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Methane Emissions from Sandy Clay Loam Paddy Soils Under Different Rice Straw Management Strategies

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Incorporating rice straw into the soil is increasingly being practised by rice farmers not only in Korea but the world over. It is partly because of the need to boost organic matter stocks of the soils, but it is also in response to the current environmental regulations which strongly decree against the use of thermal treatment to dispose of rice straw. Although this method has come in handy to solve the rice straw waste problem, studies indicate that it also increases levels of methane emissions from the paddy fields. In the current study, we quantified methane emissions from sandy clay loam soils in which the straw was incorporated at different intervals after the rice harvest. There is currently hardly any data concerning methane emissions from this type of soil texture yet soil texture is one of the main factors influencing methane emissions. There were four treatments which included; spreading and ploughing straw into the soil immediately after the autumn harvest (ASS+AP), spreading straw on to the soil after the autumn harvest but ploughing it into the soil in spring (ASS+SP), spreading and ploughing the straw into the soil in the spring season (SSS+SP) and the control with no straw incorporated. All plots were fertilised with equal amounts of NPK. The control plots emitted the lowest amount of methane followed by ASS+AP. Additionally, emissions from ASS+AP and ASS+SP plots decreased in the second year while those from other treatments remained largely unchanged. ASS+AP straw management strategy boosted the soil chemical properties while the effects of other treatments were mostly dreadful. Therefore, ASS+AP can be considered the best management strategy due to lower methane emissions and better soil chemical properties obtained.

Key words: methane emissions, paddy soils, rice straw management, sandy clay loam

INTRODUCTION

Soil degradation is currently affecting between about 10% – 17% of the global land area (Daily, 1995; Sutton *et al.*, 2016). The slew of ecological and agricultural losses ensuing from this degradation underpin the urgency of finding appropriate solutions to curtail it (Han *et al.*, 2018). Soil degradation has mainly manifested itself in the form of depleted soil organic carbon (SOC) and the concomitant reduction in net primary productivity of global crop production systems (Han *et al.*, 2018). Sand textured soils with inherently low organic matter content, relatively weak aggregate structures and poor water retention capacities (Petersen *et al.*, 1968; Christensen, 1986) are the worst hit by this degradation tragedy (Calabi–Floody *et al.*, 2017).

Agricultural production has heavily depended on supply of mineral fertilisers for the last 50 years or so (Kidd *et al.*, 2017) and although crop productivity was amplified during the green revolution, yields have since plateaued to the extent that increasing fertiliser application rates no longer produce considerable yield increments (Jones *et al.*, 2013; Luyima *et al.*, 2019). There is a consensus in the scientific world that building SOC stocks can aid jump–start crop yields (Palm *et al.*, 2001; Liu *et al.*, 2010). To this effect, straw incorporation into the soil has been shown to not only increase SOC but also improve soil properties such as stability of soil aggregates (Christensen, 1986; Zhang *et al.*, 2016), levels of soil enzyme activities (Zhang *et al.*, 2016), among others.

Straw incorporation into paddy soils has become a prominent agronomic practice among rice farmers, chiefly being practised for recycling nutrients but also in response to strict laws against straw burning (Liou *et al.*, 2003; Wang *et al.*, 2016). However, the presence of this organic carbon–rich material under anaerobic soil conditions invigorates the production and emission of methane (CH_4) from the paddy fields (Sass *et al.*, 1991; Conrad, 2007). Methane with a global warming potential (GWP) 28 times higher than that of carbon dioxide (CO_2) over a time scale of 100 years (IPCC, 2013) accounts for the largest chunk of CO_2 equivalent emissions from flooded rice paddies (Sass *et al.*, 1994; Wang *et al.*, 2016; Jiang *et al.*, 2019). Our current study aimed to quantify the amount of methane emitted from sandy clay loam textured soils under different rice straw incorporation strategies. This is because soil texture is one of the factors influencing methane emissions from the soil (Sass *et al.*, 1994; Kim *et al.*, 2018b) but there isn't suffi-

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cient data currently entailing the emissions from different soil textures.

