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Impacts of soil incorporation of pre-incubated silica-rich rice residue on soil biogeochemistry and greenhouse gas fluxes under flooding and drying

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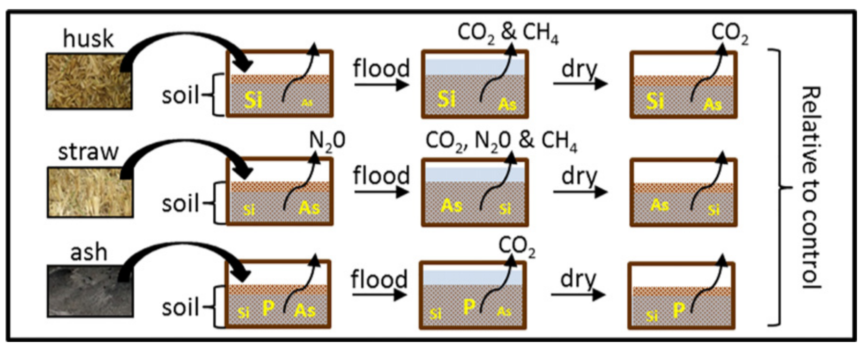
HIGHLIGHTS

- Methods to attenuate arsenic impacts on rice through soil incorporation of silica-rich residues may affect GHG emissions.
- We monitored GHG and biogeochemical impacts of pre-incubated rice residue incorporation to soil during flooding and drying.
- Soils pre-incubated with rice husk had 2-4 fold higher pore water Si than control and soils pre-incubated with rice straw.
- GHG fluxes from straw-amended soils were 2-3 fold higher than control and ash- and husk-amended soils due mainly to N_2O.

GRAPHICAL ABSTRACT



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ABSTRACT

Incorporation of silica-rich rice husk residue into flooded paddy soil decreases arsenic uptake by rice. However, the impact of this practice on soil greenhouse gas (GHG) emissions and elemental cycling is unresolved particularly as amended soils experience recurrent flooding and drying cycles. We evaluated the impact of pre-incubated silica-rich rice residue incorporation to soils on pore water chemistry and soil GHG fluxes (i.e., CO_2, CH_4, N_2O) over a flooding and drying cycle typical of flooded rice cultivation. Soils pre-incubated with rice husk had 4-fold higher pore water Si than control and 2-fold higher than soils pre-incubated with rice straw, whereas the pore water As and Fe concentrations in soils amended with pre-incubated straw and husk were unexpectedly similar (maximum ~0.85 μM and ~450 μM levels, respectively). Pre-incubation of residues did not affect Si but did affect the pore water levels of As and Fe compared to previous studies using fresh residues where straw amended soils had higher As and Fe in pore water. The global warming potential (GWP) of soil GHG emissions decreased in the order straw (612 ± 76 g CO_2-eq m^{-2}) > husk (367 ± 42 g CO_2-eq m^{-2}) > ashed husk = ashed straw (251 ± 26 and 278 ± 28 g CO_2-eq m^{-2}) > control (186 ± 23 g CO_2-eq m^{-2}). The GWP increase due to pre-incubated straw amendment was due to: a) larger N_2O fluxes during re-flooding; b) smaller contributions from larger CH_4 fluxes during flooded periods; and c) higher CH_4 and CO_2 fluxes at the onset of drainage. In contrast, the GWP of the husk amendment was dominated by CO_2 and CH_4 emissions during flooded and drainage periods, while ashed amendments increased CO_2 emissions particularly during drainage. This experiment shows that ashed residues and husk addition minimizes GWP of flooded soils and enhances pore water Si compared to straw addition even after pre-incubation.

