Role of drainage timing on mitigating methane emissions from rice paddy fields

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Key Points:

- The drainage timing maximizing the mitigation efficiency of the drainage is calculated.
- Applying the drainage at optimal timing may reduce emissions by more than 60%.
- Optimal drainage timing shifts from mid-season to early-season when added organic matter crosses a given threshold.

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Abstract

Rice fields are important contributors to the global methane budget. While rice production must increase to meet the demand from a growing population, there is a need to mitigate methane emissions through the employment of sustainable management strategies. A popular one consists of a short drainage that shortens the period of time spent in anaerobic conditions, but it is still unclear how drainage timing affects its overall effectiveness. Here we introduce a mechanistic model of methane emissions, coupled to the dynamics of redox potential and rice growth, to analyze the effect of a single drainage and the timing of its application on the temporal evolution of methane emissions. In particular, we identify the drainage timing that maximizes the mitigation efficiency of the drainage, defined as the reduction in methane emission relative to the emissions in continuous flooding. We also explore the role of organic amendment and show how it changes the optimal drainage timing. Application of this framework to a set of experiments demonstrates that emissions can be reduced by more than 60% if drainage is applied at optimal timing. The high efficiency and the limited negative effects on rice yields and N_2O emissions place this water management among the most sustainable ones.

1 Introduction

Rice paddies are among the major sources of methane (CH_4), contributing up to 20% to global emissions (IPCC, 2007; Kirschke et al., 2013; Meinshausen et al., 2017). As the global demand for rice production increases with the growing population (Cassman, 2001) and the higher atmospheric CH_4 concentration rises concerns for the global warming (Dlugokencky et al., 2011; Tian et al., 2016), effective management strategies need to be designed for mitigating CH_4 emissions while maintaining high rice yields (Islam et al., 2018). In this context, it is necessary to use experimental studies in concert with theoretical analysis for testing different management strategies aimed at minimizing water use and greenhouse gas emissions, and maximizing rice yield.

Being very sensitive to water stress (Bouman & Tuong, 2001), rice is typically grown in submerged soil conditions (Sass et al., 1992; Neue, 1993; Neue et al., 1997). Due to flooded and anaerobic conditions, the soil redox potential during the rice growing season lowers considerably, creating an environment favorable to methanogenesis (Schütz et al., 1990; Khalil et al., 1998; Le Mer & Roger, 2001). While part of the CH_4 produced is oxidized, for instance by oxygen released through the rice rooting system, the remaining is emitted to the atmosphere by diffusion, ebullition, and in particular by plant-mediated transport through the aerenchyma (Le Mer and Roger (2001) and references therein), the latter being the dominant pathway.

To contain the emissions, the traditional mitigation strategy consists in reducing the period of time under anaerobic conditions, by draining the field for a short interval during the growing season (Sass et al., 1992). The sudden exposure to air causes most of the CH_4 in the soil to be oxidized and increases the redox potential to levels that prevent methanogenesis. If the field is re-flooded before the soil moisture level drops below a critical level for the rice, the yield remains mostly unaffected. Alternative strategies, such as alternate wetting and drying combined with various fertilizer applications, have been proposed to further reduce CH_4 emissions (Huang et al., 2004; Jiao et al., 2006; Carrijo et al., 2017; Islam et al., 2018; Liao et al., 2020). Their effectiveness however is not clear yet, as negative effects have been reported (e.g., OM losses, increased N_2O emissions, decreased rice yield). Thus, while current studies attempt to develop a portfolio of available strategies to comprehensively improve the sustainability of rice cultivations, a single drainage probably remains, at the moment, the most reliable strategy to mitigate CH_4 emissions without impacting rice yield.

Previous experimental studies have explored the effect of drainage on reducing CH_4 emission to improve its implementation. These studies have provided useful insight into the relation between CH_4 production and emission and plant growth (Das & Baruah, 2008; Bhattacharyya et al., 2019), the effects of environmental conditions, such as temperature and redox potential (Wang et al., 1993; Khalil et al., 1998; Yao et al., 2001; Jiao et al., 2006), and of soil amendments (Zou et al., 2005; Tariq et al., 2017; Liao et al., 2020). Yet, these results can be complemented by theoretical studies that allow to readily explore how multiple factors simultaneously affect CH_4 emission and to quantitatively investigate the coupling between water balance, plant growth, and biogeochemistry under different water management strategies.

Towards this goal, here we develop a mechanistic model of CH_4 emissions from rice paddy fields to investigate the role of drainage timing on the temporal dynamics of CH_4 emissions. Taking advantage of the numerous experimental observations available, we model the evolution of plant biomass and soil redox potential, and introduce an expression for CH_4 emissions that takes into account the role of plants, soil redox potential, and organic amendments (Sec. 2). After showing that the model captures the general CH_4 emissions dynamics from rice fields (Sec. 3), we introduce the mitigation efficiency of the drainage and derive the optimal drainage timing as a function of a few parameters readily obtained from field measurements (Sec. 4). The results are applied to a set of experiments, with and without organic amendment, to highlight the potential reduction achievable with optimal drainage timing (Sec. 5). We conclude with a summary of the key results (Sec. 6).

2 Theory

The time evolution of CH_4 emissions from a rice field results from the interaction between soil biogeochemical processes (Neue et al., 1997; Le Mer & Roger, 2001), involving methanogens and a suitable organic substrate, rice cultivar and development stage (Singh et al., 1999; Gutierrez et al., 2013), water management practices (Yagi et al., 1996) (mid-season drainage, intermittent irrigation), and application of fertilizers (Zou et al., 2005). Here we develop a mechanistic model of CH_4 emissions, accounting for the variability in soil redox potential, the availability of labile carbon (C), plan growth, and water management, which will be used to investigate the effect of timing of a single drainage application on total CH_4 emissions.