MATERIALS AND METHODS

Field Experimental Set–Up

The experiments were run for two consecutive years (from 2017 to 2018) from the paddy fields of Juk–dong (36° 22' 20.4" N, 127° 19' 52.0" E) Yuseong–Gu, Daejeon, South Korea. Rice straw was applied in each of the plots at a rate of 8 Mg ha^{-1} and three different incorporation strategies were employed. One of them involved spreading the straw onto the field and ploughing it into the soil immediately after harvesting rice. The rice growing season usually starts in late May or early June and ends in October which implies that for the treatment mentioned above, rice straw was spread and immediately incorporated into the soil in October of every year. The second strategy involved spreading the straw in October (immediately after harvesting rice) and leaving it on the soil surface until spring, i.e. around March of the following year when it could be ploughed into the soil. The third and last strategy involved harvesting both rice and straw from the field in autumn, keeping the straw in a farm store during the winter season. The straw was then brought back to the field for spreading and ploughing into the soil in spring. Mineral fertilisers (N–P–K) were applied uniformly to all plots at rates of 90, 45 and 57 kg ha^{-1} respectively with the plots that didn't receive any rice straw incorporations constituting the control experiments. The 21 days old medium to late maturing Sindong–Jinbyeo rice variety seedlings 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.

Gas Sampling and Analysis

A closed–chamber method (Rolston, 1986; Ali *et al.*, 2009) was used for the estimation of methane gas emissions from the soil during the rice growing seasons. Chambers were made from acrylic glass with a base area of 3600 cm^2 (60 cm × 60 cm) and 120 cm height for each of them. Methane was sampled once every week throughout the rice–growing season; however additional sampling was 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. Methane emission rates from the sandy clay 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.

$$F = \rho \times \left({}^{V}\!/_{A} \right) \times \left({}^{\Delta C}\!/_{\Delta T} \right) \times \left({}^{273}\!/_{T} \right)$$

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}, V 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 was 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;

$$TCF = \sum_{i}^{r} (R_i \times D_i)$$

TCF stands for Total methane gas flux, R_i is the CH_4 emission flux (gm^{-2} d^{-1}) in the ith sampling interval, D_i represents the number of days in the ith sampling interval, while r represents the number of sampling intervals.

Collection and Analysis of Soil Samples

Soil samples were collected from the topmost layer up to a depth of 15 cm using a zigzag pattern. Air dried samples were homogenised by sifting through a 2 mm sieve and then analysed following the Soil and Plant Analysis Methods of the RDA (NIAST, 2000). 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 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 with 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).

RESULTS

Methane Emissions

The weekly methane emissions were lowest for the control (plots without any rice straw incorporations) throughout the entire experimental duration of two years. The levels of weekly methane emissions from plots with rice straw incorporations increased exponentially in the second year of the experiment as indicated in figures 1 and 2. The increments were higher for the plots on which straw was spread and ploughed into the soil immediately after the autumn harvest (ASS + AP). The weekly emissions for all the treatments started rising from the third week of each growing season and were maintained at higher levels until the 14th to the 15th week when the emissions started declining rapidly. The weekly emissions were therefore very low in the first

Table 1. Initial soil chemical properties

Treatment	pH	EC	SOC	Avail P	Ex. Cations (cmol$_c$ Kg^{-1})		
	(1: 5)	(dS m^{-1})	(g kg^{-1})	(mg kg^{-1})	K$^+$	Ca^{2+}	Mg^{2+}
Control (NPK)	6.3±0.02	0.45±0.12	7.73±0.8	97.79±4.8	0.36±0.07	1.76±0.1	0.52±0.1
ASS+AP	6.1±0.01	0.52±0.10	9.59±1.3	126.24±6.2	0.35±0.09	1.61±0.07	0.62±0.3
ASS+SP	6.0±0.03	0.35±0.04	9.48±1.3	108.71±5.7	0.39±0.10	1.57±0.04	0.56±0.1
SSS+SP	6.1±0.05	0.38±0.07	8.76±1.1	99.93±4.5	0.39±0.07	1.47±0.04	0.54±0.1

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

three and the last six or seven weeks of each growing season.

The total methane (seasonal average) flux was lowest for the control experiment. Although the weekly emissions increased in the second year of the experiment, the seasonal average flux from most of the treatments reduced (see graphs 1 and 2). The seasonal average flux from the control and ASS + AP plots remained almost the same in both seasons while that from ASS + SP plots decreased significantly from a flux of about 700 mg m^{-2} in the first growing season to about 600 mg m^{-2} in the last one. On the other hand, SSP + SP plots had their seasonal flux average slightly increasing from about 700 mg m^{-2} to 800 mg m^{-2}.

Soil Chemical Properties

All treatments induced adverse effects on most of the soil chemical properties studied. For example, pH, EC and potassium ions plummeted in all the four treatments. Soil organic carbon and available phosphorus increased only in ASS + AP treated soils while the other treatments registered decreased concentrations. Calcium ion concentrations, however, increased significantly in all the treatments whereas the increments in magnesium concentrations were just slight as shown in table 2 below.

