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Groundwater impact on methane emissions from flooded paddy fields

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ABSTRACT

High methane (CH_4) fluxes emitted from paddy fields strongly contribute to the accumulation of greenhouse gases into the atmosphere, compromising the eco-compatibility of one of the most important world foods. A strong link exists between infiltration rates of irrigation water and CH_4 emissions. Since depth to the groundwater table affects infiltration rates, a relevant groundwater impact is expected on CH_4 emissions from paddy fields. In this work, a theoretical approach is adopted to investigate the aquifer effect on CH_4 dynamics in paddies. Infiltration rates are strongly affected by the development of different connection states between aquifer and irrigation ponded water. A strong reduction in infiltration rates results from a water table near to the soil surface, when the system is hydraulically connected. When the groundwater level increases, the infiltration rate reduction due to the switch from disconnected to connected state promotes a relevant increase of CH_4 emissions. This is due to a strong reduction of dissolved organic carbon (DOC) percolation, which leads to higher DOC availability for microbial CH_4 production and, consequently, higher CH_4 emissions. Our simulations show that CH_4 fluxes can be reduced by up to 24% when groundwater level is decreased and the aquifer is disconnected from ponding water. In paddies with shallow aquifers, lowering the water table with a drainage system could thus represent a promising CH_4 mitigation option.

1. Introduction

Paddy rice fields are worldwide one of the most important food sources and, as wetlands, provide different benefits in terms of environmental and ecological functions, such as flood alleviation, groundwater recharge, water purification, soil-erosion control, air purification, and biodiversity conservation [e.g. 1]. However, paddy fields are also *a great source of* source of methane (CH_4) in atmosphere. CH_4 is one of the most radiatively important greenhouse gases, with a global warming potential at 100 years that is 28 times higher than carbon dioxide [2]. CH_4 emissions from paddy fields play a major role among the different natural and anthropogenic sources (9–19% and 15–26% of the global and anthropogenic CH_4 emissions, respectively [3]), strongly threatening the eco-compatibility of rice cultivation. Since rice is the main staple food for the Asian population, management of CH_4 emissions from paddies is an urgent open issue for mitigation of climate change [4,5].

CH_4 emissions from paddy fields are promoted by flood irrigation, which is commonly adopted to guarantee optimal growth conditions for rice cultivar [6]. The soil is continuously covered by a ponded water layer during the growing season. This develops favorable anaerobic conditions for methanogenic microbes, which produce CH_4 through dissolved organic carbon (DOC) degradation [7]. Different mitigation options for CH_4 emissions have been proposed [5], such as alternate wetting and drying, green manure incorporation, and addition of an alternative electron acceptor.

A possible alternative mitigation action concerns water infiltration rates. They in fact have a strong effect on CH_4 emissions from paddies, as it has been highlighted by both laboratory and modeling studies. Lysimeter experiments performed by [8] and [9] have shown a decrease in CH_4 emissions due to an increase in infiltration rates. Accordingly, a high overestimation of CH_4 emissions has been reported by the modeling investigation of [10] when infiltration is neglected, due to the lack of simulated DOC percolation.

Infiltration rates in paddy fields are regulated both by the hard pan layer and by the water table position in the case of unconfined phreatic aquifer. The hard pan – also called plough pan, or plow sole [e.g. 11, 12] – is a compacted layer resulting from the practice of soil puddling to reduce water percolation losses. The soil puddling practice develops the typical stratigraphy of paddy soils (from top to bottom): (i) a highly permeable superficial muddy layer, where rice roots can grow; (ii) a thin and less permeable hard pan layer; (iii) a highly permeable layer, here called non-puddled layer. The aquifer affects infiltration rates depending on the water table position: a shallow water table directly changes infiltration rates [13–15], while a deep

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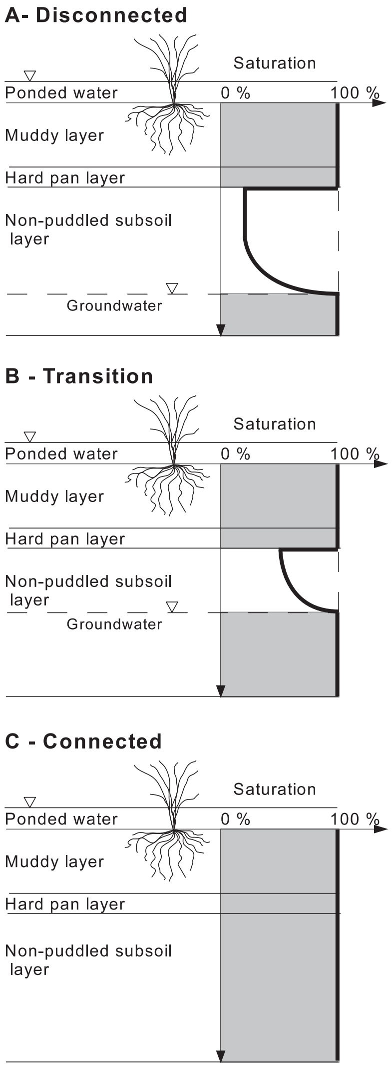

Fig. 1. Typical stratigraphy of paddy soil and different connection states between irrigation ponded water and groundwater. Thick lines and gray areas represent the saturation state within the soil and fully saturated soil portions, respectively.

water table promotes strongly unsaturated conditions and a gravitational infiltration rate below the hard pan layer [11,12,16].