2.1 Soil redox dynamics

Methanogenesis, the bio-production of CH_4 by methanogens, requires very low soil redox potential to occur, at least Eh < -100 mV (Wang et al., 1993; Jiao et al., 2006). From the beginning of soil submersion, some time elapses before available electron acceptors are utilized to decompose labile C and soil redox conditions become favorable to methanogenesis (LaRowe & Van Cappellen, 2011; Stumm & Morgan, 2012). The soil redox potential hence is a fundamental variable determining both when methanogenesis begins and its temporal evolution during the rice growing season, and it is crucial to model its dynamics, especially given the fact that Eh measurements are not always available.

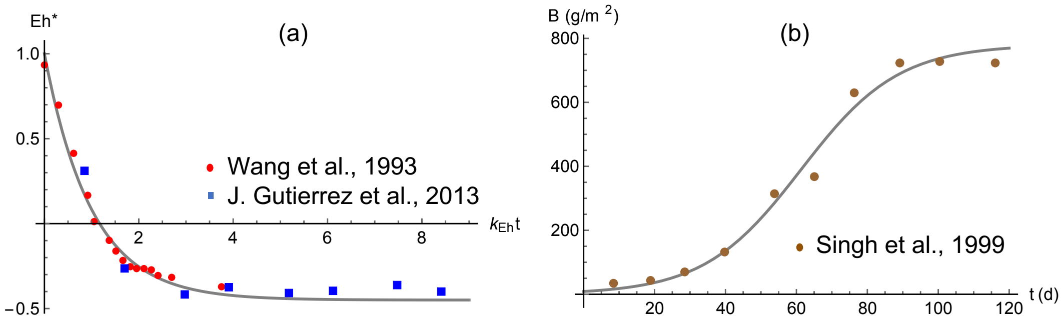

Figure 1. (a) Comparison between modeled (gray line) and observed (dots) evolution of the soil redox potential in normalized variables, $eh^* = (Eh - Eh_{min})/(Eh_0 - Eh_{min})$ and $k_{Eh}t$. Comparison between modeled (gray line) and observed (dots) evolution of rice biomass during the growing season. Parameters are provided in Table 1.

As observed experimentally, as soon as the soil is flooded, Eh decreases following very closely an exponential decay (Figure 1(a)), so that the temporal evolution of Eh can be described by the following differential equation,

$$\frac{dEh^*}{dt} = -k_{Eh}Eh^*, \quad \text{being} \quad Eh^*(t) = \frac{Eh(t) - Eh_{min}}{Eh_0 - Eh_{min}} \tag{1}$$

where Eh_0 is the redox potential before flooding (typically between 300-500 mV) and Eh_{min} is the lower bound set on Eh (around negative 250-300 mV). The decay constant k_{Eh} is a property of the soil and the availability of alternative electron acceptors (N, Mg, Fe).

From the beginning of the inundation, methanogenesis begins when the electrochemical potential crosses the threshold $\tilde{Eh}$ ($\tilde{Eh} = -100$ mV). From the dynamics of Eh, the time τ needed from the beginning of the flooding to reach this threshold can be obtained by solving equation (1) and inverting,

$$\tau = \frac{1}{k_{Eh}} \ln\left(\frac{\tilde{Eh} - Eh_{min}}{Eh_0 - Eh_{min}}\right). \tag{2}$$

When Eh measurements are not available, equation (1) can also be used to provide an estimate of k_{Eh} from observations of τ.

2.2 Plant growth and activity

The presence of the rice plant enhances both the formation and the emission of CH_4 (Sass et al., 1992; Singh et al., 1999). The plant provides labile C for methanogens by releasing exudates and photosynthetic products from the rooting system (Sass et al., 1991; Chidthaisong & Watanabe, 1997; Das & Baruah, 2008), hence stimulating the formation of CH_4, and, in addition, the development of its aerenchyma provides CH_4 with a direct pathway to the atmosphere (Kim et al., 1999; Purvaja et al., 2004; Bhattacharyya et al., 2019).

The extent to which the rice plant affects CH_4 production and emissions is controlled by its development stage, measured for instance by the plant biomass, B. During the growing season, the growth of the plant biomass is well represented by a sigmoid curve (Figure 1(b)), typically modeled through a logistic growth curve (Huang et al., 2004),

$$B(t) = \frac{B_{max}}{1 + K_B e^{-rt}}, \tag{3}$$

where B_{max}, maximum biomass, $K_B = B_{max}/B_0 - 1$, B_0 being the initial biomass, and r, growth rate, are parameters related to the specific plant cultivar and the environmental conditions (i.e., soil and atmospheric) under which rice is grown.

Photosynthetic activity and the release of exudates follows closely the growth and development of the plant until approximately the flowering stage, after which the rate of photosynthesis stabilizes and the permeability of the root epidermial layer decreases (Nouchi et al., 1994; Sinha, 1995; Das & Baruah, 2008). In addition, as the aerenchyma system develops, more oxygen reaches the rhizosphere, oxidizing part of the CH_4 before it can reach the atmosphere (Sass et al., 1992; Huang et al., 2004). All these factors will affect CH_4 production, oxidation and emission (see section 2.3).

2.3 Methane emissions

From the evolution of Eh, plant biomass, B, net CH_4 emissions can be estimated as

$$E(t) = f(Eh) \cdot g(B) \cdot (I_p + I_C), \tag{4}$$

where $f(Eh)$ is a factor dependent on soil redox conditions, accounting for the inhibition of methanogenesis at $Eh > \tilde{Eh}$, and $g(B)$ is a factor accounting for both the decline in gas transport through roots and aerenchyma, due to plant aging, and the increase in CH_4 oxidation (section 2.2). Specifically, the factor f is calculated as

$$f(Eh) = \begin{cases} 0, & Eh > \tilde{Eh}, \\ \frac{Eh - \tilde{Eh}}{Eh_{min} - \tilde{Eh}}, & Eh \leq \tilde{Eh}, \end{cases} \tag{5}$$

where we recall that Eh_{min} is the lower bound for soil Eh. The factor g is a decreasing function of the plant biomass, which can be modeled as (Huang et al., 1998, 2004)

$$g(B) = \left(1 - \frac{B}{B_{max}}\right). \tag{6}$$

The terms I_p and I_C are input functions accounting for CH_4 produced and emitted from the decomposition of plant exudates and organic amendment, respectively. The term I_p increases as the plant grows, because more labile C is released and the aerenchyma is more developed, and can be modeled as (Huang et al., 2004)

