Rural Development Agency of Korea (RDA). Soil pH and electrical conductivity (EC) were determined with a pH and EC meter (ORION Versa Star Pro, Thermo Scientific Inc., USA) after extraction with distilled water in a ratio of 1:5 (v/w), available phosphorus was measured by the Lancaster method using a UV–VIS spectrophotometer (Evolution 300, Thermo Scientific Inc., USA). Exchangeable cations of K^+, Ca^{2+} and Mg^{2+} were analysed using inductively coupled plasma optical emission spectrometry (ICP–OES; GBC Scientific, Australia) after leaching with 1N NH_4OA_C solution at a neutral pH (pH 7.0) The total organic carbon (TC) was analyzed using an elemental analyzer–TCD (Flash EA 1112 series, CE Instruments, Italy). The soil chemical properties before the experiment are shown in table 1 below.

RESULTS

Methane Emissions

The general trend was the decreasing weekly methane emissions season after season except for the control whose weekly emissions remained almost constant throughout the experimental period. That is evidenced in the highest peak emissions (from spring straw incorporation) that stood at 1700 mg m^{-2} hr^{-1} in the first season which decreased to 1500 mg m^{-2} hr^{-1} in the second season with the final season registering the lowest peak value of just below 1000 mg m^{-2} hr^{-1}. Incorporating rice straw into the soil in spring culminated into the highest weekly emissions in all the seasons that this experiment

Table 1. Initial soil chemical properties

Treatment	pH (1: 5)	EC (ds m^{-1})	TC (g kg^{-1})	Avail P (mg kg^{-1})	Ex. cation		
					K^+	Ca^{2+}	Mg^{2+}
Control Expt	5.62±0.01	0.30±0.01	7.07±0.3	134.21±9.90	0.57±0.08	1.70±0.21	0.63±0.10
Spring Straw	5.84±0.00	0.31±0.04	8.66±0.5	122.45±11.2	0.51±0.06	1.62±0.17	0.69±0.14
Autumn Straw	5.80±0.03	0.33±0.01	8.15±0.3	143.68±14.3	0.58±0.11	1.81±0.14	0.67±0.08

EC: Electrical conductivity, Avail. P: Available Phosphorus, TC: Carbon, Ex. Cation: Exchangeable cation was conducted.

On the contrary, however, weekly methane emissions from the plots whose straw was incorporated immediately after the autumn harvest were low and lower than those from the control plots in the final season of the experiment. Apart from the first season when the weekly emissions from the Autumn straw treatment exceeded those from the control, emissions from the autumn treatment in the second season were at par with those from the control plots while in the final season the control plots emitted more methane than the autumn straw plots did. Generally, the weekly emissions were high between the 2nd and 17th weeks in the first season, 3rd and 15th weeks in the second season and, 2nd and 15th weeks in the last season as shown in figures 1, 2 and 3 below.

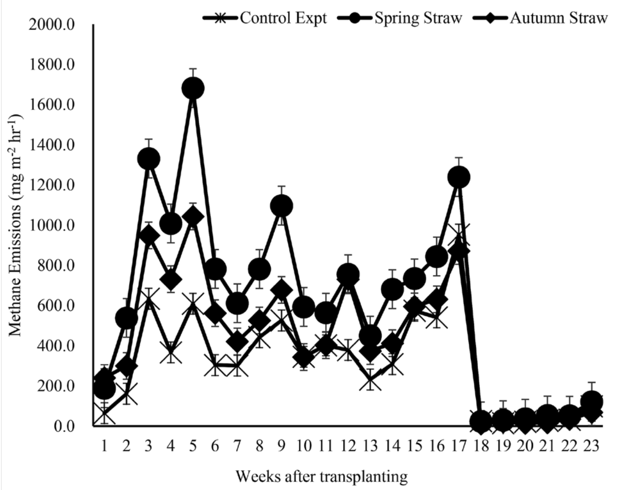

Fig. 1. Weekly emissions in the first season (2016).

Soil Chemical Properties and Rice Yield

All the assessed soil chemical properties decreased except total organic carbon of the autumn straw treated soils (see table 2 below). The weight of a 1000 grains harvested from both the control and spring straw treated soils plunged season after season while those from the autumn straw treated soils increased slightly. All treatments registered modest improvements in grain filling rates as the experiment progressed while the vegetative yield as measured by the rice straw output decreased. The total grain yield from the control plots decreased from season to season until the end of the experiment. Conversely, the yield from the plots with straw incorporations gradually increased season after season until the final season (see tables 3, 4 and 5 below)

