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Research article

Paddy soil drainage influences residue carbon contribution to methane emissions

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ABSTRACT

Water drainage is an important mitigation option for reducing CH_4 (methane) emissions from residue-amended paddy soils. Several studies have indicated a long-term reduction in CH_4 emissions, even after re-flooding, suggesting that the mechanism goes beyond creating temporary oxidized conditions in the soil. In this pot trial, the effects of different drainage patterns on straw-derived CH_4 and CO_2 (carbon dioxide) emissions were compared to identify the balance between straw-carbon CH_4 and CO_2 emissions influenced by soil aeration over different periods, including effects of drainage on emissions during re-flooding. The water treatments included were: continuous flooding [C] as the control and five drainage patterns (pre-planting drainage [P], early-season drainage [E], midseason drainage [M], pre-planting plus midseason drainage [PM], early-season-plus-midseason drainage [EM]). An equal amount of ^{13}C-enriched rice straw was applied to all treatments to identify straw-derived ^{13}C-gas emissions from soil carbon derived emissions.

The highest fluxes of CH_4 and δ^{13}C-CH_4 were recorded from the control treatment in the first week after straw application. The CH_4 flux and δ^{13}C-CH_4 were reduced the most (0.1–0.8 µg CH_4 g^{-1} soil day^{-1} and -13 to −34‰) in the pre-planting and pre-planting plus midseason drainage treatments at day one after transplanting. Total and straw-derived CH_4 emissions were reduced by 69% and 78% in pre-planting drainage and 77% and 87% in pre-planting plus midseason drainage respectively, compared to control. The early-season, midseason, pre-planting plus midseason and early-season-plus-midseason drainage treatments resulted in higher total and straw-derived CO_2 emissions compared to the control and pre-planting drainage treatments. The pre-planting and pre-planting plus midseason drainage treatments lowered the global warming potential by 47–53%, and early-season and early-season-plus-midseason drainage treatments reduced it by 24–31% compared to control. By using labelled crop residues, this experiment demonstrates a direct link between early drainage and reduced CH_4 emissions from incorporated crop residues, eventually leading to a reduction in total global warming potential. It is suggested that accelerated decomposition of the residues during early season drainage prolonged the reduction in CH_4 emissions. Therefore, it is important to introduce the early drainage as an effective measure to mitigate CH_4 emissions from crop residues.

1. Introduction

Paddy rice is an important source of anthropogenic agricultural CH_4 (methane) emission, contributing up to 19% of global total CH_4 emissions (Forster et al., 2007). The carbon sources for CH_4 production and emission from paddy soils are SOM (soil organic matter), root exudates, and incorporated organic material such as crop residues and manure (Lu et al., 2000). The contribution of crop residues, such as rice

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straw and stubbles, is much higher than SOM and root exudates during the initial 40–50 days of the season (Wassmann et al., 2000), due to the high availability of these substrates for methanogenesis (Kögel-Knabner et al., 2010). Residue amendments result in higher ebullitive CH_4 emissions during the early growth period when plants have not developed their aerenchyma, with a smaller contribution made by root exudates (Wassmann and Aulakh, 2000). 50–66% of the total seasonal CH_4 emissions are derived from rice straw carbon in straw-amended paddy soils (Minoda and Kimura, 1994; Wassmann et al., 2000).

Crop residues are widely used as an organic source to improve soil fertility. The addition of crop residues directly (providing carbon substrates) and indirectly (reducing soil redox potential) provide a favorable environment for methanogenesis, accelerating CH_4 production and ultimately increasing CH_4 emissions (Zou et al., 2005; Zhang et al., 2012). Improved water management practices (such as AWD (alternate wetting and drying), early-season drainage and midseason drainage) have been found to be promising options for mitigating CH_4 emissions from paddy soils (Wassmann et al., 1993; Tyagi et al., 2010). Numerous studies have reported a considerable reduction in CH_4 emissions following single or multiple drainages during the rice growth period (Zheng et al., 2000; Pandey et al., 2014; Tariq et al., 2017a, 2017b). Single drainage in the middle of the rice season reduces CH_4 emissions by 36%–50% compared to continuous flooding (Gupta et al., 2002; Tyagi et al., 2010). In previous laboratory and field studies, early-season drainage in combination with midseason drainage has been found to reduce CH_4 emissions from residue-amended soils by 89–92% (Tariq et al., 2017a) and 43–67% (Tariq et al., 2017b). Ly et al. (2015) report that multiple drainage during the season lowered CH_4 emissions by 44% from rice straw-amended paddy soil. It has been suggested that the mitigation potential of improved drainage practices lies in the aerobic oxidation of organic material in the early stage, leading to a reduction in CH_4 emissions long after re-flooding, and ultimately reducing the total GWP (global warming potential) (Ly et al., 2015; Tariq et al., 2017a; Islam et al., 2018). However, the direct effect of drainage on a possible accelerated residue respiration has not been documented in the literature.