DISCUSSION

Several previous studies for example by Liou *et al.* (2014), Wang *et al.* (2016) and Kim *et al.* (2018a) have confirmed the increment in methane emissions after rice straw incorporation into the soil. Methane is a by–product of methanogenesis which is fuelled by the presence of organic carbon under anaerobic conditions which prevent oxidation of methane hence its subsequent release to the atmosphere (Xu *et al.*, 2000; Gaihre *et al.*, 2013). Yagi and Minami (1990) highlighted organic matter availability as the main factor controlling CH_4 emissions from the paddy soils which can, therefore, explain the very low methane emission levels observed in the control plots without any rice straw incorporations. Wang *et al.* (1992) demonstrated that although the application of Urea increased methane emissions from the soil, the emissions were far much higher in soils with straw incorporations. They attributed these ratcheted up emissions to rapid increment in soil pH observed in the urea treated paddy soils, something that didn't accord with our current study because the pH of the NPK treated soils decreased, but methane emissions remained substantially high.

The time interval between rice straw incorporation and the growing season has a direct implication on the quantity of methane emitted from the soil (Wang *et al.*, 2016; Gang *et al.*, 2017). The preceding assertion can explain the observed differences in the amounts of methane emitted from the paddy soils in the current study as the longer interval resulted in the least emissions. The cumulative emission values obtained concurred with those obtained in studies by Naser *et al.* (2007) and Gang *et al.* (2017). Among the three rice straw incorporation strategies, the one involving spreading and ploughing straw into the soil immediately after autumn harvest was the most effective in controlling methane emissions. Tang *et al.* (2016) proved that rice straw decomposition during the fallow season caused decreases in methane emissions during the subsequent rice growing season which can explain that observation. The straw decomposed during the fallow season of winter and early spring consequently reducing the quantity of available organic material during the growing season. The higher weekly methane emissions observed between the third and 14th/15th weeks was due to the active growth of rice and the abundance of root secretions that provided substrates for methanogens (Schutz *et al.*, 1989; Yagi and Minami, 1990).

CONCLUSIONS AND RECOMMENDATIONS

Since several former studies have iterated the positive effects of incorporating organic wastes into the soil on soil properties and quality, confirmation of the observations of this study may, therefore, require several similar studies conducted in the same setting and on the same type of soil texture reporting similar adverse effects. Methane emissions on the other hand, however, followed a familiar trend since many past studies indicated that incorporating straw during the fallow indeed abated methane emissions in the rice growing season and we thus recommend that straw should be incorporated immediately after the rice harvest.

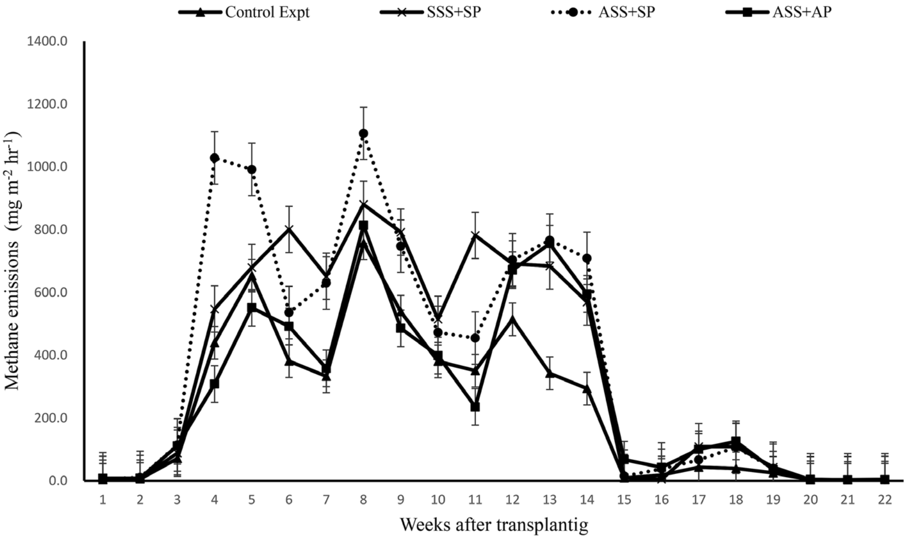

Fig. 1. Weekly methane emissions from rice paddy plots in the first season (year 17).