The hydraulic configuration of paddy soils exhibits a strong analogy with the stream-aquifer system in the presence of a clogged streambed theorized by [17], where the infiltration flow regime strongly depends on the connection state between stream and aquifer. The similarity is suggested by the similar role played by the clogged streambed and the hard pan in the two different systems, i.e., they both reduce infiltration rates because of their very low hydraulic conductivities concentrated in a thin sediment/soil layer. Indeed, infiltration rates behave similarly in both streams and paddies affected by groundwater; in the case of a deep water table that is sufficiently far from the clogged/hard pan layer, infiltration rate values are maximum and equal to the flux induced by gravity, while these values decrease when the groundwater level rises and connects to stream/irrigation water. Following the classification proposed by [17], we define three connection states in paddy soils depending on the position of the water table and on the saturation degree, as shown in Fig. 1: (i) disconnected; (ii) transition; (iii) connected. The paddy system is disconnected when the non-puddled subsoil is unsaturated and infiltration rates do not significantly change with water table position (Fig. 1A). On the contrary, the connected state occurs when the paddy soil is fully saturated, i.e. when the top of the capillary fringe reaches the bottom of the hard pan layer (Fig. 1C). Finally, we refer to transition state (Fig. 1B) when the non-puddled layer is unsaturated but the capillary rise above water table determines a change in water pressure sufficient to reduce the maximum gravitational flux.

The influence of water table position on CH_4 dynamics has been already highlighted in works for natural wetlands (e.g., peatland and forbs), but mainly focusing on the shift between aerobic and anaerobic conditions promoted by changes in soil moisture conditions [e.g. 18, 19, 20]. However, the muddy layer in a flooded paddy soil is continuously saturated and the impact on the CH_4 cycle of soil moisture driven by groundwater level is negligible. Differently, we focus on groundwater effects on infiltration rates, which are known to strongly influence CH_4 dynamics in paddy soils [8–10]. Hence, the position of groundwater table in flooded paddy soils is expected to play a role in controlling CH_4 emissions. In particular, lower infiltration rates in the case of a connected state should lead to higher CH_4 emissions. Although some studies about changes in percolation flow as a function of water table position in paddy soils are available [e.g. 13, 15], the negative feedback of groundwater on CH_4 emissions at different connection states (higher CH_4 emissions for shallow water table) in paddy systems has not been investigated. Due to the lack of both laboratory and field data on water table effect on CH_4 emissions in the paddy environment, our purpose is to theoretically investigate this gap through a modeling approach. To this aim, the process-based model for CH_4 emissions developed and validated by [10,21] is applied to describe groundwater effects on flow regime and soil biogeochemistry of flooded paddy fields. The results provide insights on the potential efficiency of a CH_4 mitigation option based on water table control in flooded paddy fields.

2. Methods

The work is based on the one-dimensional hydro-biogeochemical model proposed and validated by [10,21], in which the spatio-temporal dynamics of chemical compounds affecting CH_4 production, oxidation, and emission along soil depth are simulated. Different physico-chemical processes and paddy soil characteristics are considered, such as paddy soil stratigraphy, detailed root compartment modeling, water and heat flows, seasonally variable air temperature, biogeochemical reactions, and gas transport and respiration within roots. In this work, the biogeochemistry and the plant/root compartments are modeled as in [10] and [21], while the hydraulic model is modified to simulate the impact of the water table depth on CH_4 emissions from paddies. Moreover, the temperature model is also updated to account for heat exchange within the aquifer. In the following sections, the modifications to the original framework are reported, while the features of the biogeochemical and the plant/root models are briefly recalled. Lists of model parameters and equations (Tables B.4 and B.5) are summarized in the appendix (see also [10] and [21] for more details on model approach and assumptions).

2.1. Model domain subdivision

Fig. 2 shows the vertical domain subdivided into different subdomains, following the typical vertical stratigraphy of paddy soils [7,10,12]: muddy, hard pan, and non-puddled layers. Within each subdomain, physical parameters (e.g., soil porosity and saturated hydraulic conductivity) are set constant to limit model complexity. The chosen subdivision has been shown to reproduce the most relevant vertical variations of soil properties and their influence on CH_4 emissions [10]. In order to model heat exchange within the deep aquifer, an extended non-puddled layer is added below the non-puddled layer for the temperature model only (see Fig. 2 and discussion in Section 2.3). For this extended non-puddled layer, the same physical characteristics of the non-puddled layer are assumed (bulk density, soil porosity). The subscript *k* refers to different layers, with