The reduction in CH_4 emissions with soil drainage can significantly increase CO_2 (carbon dioxide) emissions due to the removal of the diffusive water layer and increased soil respiration resulting from available organic C and microbial activities (Saito et al., 2005). The pattern of CO_2 emission is not consistent in paddy soils, since CO_2 is not only produced but also reduced in the anaerobic paddy soil due to methanogenic activities (Kuzyakov, 2010). Furthermore, in paddy soils, the emitted CH_4 and CO_2 derived from different sources (SOM, exudates and residues) have similar $\delta^{13}C$ values, since all carbon sources ultimately stem from rice plants (Penning and Conrad, 2007). The source partitioning of CH_4 emissions in paddy soils is possible if each source has a different carbon signature. The use of ^{13}C-enriched rice straw has been proved to be beneficial in partitioning the residue C contribution in CH_4 emissions from paddy soils (Yuan et al., 2012).

Rice residue burning has been banned in many rice producing countries due to negative effects of open-air burning on air quality and earth climate (Gupta et al., 2004; Bijay-Singh et al., 2008). The sustainable and agro-ecological options for residue management (biochar, compost *etc.*) are often not possible in intensive cropping system due to lack of time and labor (Gupta et al., 2004). Currently, the most feasible alternative to burning is therefore to incorporate the residue into the soil, which improves the soil fertility and increases the soil organic C (Dobermann and Fairhurst, 2002). Addition of residues leads to high CH_4 emissions due to availability of labile C and buildup of background soil C (Smith et al., 2005; Zou et al., 2005). Alternatively, the removal of all residues as a potential source for bioenergy production will lead to depletion of soil nutrient and fertility status (Rasmussen et al., 1980). In this perspective, the relative contribution of residue and soil C to emissions and mitigation potential of drainage is important for the design of optimal mitigation practices. In the previous study, we found that different soil carbon levels had no effect on CH_4 emissions and GWP across several drainage regimes in a laboratory experiment (Tariq et al., 2017a).

Understanding on the contribution of added organic residue carbon to CH_4 and CO_2 emissions is essential in order to understand C dynamics with changing water management in paddy soils. There is little experimental evidence showing the direct relationship between soil aeration and changes in residue C contribution in CH_4 and CO_2 emissions. However, it is essential to understand the quantitative and mechanistic changes in the contribution of the potential C pool (crop residue) to CH_4 and CO_2 emissions with different drainage practices, which are considered a potential management option for CH_4 mitigation from paddy fields. The present study was conducted in the laboratory with ^{13}C-enriched rice straw as a tracer with the objectives of i) monitoring the effect of different drainage patterns on residue C contribution to CH_4 emissions, ii) establishing the CH_4 mitigation potential of drainage patterns, and iii) elucidating the mechanism of prolonged methane flux reduction after re-flooding.

2. Materials and methods

2.1. Soil collection and pot preparation

The soil used in the experiment was collected from the plow layer (20 cm) in farmers' paddy fields in the Red River Delta, 80 km east of Hanoi in northern Vietnam (21° 0.298′N, 106° 21.254′E). The soil was alluvial lowland paddy soil (Acrisols), with a poor soil structure and low fertility. The soil samples were air dried and stored at room temperature before being transported to the Department of Plant and Environmental Sciences at the University of Copenhagen in Denmark. The soil texture was 10.7% clay, 38.3% silt and 51.0% sand. The soil bulk density was 1.2 g cm^{-3} and the soil contained 13.1 g kg^{-1} organic C, 1.3 g kg^{-1} total N, 0.80 g kg^{-1} total P and 4.55 g kg^{-1} total K, with a pH of 5.14 (1 M KCL). The $\delta^{13}C$ value (the ratio of stable isotopes of carbon ^{13}C:^{12}C, which quantified in parts per thousand (per mil, ‰)) of the soil was −28.12. The pots with an inner diameter 14 cm and height of 30 cm were filled with sieved (< 2 mm) 3 kg dried soil. The rice residue was thoroughly mixed with the soil prior to packing. After packing the soil, water was added to each pot to saturate the soil and it was then incubated for two days at 28 °C.

2.2. ^{13}C-enriched rice straw

The rice plants for ^{13}C-enriched rice straw were grown in a greenhouse located at the Campus Klein-Altendorf in Meckenheim, Germany, in the summer of 2015. The rice plants ("Landrasse NTS138") were pulse-labelled with $^{13}CO_2$ by acidification of $Na_2{}^{13}CO_3$ (99 atom-%, Campro Scientific GmbH, Netherlands) solution with 2 M H_2SO_4. The characteristics of the ^{13}C-enriched rice straw are given in Table 1.

2.3. Experimental set-up

The experiment was carried out in a controlled environment growth chamber at 28 °C and with 12 h of daylight (400 μE m^{-2} s^{-1}) per 24 h cycle. The pots were divided into two groups: 18 pots with rice plants and 6 pots without rice plants (for CO_2 flux measurements only). The

Table 1
Properties of ^{13}C-enriched rice straw.

Properties	Values
Total C (g kg^{-1})	397.7
Total N (g kg^{-1})	14.5
C:N ratio	27
$\delta^{13}C$ (‰)	212.8
Atom% ^{13}C	1.34

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