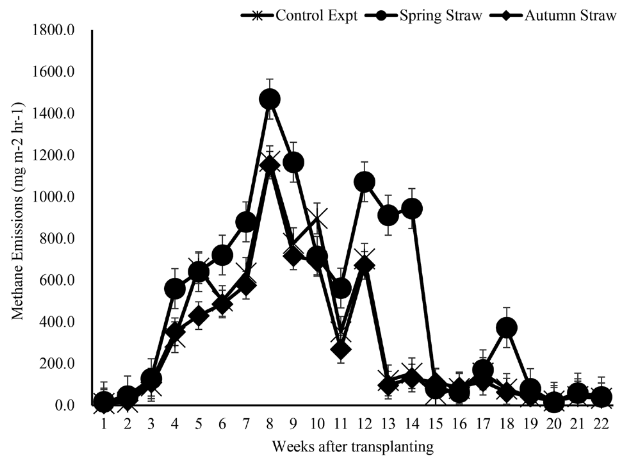

Fig. 2. Weekly emissions in the second season (2017).

DISCUSSION

Methane Emissions

A lot of former studies have reported increased CH_4 emissions on the addition of rice straw into the soil. For example, Naser *et al.*, 2007 reported a direct correlation between the quantity of straw incorporated and methane emissions. Similar observations have also been made by Schütz *et al.* (1989), Sass *et al.* (1990), Yagi and Minami (1990) and Kongchum *et al.* (2006). The emissions obtained in the first season of this study concurred with those observations in a way that even though the quantity of rice straw incorporated into the soils were the same, plots with incorporated straw emitted much more methane than the control. In the second and third season of our study, it is only the plots whose straw was added in spring that emitted more methane than the control. This observation suggests that methane emissions from rice straw incorporation may be comparable to those of the control during the rice cultivation season depending on when they are incorporated into the soil.

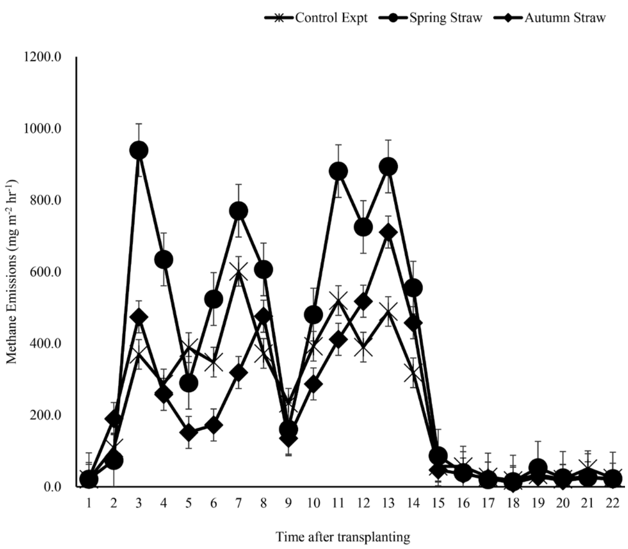

Fig. 3. Weekly emissions in the third season (2018).

The lower methane emissions from the autumn straw application were in line with what Wang *et al.* (2015) reported that incorporating rice straw early lowered the amount of methane emitted during the rice growing season. They attributed this to the partial oxidation of the straw during the fallow which reduces the

Table 2. Chemical soil properties at the end of the experiment

Treatment	pH (1: 5)	EC (ds m^{-1})	TC (g kg^{-1})	Avail P (mg kg^{-1})	Ex. cation K^{+}	Ca^{2+}	Mg^{2+}
Control Expt	5.4±0.01	0.18±0.06	7.71±0.99	108.2±12.25	0.12±0.04	2.58±0.34	0.37±0.07
Spring Straw	5.3±0.01	0.16±0.07	6.55±1.12	76.9±8.79	0.11±0.06	2.70±0.48	0.31±0.04
Autumn Straw	5.5±0.01	0.2±0.06	10.56±1.71	136.4±19.4	0.11±0.03	2.77±0.39	0.36±0.01

Table 3. Rice yield in the first season (2016)

Treatment	1000 grain weight (g)	Grain Filling rate (%)	Weight of rice straw (Tonne per ha)	Total Grain Yield
Control Expt	33.93±0.38[a]	94.98±0.83[b]	8.51±0.70[a]	6.06±0.57[ab]
Spring Straw	34.14±1.55[a]	94.56±1.25[b]	9.60±0.62[b]	5.57±0.72[a]
Autumn Straw	34.32±0.80[a]	89.68±2.14[a]	9.71±0.80[b]	5.81±0.61[a]

Table 4. Rice yield in the second season (2017)