$$I_p(t) = K_p \cdot B(t), \tag{7}$$

where the proportionality constant K_p relates plant growth and release of labile C to CH_4 emissions. The term I_C not only depends on the amount of organic matter, C, but also on the plant biomass, B, because even emissions from organic amendment rely on the aerenchyma as a fast route to the atmosphere. Therefore, similarly to (7), the term I_C can be modeled as

$$I_C(t) = K_C \cdot B(t) \cdot C, \tag{8}$$

where C is the amount of organic matter and K_C is a proportionality constant relating C decomposition to CH_4 emissions. Assuming that organic matter is decomposed according to a first order kinetics, C decays in time following an exponential decay, $C = C_0 e^{-k_d t}$, C_0 and k_d being the initial C content and decomposition rate constant, respectively. It follows that I_C can be expressed as

$$I_C(t) = K_C \cdot B(t) \cdot C_0 e^{-k_d t}, \tag{9}$$

Combining equations (4), (7), and (9), the overall CH_4 emissions can be computed as,

$$E(t) = f(Eh) \cdot g(B) \cdot B(t) \cdot (K_p + K_C^{'} e^{-k_d t}), \tag{10}$$

where $K_C^{'} = K_C C$. It follows that the total amount emitted throughout the entire duration of the season is

$$E^{TOT} = \int_0^T E(t)dt = \int_0^T f(Eh) \cdot g(B) \cdot B(t) \cdot (K_p + K_C^{'} e^{-k_d t})dt, \tag{11}$$

where T is the final drainage time before harvest. Recall that for a time τ after flooding and re-flooding following a drainage, $Eh > \hat{Eh}$ and hence $f = 0$. Thus, emissions only occur from time $t = \tau$ to the drainage timing, t_d, and from a time τ after the drainage, $t = t_d + \tau$, until the end of the season T, i.e., $E^{TOT} = \int_0^T E(t)dt = \int_\tau^{t_d} E(t)dt + \int_{t_d+\tau}^T E(t)dt$.

3 Seasonal CH_4 emissions: the role of drainage

Prior to using the model developed above to optimize the drainage timing, we show that it captures the typical seasonal dynamics observed in rice fields. Equation (10) indeed reproduces the observed general pattern of CH_4 emissions (Neue et al., 1997; Le Mer & Roger, 2001). In continuously flooded conditions and without organic amendment, the temporal evolution of CH_4 emissions closely resembles the development stage of rice (Figure 2). After the interval of time needed for the redox potential to reach reducing conditions, emissions increase as the plant grows and reach their peak at the rice flowering stage, after which they are negatively affected by the decline of plant photosynthetic activity, aerenchyma gas transport, and by higher CH_4 oxidation.

In many rice cropping systems, rice straw residues or manure are incorporated in the soil as organic fertilizers (Le Mer & Roger, 2001; Adhya et al., 2014). Fertilization is needed to increase rice yield and meet the growing demand for rice. However, organic fertilizers provide additional labile C to methanogens, in turn altering the generic tem-

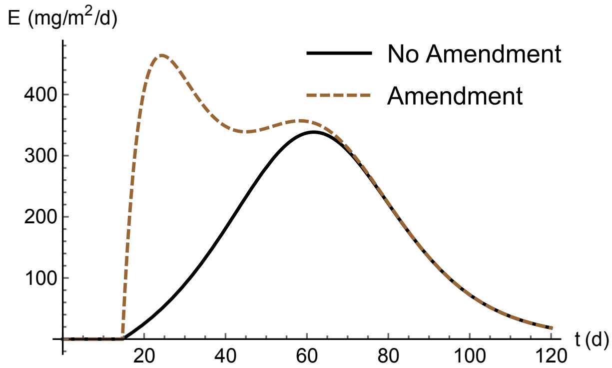

Figure 2. Seasonal evolution of CH_4 emissions with (brown line) and without (black line) organic amendment.

poral pattern discussed above (Figure 2). First, the additional labile C available readily increases overall CH_4 emissions. Second, because this substrate is available to methanogens before plant begins realising labile C, emissions peak as soon as the soil redox potential becomes favorable, i.e, a time τ after flooding. A second peak in CH_4 emissions, from the decomposition of labile C by released by plants, is observed later in the season.

The seasonal evolution of CH_4 emissions is greatly affected by the application of a drainage. As the soil is drained and oxygen quickly penetrates the soil, CH_4 oxidation by methanotrophs (i.e., methane oxidizing bacteria) becomes largely favored over production by methanogens. The redox potential increases to values typical of aerated conditions and, in turn, methanogenesis stops. After re-flooding, CH_4 production and emission initiate again only after low Eh conditions are reestablished, i.e., after another interval τ (see Figure 3). The mid-season drainage hence decreases the total amount of CH_4 emitted throughout the season by reducing the time spent under favorable low redox potentials. A factor that was not explicitly included in our analysis is the negative effect of the drainage on the development of the aerenchyma, which may lead to reduced transport to the atmosphere (Kludze et al., 1993). This factor may result in a further decrease in total CH_4 emissions.