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1. Introduction

The management of rice paddy soils influences global greenhouse gas (GHG) emissions (Delwiche and Cicerone, 1993; Neue, 1997), nutrient dynamics (Kaewpradit et al., 2008; Penido et al., 2016; Seyfferth et al., 2013), and arsenic (As) availability to rice (Arao et al., 2009; Li et al., 2009; Linquist et al., 2015; Seyfferth and Fendorf, 2012; Seyfferth et al., 2016). As a staple food for over 50% of the global population, rice yield is directly linked to global food security. The highest rice yield is typically obtained under flooded paddy cultivation in which soils are flooded and remain so until grain filling. The timing of the drainage impacts both As uptake by rice and soil GHG emissions. (Adviento-Borbe et al., 2015; Kim et al., 2012; Linquist et al., 2012; Linquist et al., 2015). While rice paddy flooding is beneficial for yield, it exacerbates both CH_4 emissions and As mobilization in soils due to anaerobic metabolic reactions under reduced soil conditions (Linquist et al., 2012; Linquist et al., 2015). The mobilized As, in turn, may be taken up by rice (Ma et al., 2008) and transferred to grain (Carey et al., 2010), where it can compromise yield (Duxbury et al., 2003; Panaullah et al., 2009) and impact human health (Banerjee et al., 2013; Williams et al., 2005) upon consumption. Decreasing As uptake is a primary local-to-global food security goal, but sustainable solutions must consider its impacts on yield and its biogeochemical implications such as short- and long-term GHG emissions.

Soil incorporation of silica is an emerging method to decrease toxic As uptake by rice and storage in grain (Seyfferth et al., 2016). Silica affects rice As concentrations because dissolved silica (silicic acid) and reduced arsenic (arsenous acid) are chemically similar and share root transporters (i.e., Lsi1 and Lsi2) in rice (Ma et al., 2008). Due to weathering and leaching, many rice soils are depleted in plant-available silica (Savant et al., 1997a), which leads to upregulation of Si transporters in rice roots and inadvertently increases the potential for As uptake. Addition of silica to soil may decrease As uptake by downregulation of Si transporters and competition between Si and As for uptake (Ma et al., 2008). However, Si addition may also cause As desorption from soil solids (Luxton et al., 2006), stabilization of poorly crystalline Fe (oxyhydr)oxides in soil and on root-bound Fe (oxyhydr)oxide plaque (Schwertmann and Thalmann, 1976), and co-precipitation with As-adsorbing Fe (oxyhydr)oxides in bulk soil and in plaque (Swedlund and Webster, 1999). The overall impact of Si on As in rice reflects an interplay of the aforementioned plant physiological and soil chemical processes.

Soil silica amendments can affect grain As concentrations and GHG emissions, but the impacts depend on the type of silica added (Ma et al., 2014; Penido et al., 2016; Seyfferth and Fendorf, 2012; Seyfferth et al., 2016). Under typical flooded paddy cultivation, soil incorporation of silica gel decreases grain As concentrations without affecting soil CH_4 production or rice yield (Li et al., 2009; Seyfferth and Fendorf, 2012), whereas silica-rich diatomaceous earth increases grain As concentrations (Seyfferth and Fendorf, 2012). Soil incorporation of silica-rich rice straw increases grain As (Ma et al., 2014) and exacerbates soil CH_4 production (Penido et al., 2016) and emissions (Liu et al., 2014; Vibol and Towprayoon, 2010; Wang et al., 2012; Wassmann et al., 2000). In contrast, soil incorporation of silica-rich rice husk, a holistic yet seldom used soil amendment, decreases inorganic grain As levels by 25–50% without affecting yield or CH_4 production (Seyfferth et al., 2016). Far fewer studies have focused on multiple GHG emissions and As cycling due to rice husk incorporation than due to rice straw incorporation. To evaluate the impact of husk residue incorporation on GHG emissions and compare it to other silica-rich amendments, research efforts need to consider the impact of husk amendment on soil biogeochemistry for multiple flooding and drying events and CH_4, CO_2 and N_2O emissions simultaneously.