Treatment	1000 grain weight (g)	Grain Filling rate (%)	Weight of rice straw (Tonne per ha)	Total Grain Yield
Control Expt	32.34±0.36[a]	97.20±0.66[ab]	8.17±0.36[a]	5.72±0.70[a]
Spring Straw	32.25±0.81[a]	96.73±0.59[a]	8.63±0.58[a]	6.01±1.15[ab]
Autumn Straw	34.51±0.73[b]	96.47±0.82[a]	8.24±0.51[a]	5.99±0.91[ab]

Table 5. Rice yield in the third season (2018)

Treatment	1000 grain weight (g)	Grain Filling rate (%)	Weight of rice straw (Tonne per ha)	Total Grain Yield
Control Expt	32.21±0.41[b]	96.00±0.81[ab]	8.22±0.68[a]	5.89±0.94[a]
Spring Straw	30.54±0.47[a]	95.20±1.13[a]	8.23±0.70[a]	6.01±1.13[ab]
Autumn Straw	35.56±0.64[c]	97.10±0.78[ab]	8.74±0.75[a]	6.23±0.99[b]

concentration of oxidisable organic materials in the main growing season. This stance was later reiterated by Tang *et al.* (2016) who reported that rice straw decomposition during the fallow season resulted in a decrease in CH_4 emission during the subsequent rice growing season. The decreasing pattern of emission rates observed with progression of the experiment contradicted observations made by several studies including for example by Liou *et al.* (2003) and Wang *et al.* (2015) who reported an increasing pattern of methane emissions as the experiments progressed. They argued that this was due to the accumulation of organic materials in the soil due to repeated straw applications. The emissions remained high during the rice growing season because there were no conducive conditions for methanogenesis both before transplanting and after harvesting since the paddy fields were not flooded as explained by Kim *et al.* (2018b).

Soil Chemical Properties and Rice Yield

Many studies for example by Roldán *et al.* (2003) and Dolan *et al.* (2006) have proved that applying crop residues to the soil greatly affects its physical and chemical properties with concomitant improvements in soil organic matter contents and nutrients (Smith *et al.*, 1992) thus improved crop productivity. Wei *et al.* (2015) indicated that the incorporation of crop residues into the soil and its subsequent decomposition replenishes the soil organic matter content and also helps in the supply of essential nutrients after mineralisation. A 10–year study by Power *et al.* (1998) who assessed the effects of various crop residues on selected soil properties showed that the enhanced soil available nitrogen and phosphorus were directly correlated with the quantity of straw incorporated. That was later confirmed by Liu *et al.* (2010) who showed that long–term straw and chemical fertilisers application could increase available phosphorus and potassium concentrations in the upper soil layers in comparison with soils without straw.

The results of our current study, however, negates all the studies mentioned above because the straw incorporation mainly produced undesirable soil chemical properties. But Liu *et al.* (2017) stressed that straw incorporation could have both negative and positive effects on soil properties and crop yields depending on the incorporation method, the incorporation time, the characteristics of the straw, and the amount of fertiliser applied. For example, Dong *et al*. (2012) found no obvious differences in the concentrations of nitrogen and phosphorus between straw incorporation and chemical fertiliser (NPK) treatments throughout the entire experimental period in the ploughed layer of a paddy soil, possibly because the levels of N and P in the residues were small compared with the total levels in the soil. Studies by Karami *et al*. (2012) and Wei *et al*. (2015) found that enormous benefits were accruing from straw applications in the soil with positive effects on both the soil quality and crop yield. In our current study, however, rice straw application mainly evoked negative effects on almost all the soil properties studied but unexpectedly higher rice yields. The higher yields might have been a result of the chemical fertiliser (NPK) applied together with the straw.

CONCLUSIONS AND RECOMMENDATIONS

The observed negative impact of rice straw incorporation on soil chemical properties might have been due to the incomplete decomposition of the straw because rice straw has high C: N ratios and thus more time is required for its complete decomposition. These high C: N ratios also increase the likelihood of nitrogen immobilisation and recalcitrance of carbon contained in them (Luyima *et al*., 2019). Higher rice yields observed with rice straw incorporations might have resulted from the applications of NPK. With regards to methane emissions control, incorporating straw immediately after rice harvest (fallow season incorporation) results in the least emissions and is thus recommended for the sustainable management of rice straw. We recommend that long term experiments (10 years and above) be conducted to properly discern the extent by which straw incorporation affect soil fertility and methane emissions over a long time scale.

AUTHOR CONTRIBUTIONS

D. Luyima and H. C. Jeong wrote the paper and designed the study. S. H. Kim and J. H. LEE analyzed the data. Y. SHINOGI commented on the manuscript. T. K. OH and C. H. Lee supervised the work. All authors assisted in editing the manuscript and approved the final version.

ACKNOWLEDGEMENTS

This work was carried out with the support of the "Cooperative Research Program for Agriculture Science & Technology Development (Project No. PJ01185505)," Rural Development Administration, Republic of Korea.

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