The emissions avoided (gray shaded area in Figure 3) by applying a drainage largely depends upon the timing of its application. Reasonably, the season drainage is more effective if it prevents emissions when conditions would be more favorable, such as lower Eh, higher labile C and plant gas transport. On the contrary, if the field is drained too

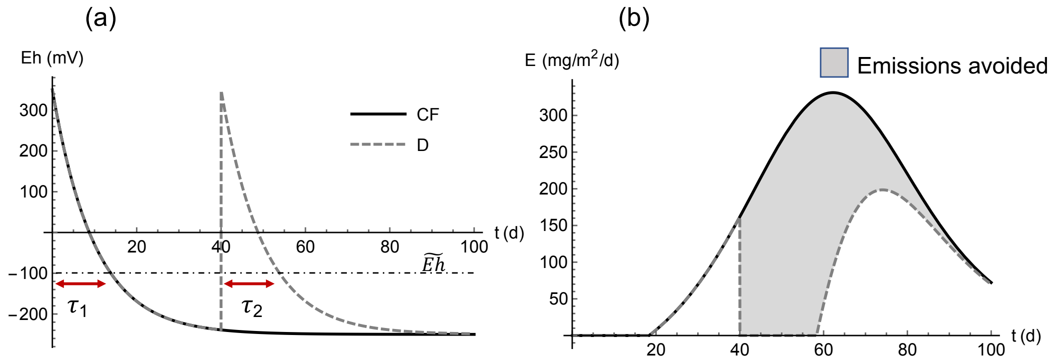

Figure 3. (a) Dynamics of redox potential Eh as affected by water management, continuous flooding and mid-season drainage. (b) CH_4 emissions under continuous flooding (black line) and mid-season drainage (dashed gray line) regimes. The gray shaded area corresponds to the total emissions avoided.

early, the plant is at an early development stage (e.g., $t_d = 20$ d, Figure 4(b)), in which it is not supplying enough labile C to support methane production. As a result, the drainage prevents only emissions when they are still not contributing substantially to the total amount of CH_4 emission. On the other hand, if the field is drained too late in the season, most of the emissions have already occurred (Figure 4(d)).

4 Mitigation efficiency of the drainage

The effect of drainage timing can be quantified by evaluating how efficiently emissions are reduced. The mitigation efficiency of the drainage can be defined as the reduction obtained with drainage relative to the emissions in continuous flooding (CF) conditions,

$$\eta(t_d) = \frac{E_{CF}^{TOT} - E_D^{TOT}(t_d)}{E_{CF}^{TOT}}, \tag{12}$$

where E_D^{TOT} and E_{CF}^{TOT} are the total emissions with a drainage and with continuous flooding conditions, respectively, and t_d is the time of drainage. For both $t_d = 0$ and $t_d = T$, $E_D^{TOT} = E_{CF}^{TOT}$ and the efficiency $\eta(0) = \eta(T) = 0$, so one must expect that there is a time $\hat{t}_d$ for which η is maximum (Rolle's lemma). In other words, there is an optimal t_d that minimizes the emissions E_D^{TOT}, which can be readily found by setting

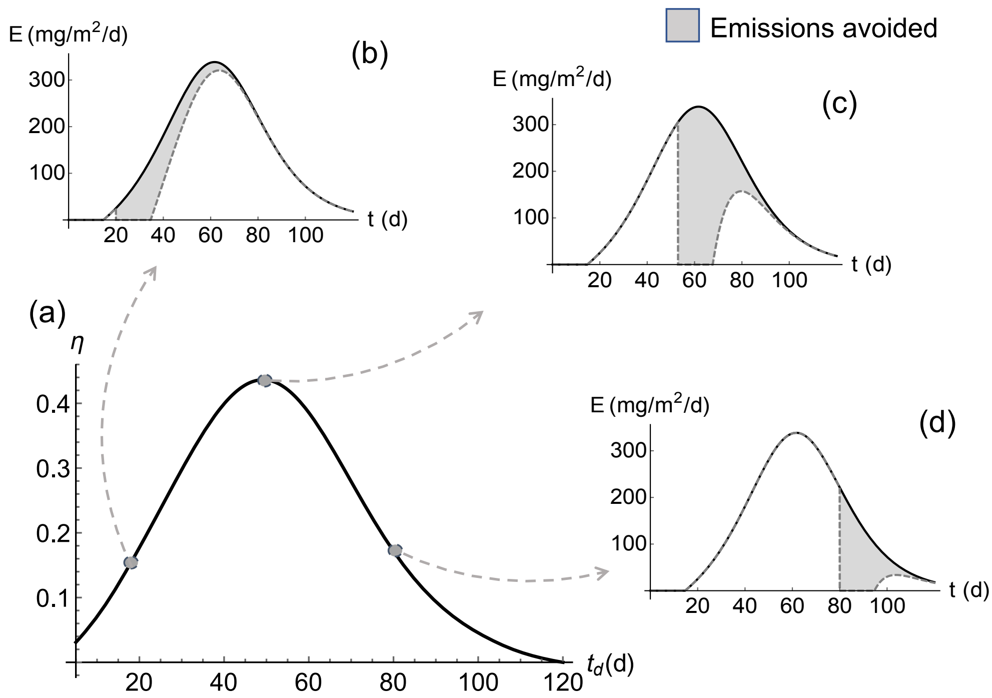

Figure 4. (a) Mitigation efficiency of the drainage, η, as a function of drainage timing, t_d. The insets show the time evolution of CH_4 emissions under continuous flooding (black line) and drainage (dashed gray line) regimes for early-season drainage (b), mid-season drainage (c), and late-season drainage (d).

$$\frac{d\eta}{dt_d} = 0, \tag{13}$$

and solving for t_d. This of course corresponds to finding the time of drainage that minimizes E_D^{TOT} (i.e., $dE_D^{TOT}/dt_d = 0$).

As can be seen in Figure 4(c), the optimal drainage timing, $\hat{t}_d$, is some time before methane emissions reach their maximum in the corresponding CF management. This guarantees that Eh is not favorable to methanogenesis when emissions would be at their peak. After the field is re-flooded and low Eh conditions are re-established (after an interval τ), methane emissions have already begun their decline and may no longer contribute significantly to total emissions.