Factors that promote CH_4 emissions include strongly reduced soil conditions and labile carbon availability, whereas N_2O emissions are promoted under suboxic soil conditions and in response to NO_3^- fertilization (Zou et al., 2005). Organic residue incorporation such as rice straw is known to increase CH_4 production and efflux (Conrad et al., 2012; Weber et al., 2001). Flooded rice fields, particularly those amended with organic residues, are thus major sources of CH_4 emissions and comprise between 9 and 13% of global anthropogenic emissions (Pedersen et al., 2006). While CH_4 emissions tend to dominate in flooded rice production (Wassmann et al., 2000), periods of suboxic soil conditions such as those that occur during drainage may increase N_2O emissions (Adviento-Borbe et al., 2015). Moreover, the management history (e.g., incorporation of organic matter such as plant residues) of the soil also affects the microbial community structure, which in turn affects GHG production and fluxes (Lagomarsino et al., 2016).

We previously reported that rice husk incorporation to flooded soil led to higher dissolved silica, lower dissolved As, and lower dissolved CH_4 concentrations than rice straw incorporation in a six-week flooded incubation study without plants (Penido et al., 2016). That study utilized a 1% residue:soil ratio, which was designed to provide silica benefits for multiple growing seasons and thus recurrent flooding and drying cycles. The findings from that work open the following question: *To what extent does pre-incubation under flooded conditions affect biogeochemical cycling and GHG emissions when amended soils are re-flooded and again dried*? This question is relevant to evaluate how biogeochemical processes of amended soils respond to multiple flooding-drying cycles, and to inform long-term soil management practices.

To address that question, we experimentally tested the influence of soil incorporation of pre-incubated silica-rich rice residues of straw, husk, ashed husk and ashed straw over dynamic soil moisture conditions. We simulated a flooded rice cultivation cycle that consists of a wetting up-flood-drainage cycle of the approximate length of a growing season. We conducted the experiment under laboratory conditions (i.e., controlled temperature) without plants to isolate the amended soil impacts and avoid confounding effects. We monitored biogeochemical dynamics in pore water and CO_2, CH_4, and N_2O fluxes, and calculated the 100-year global warming potential (GWP) of these GHG emissions. We hypothesized that soil incorporation of pre-incubated 1) rice husk would lead to the highest pore water Si concentrations and lower dissolved As and GWP than rice straw; 2) rice straw would lead to the highest pore water As concentrations and GWP, mainly as CH_4, due to strongly reduced soil conditions; and 3) ashed residues would lead to the lowest GWP because these residues have more recalcitrant carbon.

2. Materials and methods

2.1. Soil sampling and experimental set-up

Soils and treatments were identical to those described in Penido et al. (2016). Briefly, air-dried soil collected from 2 to 30 cm depth (to avoid collection of overlying grass vegetation) at the University of Delaware's Newark farm, Newark DE, USA was used for the experiments. This soil was chosen because of its similar weathering extent, plant-available silica and arsenic concentration to rice paddy soils in Cambodia (Seyfferth et al., 2014). Soil characteristics were reported in Penido et al. (2016) and are briefly summarized in Table 1. During collection, care was taken to remove vegetation and roots while keeping the soil structure as intact as possible. Approximately 3.5 kg soil was added to each of 15 acid-washed, 4 L high-density polyethylene pots.

For treatments, 1% (w/w) of rice residues were incorporated by hand into the soil; these consisted of rice husk, rice straw, ashed husk, or ashed straw. Both husk and straw were ground to a powder using a Wiley Mill prior to soil incorporation. The total As, Si, Fe and P was <0.02, 4028, 6.7, and 10.8 mmol kg^{-1} for husk and 0.11, 2128, 15.1, and 33.9 mmol kg^{-1} for straw (Penido et al., 2016). The C content of both husk and straw is ~36% and the N content is ~0.45% for husk and ~0.6% for straw (Kajiura et al., 2015). Ashed husk residues were obtained from a mill in Battambang, Cambodia where fresh husk is used as a