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

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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 N0 emissions place this water management among the most sustainable ones.

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9 Key Points:

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10	•	The drainage timing maximizing the mitigation efficiency of the drainage is cal-
11		culated.
12	•	Applying the drainage at optimal timing may reduce emissions by more than 60% .
13	•	Optimal drainage timing shifts from mid-season to early-season when added or-

ganic matter crosses a given threshold.

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15 Abstract

Rice fields are important contributors to the global methane budget. While rice 16 production must increase to meet the demand from a growing population, there is a need 17 to mitigate methane emissions through the employment of sustainable management strate-18 gies. A popular one consists of a short drainage that shortens the period of time spent 19 in anaerobic conditions, but it is still unclear how drainage timing affects its overall ef-20 fectiveness. Here we introduce a mechanistic model of methane emissions, coupled to the 21 dynamics of redox potential and rice growth, to analyze the effect of a single drainage 22 and the timing of its application on the temporal evolution of methane emissions. In par-23 ticular, we identify the drainage timing that maximizes the mitigation efficiency of the 24 drainage, defined as the reduction in methane emission relative to the emissions in con-25 tinuous flooding. We also explore the role of organic amendment and show how it changes 26 the optimal drainage timing. Application of this framework to a set of experiments demon-27 strates that emissions can be reduced by more than 60% if drainage is applied at opti-28 mal timing. The high efficiency and the limited negative effects on rice yields and N_2O 29 emissions place this water management among the most sustainable ones. 30

31 1 Introduction

Rice paddies are among the major sources of methane (CH_4) , contributing up to 32 20% to global emissions (IPCC, 2007; Kirschke et al., 2013; Meinshausen et al., 2017). 33 As the global demand for rice production increases with the growing population (Cassman, 34 2001) and the higher atmospheric CH₄ concentration rises concerns for the global warm-35 ing (Dlugokencky et al., 2011; Tian et al., 2016), effective management strategies need 36 to be designed for mitigating CH_4 emissions while maintaining high rice yields (Islam 37 et al., 2018). In this context, it is necessary to use experimental studies in concert with 38 theoretical analysis for testing different management strategies aimed at minimizing wa-39 ter use and greenhouse gas emissions, and maximizing rice yield. 40

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 CH₄ 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 50 the period of time under anaerobic conditions, by draining the field for a short interval 51 during the growing season (Sass et al., 1992). The sudden exposure to air causes most 52 of the CH_4 in the soil to be oxidized and increases the redox potential to levels that pre-53 vent methanogenesis. If the field is re-flooded before the soil moisture level drops below 54 a critical level for the rice, the yield remains mostly unaffected. Alternative strategies, 55 such as alternate wetting and drying combined with various fertilizer applications, have 56 been proposed to further reduce CH_4 emissions (Huang et al., 2004; Jiao et al., 2006; Car-57 rijo et al., 2017; Islam et al., 2018; Liao et al., 2020). Their effectiveness however is not 58 clear yet, as negative effects have been reported (e.g., OM losses, increased N_2O emis-59 sions, decreased rice yield). Thus, while current studies attempt to develop a portfolio 60 of available strategies to comprehensively improve the sustainability of rice cultivations, 61 a single drainage probably remains, at the moment, the most reliable strategy to mit-62 igate CH₄ emissions without impacting rice yield. 63

Previous experimental studies have explored the effect of drainage on reducing CH_4 64 emission to improve its implementation. These studies have provided useful insight into 65 the relation between CH₄ production and emission and plant growth (Das & Baruah, 66 2008; Bhattacharyya et al., 2019), the effects of environmental conditions, such as tem-67 perature and redox potential (Wang et al., 1993; Khalil et al., 1998; Yao et al., 2001; Jiao 68 et al., 2006), and of soil amendments (Zou et al., 2005; Tariq et al., 2017; Liao et al., 2020). 69 Yet, these results can be complemented by theoretical studies that allow to readily ex-70 plore how multiple factors simultaneously affect CH₄ emission and to quantitatively in-71 vestigate the coupling between water balance, plant growth, and biogeochemistry un-72 der different water management strategies. 73