This optimal timing therefore depends on the interplay between plant growth and redox potential, namely on the two parameters governing their dynamics: the speed at which the plant develops, r, and the Eh decay constant, k_{Eh}. The sooner the rice plant

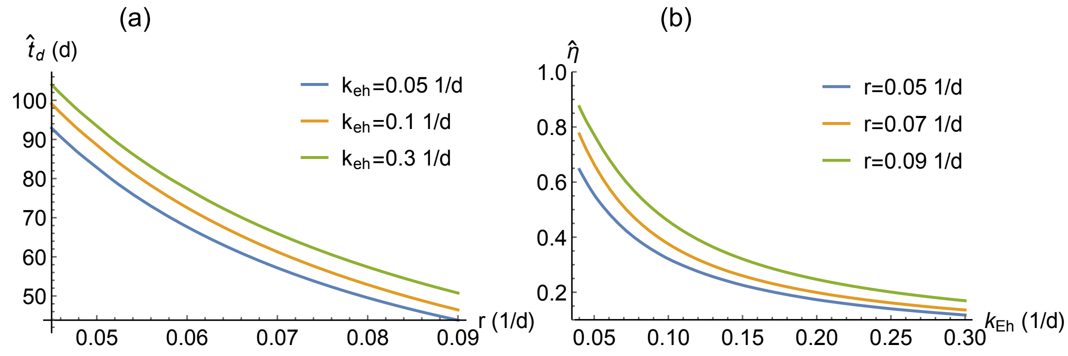

Figure 5. (a) Optimal timing, $\hat{t}_d$, as a function of rice growth parameter, r, for three different values of k_{Eh}. (b) Maximum mitigation efficiency, $\hat{\eta}$, as a function of k_{Eh}, for three values of r.

develops and the slower Eh decays, the earlier the field should be drained (Figure 5 (a)). The maximum mitigation efficiency achievable, $\hat{\eta}$, also depends on rice and soil characteristics. For instance, efficiencies in soils with high k_{Eh} tend to be low, because after re-flooding the soil quickly returns back to reducing conditions, decreasing the effect of the drainage. With respect to rice growth, higher efficiencies are achieved for cultivars with higher r, as this tends to concentrate the bulk of the emissions over a shorter period of time, so it is more likely that the effect of a drainage covers most of the emissions.

Because the use of organic amendments is increasing, it is important to understand and quantify their effects on CH_4 emissions, especially when combined with various water managements. Organic fertilizers (manure or rice straw) are in fact largely favored over chemical ones, because of their slower N release and because they promote soil health in the long term (Le Mer & Roger, 2001). Additionally, soil incorporation of rice straws is a common practice for their disposal, as opposed to burning them (Islam et al., 2018). As we have discussed above, organic amendment gives rise to seasonal pattern of CH_4 emissions characterized by two peaks (Figure 6(a)), originated by the decomposition of the incorporated organic matter and of the labile C released by plants, respectively. As a consequence, the dependence of the mitigation efficiency η on drainage timing also may characterized by two local maxima, corresponding to the two peaks of emissions (Figure 6(b)).

The optimal drainage timing, is determined by which of the two maxima prevails and is mainly controlled by the soil organic matter content. For small amounts, it is the

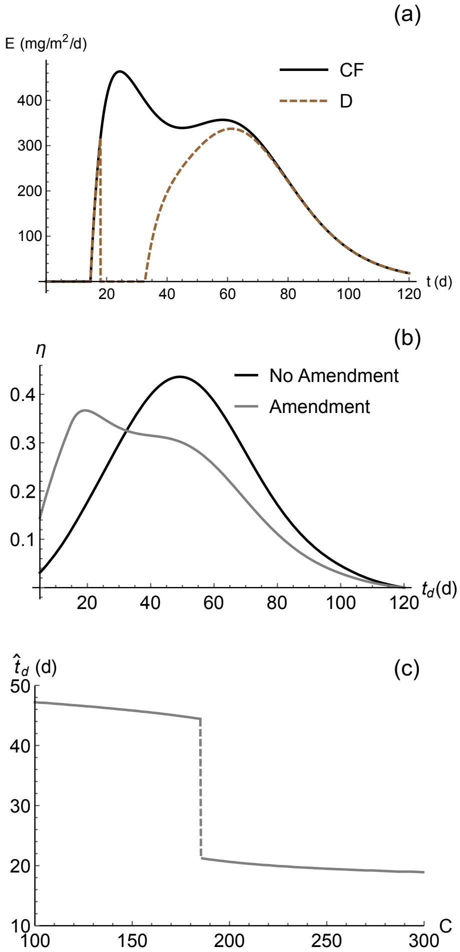

Figure 6. (a) CH_4 emissions with organic amendment under under continuous flooding (black line) and drainage (dashed brown line) regimes. (b) Comparison of mitigation efficiency of the drainage for rice field with and without organic amendment. (c) Optimal drainage timing as a function of the amount of incorporated organic matter.

rice growth which determines the seasonal pattern of emissions and, hence, the optimal drainage timing will be similar to the case of no organic amendment, although slightly earlier. In other words, it is more convenient to mitigate emissions from the carbon substrate released by the rice plant. On the contrary, for large C amount, the emissions originated by the soil organic matter are predominant. Therefore, it is more convenient to mitigate the first peak and the optimal timing will suddenly shift towards it (Figure 6(c)).

5 Case studies

As an application of the above results, we analyze the experiments conducted by Liao et al. (2020) and by Islam et al. (2018) aimed at comparing the role of different water managements on CH_4 emissions and rice yield. In the experiments by Liao et al. (2020) organic amendment was not included, whereas in the ones by Islam et al. (2018) 10 t/ha^{-1} of rice straws were incorporated. While various water managements were tested in the experiments, here we compare specifically the experiments conducted under a continuous flooding regime and with a single drainage. Full detailed about the experiments setups are provided in the corresponding references.

Table 1. Model parameters descriptions and values used in Figures 1 to 6, and case studies.

Symbol	Description	Units	Fig. 1-6*	No OM⋆	OM‡
		Rice growth			
r	Growth rate	d^{-1}	0.07	0.065	0.10
B_{max}	Intrinsic maximum biomass	g m^{-2}	780	1500	410
K_B	Related to initial biomass	-	88	150	50
		Redox potential			
Eh_{min}	Lower bound on Eh	mV	-250	-250	-250
$\tilde{Eh}$	Eh threshold for CH_4 production	mv	-100	-100	-100
k_{Eh}	Eh decay rate	d^{-1}	0.10	0.07	0.07
		Soil Organic Matter			
K_d	Decomposition rate constant	d^{-1}	0.15	-	0.15
C	Organic matter amended	t ha^{-1}	6	-	10
		Emission coefficients			
K_p	Emissions per unit biomass	mgCH_4 g^{-1} d^{-1}	24	0.8	58
K_s	Emissions per unit C content and biomass	mgCH_4 ha t^{-1} g^{-1} d^{-1}	$1 \cdot 10^3$	-	$12 \cdot 10^3$

*Values used in Figures 1 to 6.

