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Decreasing of methanogenic activity in paddy fields via lowering ponding water temperature: A modeling investigation

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ABSTRACT

Methane (CH_4) is a potent greenhouse gas and the huge CH_4 fluxes emitted from paddy fields can prejudice the eco-compatibility of rice cultivation. CH_4 production in submerged rice crops is known to be highly influenced by water temperature. Hence, lowering ponding water temperature (LPWT) could be an option to mitigate CH_4 emissions from paddy environments when it is possible either to irrigate with slightly colder water or to increase ponding water depth. However, paddy soil is a complex environment in which many processes are simultaneously influenced by temperature, leading to a difficult prediction of LPWT effects. For this reason, LPWT efficiency is here theoretically investigated with a one-dimensional process-based model that simulates the vertical and temporal dynamics of water temperature in soil and the fate of chemical compounds that influence CH_4 emissions. The model is validated with literature measured data of CH_4 emissions from a paddy field under time-variable temperature regime. Based on modeling results, LPWT appears promising since the simulated reduction of CH_4 emissions reaches about −12% and −49% for an LPWT equal to −5 °C during the ripening stage only (last 30 days of growing season, when rice is less sensitive to temperature variations) and −2 °C over the whole growing season, respectively. LPWT affects CH_4 emissions either directly (decreasing methanogenic activity), indirectly (decreasing activity of bacteria using alternative electron acceptors), or both. The encouraging results provide the theoretical ground for further laboratory and field studies aimed to investigate the LPWT feasibility in paddy environments.

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1. Introduction

In paddy fields, anaerobic conditions occur during flooding irrigation, leading to high emissions of methane (CH_4) (e.g. Kogel-Knabner et al., 2010) which is one of the most potent greenhouse gas. CH_4 emissions from paddy fields have been estimated as 9–19% and 15–26% of the global and anthropogenic CH_4 emissions, respectively (Denman, 2007), compromising the eco-compatibility of rice production.

In recent years, many CH_4 mitigation strategies have been proposed and tested (Uprety et al., 2011): crop diversification, drainage during growing season, biological mitigation, chemical fertilizer amendments technology, potassium fertilization, green manure incorporation, and electron acceptor addition. In general, all the cited mitigation strategies are able to reduce CH_4 emissions from paddy soil; however, their application is often limited by cost-benefit reasons (Wassman and Pathak, 2007). Hence, the search for novel approaches to reduce CH_4 emissions with minimal costs for farmers is still urgent. To this aim, the lowering of ponding water temperature (LPWT) can be an interesting alternative and low-cost option when it is possible either to increase ponding water depth or to irrigate with colder water. Indeed, in paddy soils CH_4 is produced by the dissolved organic matter (DOC) oxidation performed by anaerobic microorganisms (Kogel-Knabner et al., 2010), which are very sensitive to changes in temperature (van Bodegom and Stams, 1999). It follows that, as long as temperature is maintained in the optimal range for rice growth (25–35 °C for vegetative and reproductive stages, and 20–25 °C for ripening stage (Yoshida, 1981)), LPWT should reduce microbial activity and consequently decrease CH_4 emissions without limitations in rice yield.

Temperature decrease affects several physical (e.g. diffusion (Segers and Leffelaar, 2001)), biological (e.g. soil organic carbon decomposition (van Bodegom et al., 2001b)), and physiological (tiller gas conductivity (Hosono and Nouchi, 1997)) processes related with CH_4 fate in paddy soils. It follows that *a priori* prediction of LPWT effectiveness is difficult. Additionally, neither field

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nor laboratory experiments have investigated the effect of LPWT on CH_4 emissions from paddy fields. The complexity of the paddy environment and the lack of clear and in-depth experimental studies suggest to begin to investigate LPWT via a process-based model approach. To this aim, the model proposed by Rizzo et al. (2013) is here improved including heat transfer processes in soil and seasonal variation in ponding water temperature, in order to simulate the dynamics of water temperature in soil and the CH_4 emissions resulting from different LPWT applications. The model is validated by data of CH_4 emissions from the paddy fields under time-variable environmental temperature regime (Khalil et al., 1998b).

Our work aims to provide a theoretical assessment of LPWT effectiveness in order to evaluate the potential of this option to mitigate CH_4 emissions from paddy fields. In this way, we hope to address future laboratory and field experiments able to make applicable this technique.

2. Methods

The study of LPWT efficiency is based on a hydro-biogeochemical process-based model (Rizzo et al., 2013), in which the dynamics of chemical compounds affecting CH_4 production, oxidation, and emission along soil depth are quantified. Many physico-chemical processes and paddy soil features have been included in the model, such as paddy soil stratigraphy, detailed root compartment modeling, transport flows, biogeochemical reactions, gas transport and respiration within roots. In order to simulate the effect of LPWT on CH_4 emissions from paddy soil, the original model is here coupled with a soil temperature model which includes seasonal variations of ponding water temperature and heat transport in the paddy soil. Moreover, other aspects such as the decomposition of organic fertilizer and root exudation are here improved. In the following sections, the main features of the original model are briefly revised (see Rizzo et al. (2013) for more details), while the temperature model and other model improvements are described in detail.