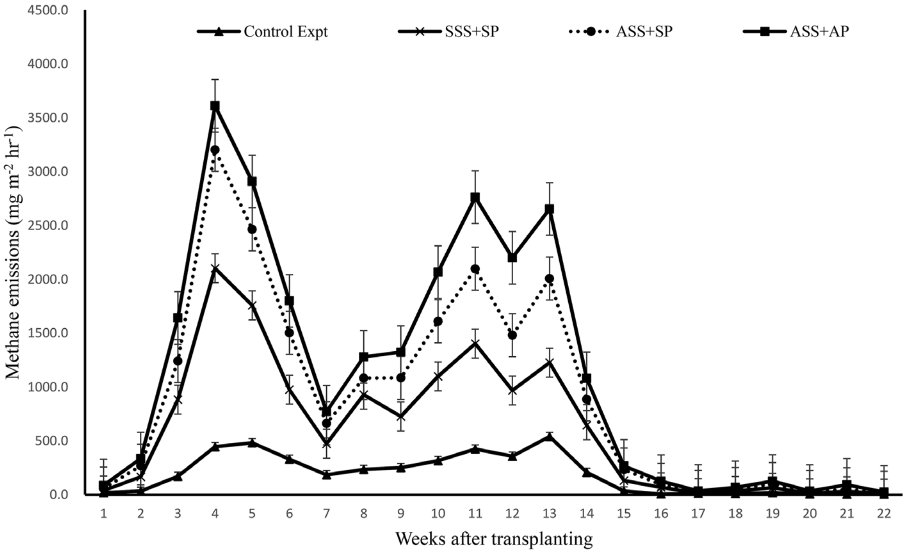

Fig. 2. Weekly methane emissions from the paddy fields in the second season (year 18).

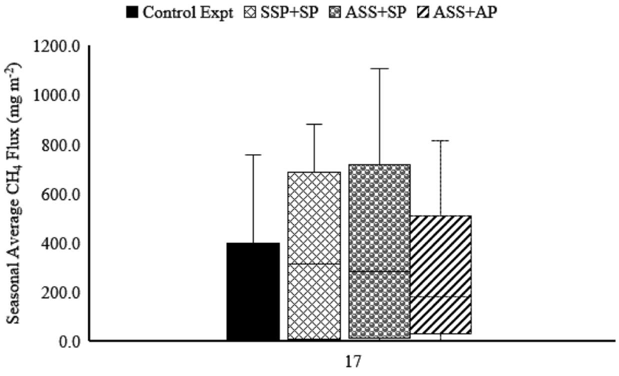

Fig. 3. Showing the average methane flux for the first season (year 17).

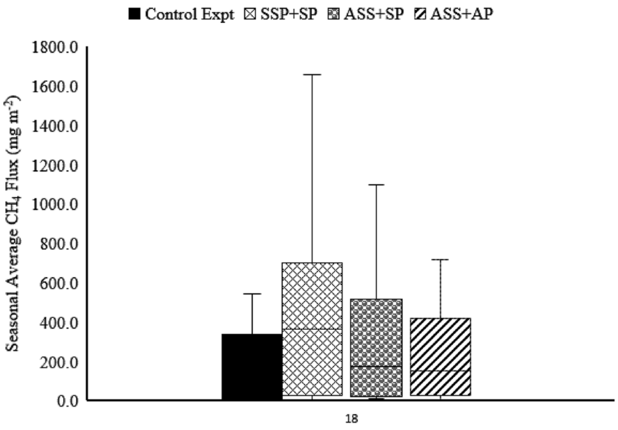

Fig. 4. Showing the average methane flux for the second season (year 18).

Table 2. Final soil chemical properties

Treatment	pH (1: 5)	EC (dS m^{-1})	SOC (g kg^{-1})	Avail P (mg kg^{-1})	Ex. Cations (cmol$_c$ Kg^{-1})		
					K$^+$	Ca^{2+}	Mg^{2+}
Control (NPK)	5.6±0.2	0.29±0.06	5.86±0.4	89.7±3.6	0.21±0.04	3.39±0.4	0.56±0.7
ASS+AP	5.5±0.0	0.40±0.09	11.66±1.3	142.8±8.2	0.21±0.03	3.90±0.7	0.59±0.8
ASS+SP	5.5±0.0	0.27±0.05	8.12±0.9	99.9±4.7	0.22±0.06	3.62±0.5	0.61±1.0
SSS+SP	6.0±0.3	0.36±0.07	5.68±0.5	89.5±4.4	0.24±0.03	4.25±0.9	0.52±0.4

AUTHOR CONTRIBUTIONS

D. Luyima and S. H. KIM wrote the paper and designed the study. J. 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.

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