⋆Values used for the experiment by Liao et al. (2020) with no organic amendment (section 5.1).

‡Values used for the experiment by Islam et al. (2018) with rice straw incorporation (section 5.2).

5.1 No organic amendment

Liao et al. (2020) conducted pot experiments in an open greenhouse at Huazhong University (Wuhan, China) with the rice variety Wuyou 308 planted in a silt loam soil. The experiments took place in 2018, from June 18th to September 21st, with a approximately constant air temperature of about 30 °C. The experiments were conducted with different levels of fertilizer application, but here we focus on the effect of water manage-

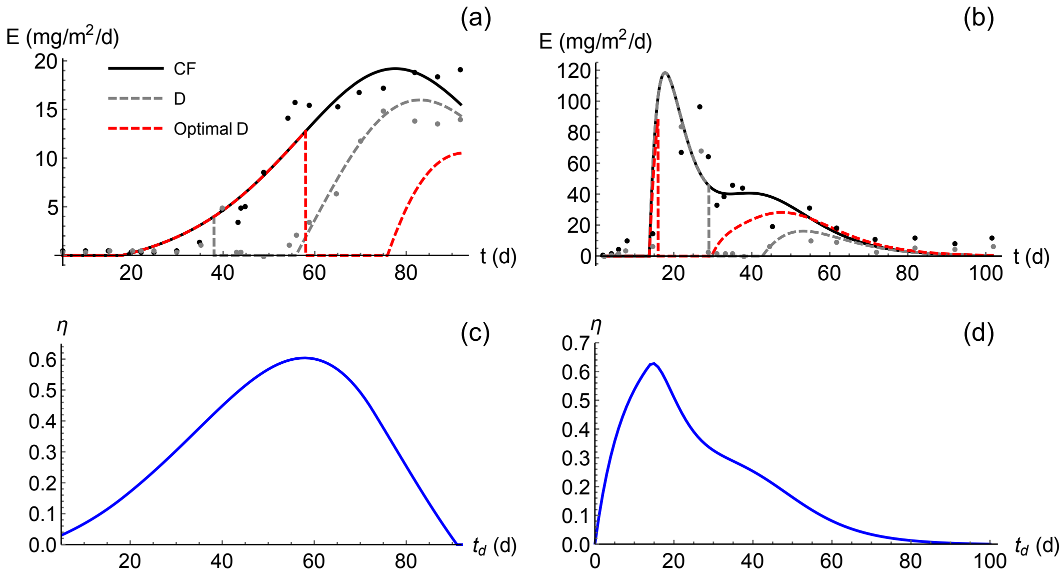

Figure 7. CH_4 emissions from experiments by (a) (Liao et al., 2020) and (b) (Islam et al., 2018). Dots and lines correspond to experimental and modeled emissions. Black refers to a continuous flooding regime, while gray refers to the emissions with a drainage. Dashed red line indicates CH_4 emissions with application of the drainage at optimal timing. The mitigation efficiencies for the case without and with organic amendment are shown in panels (c) and (d), respectively. The parameters for the model are reported in Table 1.

ment for a given N application (a total of 90 kgN/ha applied in three steps). Emissions were measured through a static chamber technique.

The evolution of CH_4 emissions for the two water managements (CF and D) is shown in Figure 7(a). For continuously flooded conditions, CH_4 emissions begin after approximately 20 days from the beginning of the experiment and then peak at about day 70 (20 mgCH_4/m^2/hr), after which they decline, as expected, until the end of the experiment at day 92. With a drainage at approximately day 37, the emissions follow a similar trajectory up to the drainage time, after which they are interrupted for about 20 days, corresponding to the time τ needed for the soil redox potential to cross again the threshold $\tilde{Eh}$. After the interruption, labile C by plants and gas conductance had started to decline, so CH_4 emissions remained limited until the end of the season.

Equation (10) captures well both dynamics, suggesting that the dominant processes driving CH_4 production and emission have been properly represented in the model. The total amount of CH_4 emitted under continuous flooding and with application of a drainage, calculated from equation (11), are 765 and 432 mgCH_4/m^2, respectively. The mitigation efficiency of the drainage thus is about 0.4.

From equation (12), one can explore the effect of a different drainage timing on the efficiency of drainage (Figure 7 (c)). The analysis reveals that the drainage was applied too early in the season, way before the peak of emissions, so that CH_4 emissions were interrupted when they were still low. The optimal drainage timing for this experimental and environmental conditions is in fact day 58, for which the total methane emitted is as low as 297 mgCH_4/m^2 and the efficiency is 0.62. Hence, for this rice cultivar, environmental conditions and soil properties, proper planning and application of the drainage at the optimal timing allows a further 20% reduction in total emissions throughout the season.

5.2 With organic amendment

Islam et al. (2018) conducted the experiments in a chamber from April to July in Copenhagen (Denmark) with daily temperatures fluctuating between 22 °C and 28 °C. Rice was planted in a sandy loam soil, in which rice straws had been incorporated (10 t/ha). Gas samples were collected during the experiment and analyzed using a gas chromatograph equipped with a flame ionisation detector.

CH_4 emissions are illustrated in Figure 7(b). In both continuous flooding conditions and with a drainage, emissions start as soon as at day 5 and peak at approximately day 20, with maximum rate of emissions approaching 3000 mgCH_4/m^2/hr. Compared to the no-amendment experiment above, the beginning of the emissions are significantly anticipated and a more than a 100-fold increase in the emissions rate is observed.