2.1. Hydro-chemical model

The vertical domain is schematized by three soil layers (Fig. 1), according to the typical vertical heterogeneity of paddy soils (Chen and Liu, 2002; Kogel-Knabner et al., 2010): the layers are denoted as muddy, hard pan, and non-puddled layers, and the subscripts $k = 1,2,3$ are used to distinguish their respective variables. In order to limit the complexity of the system, constant physical parameters are considered for each layer. The muddy and the hard pan layers are assumed in saturated conditions, while the non-puddled layer is unsaturated. The depth below ground of the lower interface of each layer is denoted as z_k (Fig. 1).

A plant-root development function, $p(t)$, is used to modulate the variation in time, t, of plant-root features such as root biomass, root exudation, plant transpiration, and tiller area extension. This function assumes a linear increase of plant features from germination up to a maximum plant development stage, t_p, followed by a linear decrease up to maturity. The proposed $p(t)$ is a linearized version of the formulation proposed by van Bodegom et al. (2001b) and Xu et al. (2007). This empirical formulation allows to simply reproduce the complex plant/root temporal development at a daily scale, i.e. not capturing the diurnal variation in photosynthetic rate of rice plants (Xu et al., 2007). The roots are assumed to be present only in the muddy layer; the root density is modeled via an exponential distribution over depth, $\varphi_r(z)$, while the root area and volume density are differentiated between primary and secondary roots and empirically linked to the root biomass.

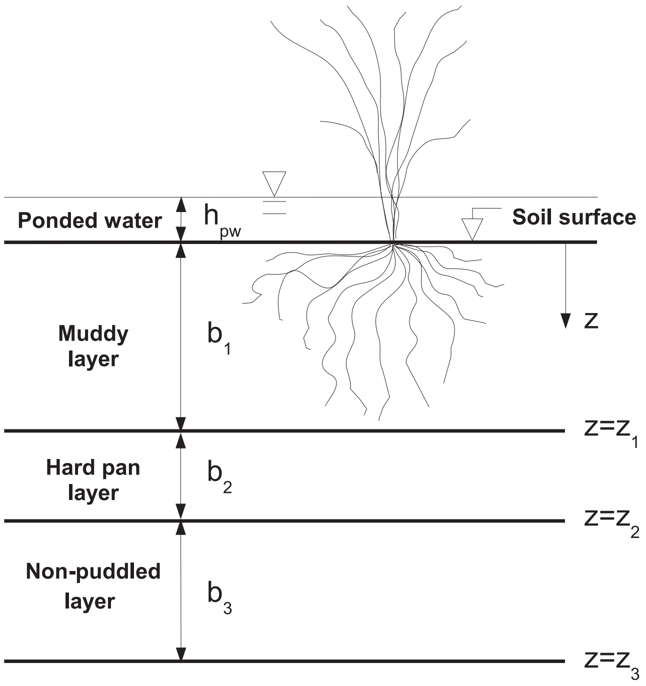

Fig. 1. Configuration of paddy rice soil layers.

The infiltration rate, q_k, is modeled by Darcy equation for the saturated layers. Due to the strong unsaturated conditions (Wopereis et al., 1992; Chen and Liu, 2002), q_k is assumed constant, and equal to the value of hard pan layer, in the non-puddled layer. A term for the root water uptake driven by plant transpiration rate, T, is included in the water mass balance equation.

The dissolved species considered in the model are: DOC, O_2, NO_3^-, NH_4^+, Fe^{2+}, and CH_4. The modeled solid species are: SOC, SOC_r, and $Fe(OH)_3$; SOC is the soil organic carbon, while SOC_r is the pool of organic carbon originated by root dieback. For each i-th dissolved species and j-th solid species the mass balance equations, referred to bulk volume of the k-th layer, are

$$\left(\theta_k + \rho_k \frac{\partial C^s_{i,\mathrm{ads}}}{\partial C^l_i}\right)\frac{\partial C^l_i}{\partial t} = -\frac{\partial}{\partial z}\left(q_k\, C^l_i - \theta_k\, D_{h,i}\frac{\partial C^l_i}{\partial z}\right) + R_i \qquad (1)$$

$$\frac{\partial C^s_j}{\partial t} = R_j, \qquad (2)$$

where z is the depth, θ_k is the soil moisture, ρ_k is the soil density, $C^s_{i,\mathrm{ads}}$ is the concentration adsorbed on solid matrix, C^l_i is the concentration of dissolved species, C^s_j is the concentration of solid species, and $D_{h,i}$ is the coefficient of hydrodynamic dispersion. R_i and R_j are the sum of all sink terms involving the i-th dissolved species and the j-th solid species, respectively, i.e. soil organic matter decomposition, primary and secondary biogeochemical reactions driven by DOC oxidation in anaerobic conditions and radial oxygen loss from roots, root solute uptake, and root exudation. A list of the biogeochemical reactions described by the model is reported in Table 1. The interactions among different pools of chemical compounds due to the modeled processes are schematized in Fig. 2.

The plant-mediated gas exchange between soil and atmosphere is modeled via a gas mass balance equation within root aerenchyma, referred to soil bulk volume, expressed as

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