The amount of rice straw incorporated in the soil is such that the first peak, originated by organic matter incorporation, largely prevails over the emissions associated to the rice growth season. Therefore, an early drainage, targeting the early emissions, would be the most convenient choice, as discussed in Section 4. The drainage indeed was applied at approximately day 27, during the first peak of emissions. Emissions dropped to zero when the redox potential increased (above -100 mV) and started again after 10 days, producing a second peak at day 55. Overall, much more CH_4 was emitted than without organic amendment. Under continuous flooding total emissions amounted to $6{\cdot}10^4$

$mgCH_4/m^2$, whereas the season drainage at day 27, with an efficiency of 0.37, reduced the emissions to $3.8 \cdot 10^4$ $mgCH_4/m^2$.

The variation of the mitigation efficiency with respect to the drainage timing, shown in Figure 7(c), confirms that higher efficiencies are obtained for early drainage. However, the optimal drainage timing is day 15, namely 12 days earlier than it was applied in the experiment. From 0.37, the mitigation efficiency would go up to 0.62 and total emissions would reduce to $2.3 \cdot 10^4$ $mgCH_4/m^2$.

6 Conclusion

We introduced a mechanistic model of CH_4 emissions from rice paddies to investigate the effect of drainage timing on the mitigation efficiency of the drainage. The model, with only a few parameters that can be readily calibrated from experiments, was used to explore the time evolution of CH_4 emissions as affected by the employment or not of a single drainage, and provided the optimal drainage timing that maximizes the mitigation efficiency of the drainage. The framework was applied to a set of experiments that tested the effect of water management on CH_4 emissions from soils with and without organic amendments (rice straw) and showed that a strategically applied drainage could reduce emissions by more than 60%. These results highlight the need to carefully plan the application of the drainage to effectively reduce emissions.

There is a variety of models, with different assumptions and level of details in the description of the processes, that can be used to test management strategies (Walter & Heimann, 2000; Walter et al., 2001; Zhang et al., 2002; Huang et al., 2004; Riley et al., 2011). Our parsimonious model accounts for the critical factors determining the seasonal pattern of CH_4 emissions, thus we do not expect the addition of further details in the model to affect our main conclusions. The model developed here has the advantage of allowing simple analytical calculations, which come handy for theoretical analysis.

Here we focused on a single drainage and the effect of organic amendments. Alternate wetting and drying (AWD), consisting of cycles of flooding and drainage throughout the season, has been advanced as alternative strategy for reaching higher mitigation efficiencies and water savings (Adhya et al., 2014; Towprayoon et al., 2005; Jiao et al., 2006; Liao et al., 2020; Bouman & Tuong, 2001; Nelson et al., 2015). However, increased exposure to oxygen enhances N_2O emissions (Pandey et al., 2014) and unsaturated conditions may negatively affect rice yield (Bouman et al., 2005; Carrijo et al., 2017). In future investigations we will extend our analysis to other water managements (e.g., AWD) to quantify their overall effectiveness under given climate, rice cultivar, and available irrigation and drainage technology.

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References

Adhya, T. K., Linquist, B., Searchinger, T., Wassmann, R., & Yan, X. (2014). Wetting and drying: reducing greenhouse gas emissions and saving water from rice production. *Installment 8 of Creating a Sustainable Food Future*, 1–28.

Bhattacharyya, P., Dash, P., Swain, C., Padhy, S., Roy, K., Neogi, S., . . . others (2019). Mechanism of plant mediated methane emission in tropical lowland rice. *Science of The Total Environment*, *651*, 84–92.

Bouman, B., Peng, S., Castaneda, A., & Visperas, R. (2005). Yield and water use of irrigated tropical aerobic rice systems. *Agricultural Water Management*, *74*(2), 87–105.

Bouman, B., & Tuong, T. P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural water management*, *49*(1), 11–30.

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, *203*, 173–180.

Cassman, K. (2001). Crop science research to assure food security. *Crop Science: Progress and Prospects. CAB International, Wallingford, UK*, 33–51.

Chidthaisong, A., & Watanabe, I. (1997). Methane formation and emission from flooded rice soil incorporated with 13c-labeled rice straw. *Soil Biology and Bio-*

chemistry, *29*(8), 1173–1181.

Das, K., & Baruah, K. (2008). A comparison of growth and photosynthetic characteristics of two improved rice cultivars on methane emission from rainfed agroecosystem of northeast india. *Agriculture, ecosystems & environment*, *124*(1-2), 105–113.

Dlugokencky, E. J., Nisbet, E. G., Fisher, R., & Lowry, D. (2011). Global atmospheric methane: budget, changes and dangers. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *369*(1943), 2058–2072.

Gutierrez, J., Kim, S. Y., & Kim, P. J. (2013). Effect of rice cultivar on ch4 emissions and productivity in korean paddy soil. *Field Crops Research*, *146*, 16–24.

Huang, Y., Sass, R. L., & Fisher, F. M., Jr. (1998). A semi-empirical model of methane emission from flooded rice paddy soils. *Global Change Biology*, *4*(3), 247–268.

Huang, Y., Zhang, W., Zheng, X., Li, J., & Yu, Y. (2004). Modeling methane emission from rice paddies with various agricultural practices. *Journal of Geophysical Research: Atmospheres*, *109*(D8).

IPCC. (2007). Climate change 2007: synthesis report. *Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change*, 95–212.

Islam, S. F.-u., Van Groenigen, J. W., Jensen, L. S., Sander, B. O., & de Neergaard, A. (2018). The effective mitigation of greenhouse gas emissions from rice paddies without compromising yield by early-season drainage. *Science of the Total Environment*, *612*, 1329–1339.

Jiao, Z., Hou, A., Shi, Y., Huang, G., Wang, Y., & Chen, X. (2006). Water management influencing methane and nitrous oxide emissions from rice field in relation to soil redox and microbial community. *Communications in Soil Science and Plant Analysis*, *37*(13-14), 1889–1903.

Khalil, M., Rasmussen, R., Shearer, M. J., Dalluge, R., Ren, L., & Duan, C.-L. (1998). Factors affecting methane emissions from rice fields. *Journal of Geophysical Research: Atmospheres*, *103*(D19), 25219–25231.

Kim, J., Verma, S. B., & Billesbach, D. P. (1999). Seasonal variation in methane emission from a temperate phragmites-dominated marsh: Effect of growth stage and plant-mediated transport. *Global Change Biology*, *5*(4), 433–440.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., ... others (2013). Three decades of global methane sources and sinks. *Nature geoscience*, *6*(10), 813.

Kludze, H., DeLaune, R., & Patrick, W. (1993). Aerenchyma formation and methane and oxygen exchange in rice. *Soil Science Society of America Journal*, *57*(2), 386–391.

LaRowe, D. E., & Van Cappellen, P. (2011). Degradation of natural organic matter: a thermodynamic analysis. *Geochimica et Cosmochimica Acta*, *75*(8), 2030–2042.

Le Mer, J., & Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: a review. *European Journal of Soil Biology*, *37*(1), 25–50.

Liao, B., Wu, X., Yu, Y., Luo, S., Hu, R., & Lu, G. (2020). Effects of mild alternate wetting and drying irrigation and mid-season drainage on ch4 and n2o emissions in rice cultivation. *Science of The Total Environment*, *698*, 134212.

Meinshausen, M., Vogel, E., Nauels, A., Lorbacher, K., Meinshausen, N., Etheridge, D. M., ... others (2017). Historical greenhouse gas concentrations for climate modelling (cmip6). *Geoscientific Model Development*, *10*, 2057–2116.

Nelson, A., Wassmann, R., Sander, B. O., & Palao, L. K. (2015). Climate-determined suitability of the water saving technology" alternate wetting and drying" in rice systems: a scalable methodology demonstrated for a province in the philippines. *PloS one*, *10*(12), e0145268.

Neue, H. U. (1993). Methane emission from rice fields. *Bioscience*, *43*(7), 466–474.

Neue, H. U., Wassmann, R., Kludze, H., Bujun, W., & Lantin, R. (1997). Factors and processes controlling methane emissions from rice fields. *Nutrient Cycling in Agroecosystems*, *49*(1-3), 111–117.

Nouchi, I., Hosono, T., Aoki, K., & Minami, K. (1994). Seasonal variation in methane flux from rice paddies associated with methane concentration in soil water, rice biomass and temperature, and its modelling. *Plant and soil*, *161*(2), 195–208.

Pandey, A., Vu, D. Q., Bui, T. P. L., Mai, T. L. A., Jensen, L. S., de Neergaard, A., et al. (2014). Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in vietnam. *Agriculture, ecosystems & environment*, *196*, 137–146.

Purvaja, R., Ramesh, R., & Frenzel, P. (2004). Plant-mediated methane emission from an indian mangrove. *Global change biology*, *10*(11), 1825–1834.

Riley, W., Subin, Z., Lawrence, D., Swenson, S., Torn, M., Meng, L., … Hess, P. (2011). Barriers to predicting changes in global terrestrial methane fluxes: analyses using clm4me, a methane biogeochemistry model integrated in cesm. *Biogeosciences*, *8*(7), 1925.

Sass, R., Fisher, F., Harcombe, P., & Turner, F. (1991). Mitigation of methane emissions from rice fields: Possible adverse effects of incorporated rice straw. *Global Biogeochemical Cycles*, *5*(3), 275–287.

Sass, R., Fisher, F., Wang, Y., Turner, F., & Jund, M. (1992). Methane emission from rice fields: the effect of floodwater management. *Global Biogeochemical Cycles*, *6*(3), 249–262.

Schütz, H., Seiler, W., & Conrad, R. (1990). Influence of soil temperature on methane emission from rice paddy fields. *Biogeochemistry*, *11*(2), 77–95.

Singh, S., Singh, J., & Kashyap, A. (1999). Methane flux from irrigated rice fields in relation to crop growth and n-fertilization. *Soil Biology and Biochemistry*, *31*(9), 1219–1228.

Sinha, S. K. (1995). Global methane emission from rice paddies: Excellent methodology but poor extrapolation. *Current Science*, 643–646.

Stumm, W., & Morgan, J. J. (2012). *Aquatic chemistry: chemical equilibria and rates in natural waters* (Vol. 126). John Wiley & Sons.

Tariq, A., Jensen, L. S., de Tourdonnet, S., Sander, B. O., & de Neergaard, A. (2017). Early drainage mitigates methane and nitrous oxide emissions from organically amended paddy soils. *Geoderma*, *304*, 49–58.

Tian, H., Lu, C., Ciais, P., Michalak, A. M., Canadell, J. G., Saikawa, E., … others (2016). The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature*, *531*(7593), 225–228.

Towprayoon, S., Smakgahn, K., & Poonkaew, S. (2005). Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. *Chemosphere*, *59*(11), 1547–1556.

Walter, B. P., & Heimann, M. (2000). A process-based, climate-sensitive model to derive methane emissions from natural wetlands: Application to five wetland sites, sensitivity to model parameters, and climate. *Global Biogeochemical Cycles*, *14*(3), 745–765.

Walter, B. P., Heimann, M., & Matthews, E. (2001). Modeling modern methane emissions from natural wetlands: 1. model description and results. *Journal of Geophysical Research: Atmospheres*, *106*(D24), 34189–34206.

Wang, Z., Delaune, R., Patrick, W., & Masscheleyn, P. (1993). Soil redox and ph effects on methane production in a flooded rice soil. *Soil Science Society of America Journal*, *57*(2), 382–385.

Yagi, K., Tsuruta, H., Kanda, K.-i., & Minami, K. (1996). Effect of water management on methane emission from a japanese rice paddy field: Automated methane monitoring. *Global Biogeochemical Cycles*, *10*(2), 255–267.

Yao, H., Jingyan, J., Lianggang, Z., Sass, R. L., & Fisher, F. M. (2001). Comparison of field measurements of ch 4 emission from rice cultivation in nanjing, china and in texas, usa. *Advances in Atmospheric Sciences*, *18*(6), 1121–1130.

Zhang, Y., Li, C., Trettin, C. C., Li, H., & Sun, G. (2002). An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems. *Global Biogeochemical Cycles*, *16*(4), 9–1.

Zou, J., Huang, Y., Jiang, J., Zheng, X., & Sass, R. L. (2005). A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in china: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochemical Cycles*, *19*(2).