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 expres-

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sion for CH_4 emissions that takes into account the role of plants, soil redox potential, 78 and organic amendments (Sec. 2). After showing that the model captures the general 79 CH_4 emissions dynamics from rice fields (Sec. 3), we introduce the mitigation efficiency 80 of the drainage and derive the optimal drainage timing as a function of a few parame-81 ters readily obtained from field measurements (Sec. 4). The results are applied to a set 82 of experiments, with and without organic amendment, to highlight the potential reduc-83 tion achievable with optimal drainage timing (Sec. 5). We conclude with a summary of 84 the key results (Sec. 6). 85

86 2 Theory

The time evolution of CH₄ emissions from a rice field results from the interaction 87 between soil biogeochemical processes (Neue et al., 1997; Le Mer & Roger, 2001), involv-88 ing methanogens and a suitable organic substrate, rice cultivar and development stage 89 (Singh et al., 1999; Gutierrez et al., 2013), water management practices (Yagi et al., 1996) 90 (mid-season drainage, intermittent irrigation), and application of fertilizers (Zou et al., 91 2005). Here we develop a mechanistic model of CH_4 emissions, accounting for the vari-92 ability in soil redox potential, the availability of labile carbon (C), plan growth, and wa-93 ter management, which will be used to investigate the effect of timing of a single drainage 94 application on total CH₄ emissions. 95

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2.1 Soil redox dynamics

Methanogenesis, the bio-production of CH_4 by methanogens, requires very low soil 97 redox potential to occur, at least Eh < -100 mV (Wang et al., 1993; Jiao et al., 2006). 98 From the beginning of soil submersion, some time elapses before available electron ac-99 ceptors are utilized to decompose labile C and soil redox conditions become favorable 100 to methanogenesis (LaRowe & Van Cappellen, 2011; Stumm & Morgan, 2012). The soil 101 redox potential hence is a fundamental variable determining both when methanogene-102 sis begins and its temporal evolution during the rice growing season, and it is crucial to 103 model its dynamics, especially given the fact that Eh measurements are not always avail-104 able. 105

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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} ($\tilde{Eh} = -100 \text{ mV}$). 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,

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

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

¹¹⁹ 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 CH₄ before it can reach the atmosphere (Sass et al., 1992; Huang et al., 2004). All these factors will affect CH₄ production, oxidation and emission (see section 2.3).

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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 inhibi-
- tion of methanogenesis at $Eh > \tilde{Eh}$, and g(B) is a factor accounting for both the de-
- cline in gas transport through roots and aerenchyma, due to plant aging, and the increase
- in CH₄ oxidation (section 2.2). Specifically, the factor f is calculated as

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

where we recall that Eh_{min} is the lower bound for soil Eh. The factor g is a decreas-

¹⁴⁹ ing 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 CH₄ 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 CH₄ 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
- $_{160}$ C decomposition to CH₄ emissions. Assuming that organic matter is decomposed ac-
- cording 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, respec-
- 163 tively. It follows that I_C can be expressed as

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

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

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

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

$$E^{TOT} = \int_0^T E(t)dt = \int_0^T f(Eh) \cdot g(B) \cdot B(t) \cdot (K_p + K'_C e^{-k_d t})dt,$$
(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., $E^{TOT} = \int_0^T E(t)dt = \int_{\tau}^{t_d} E(t)dt + \int_{t_d+\tau}^T E(t)dt$.

¹⁷³ 3 Seasonal CH₄ emissions: the role of drainage

Prior to using the model developed above to optimize the drainage timing, we show 174 that it captures the typical seasonal dynamics observed in rice fields. Equation (10) in-175 deed reproduces the observed general pattern of CH_4 emissions (Neue et al., 1997; Le Mer 176 & Roger, 2001). In continuously flooded conditions and without organic amendment, the 177 temporal evolution of CH_4 emissions closely resembles the development stage of rice (Fig-178 ure 2). After the interval of time needed for the redox potential to reach reducing con-179 ditions, emissions increase as the plant grows and reach their peak at the rice flowering 180 stage, after which they are negatively affected by the decline of plant photosynthetic ac-181 tivity, aerenchyma gas transport, and by higher CH₄ oxidation. 182

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.

¹⁸⁷ poral pattern discussed above (Figure 2). First, the additional labile C available read-¹⁸⁸ ily increases overall CH₄ emissions. Second, because this substrate is available to methanogens ¹⁸⁹ before plant begins realising labile C, emissions peak as soon as the soil redox potential ¹⁹⁰ becomes favorable, i.e, a time τ after flooding. A second peak in CH₄ emissions, from ¹⁹¹ 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 192 a drainage. As the soil is drained and oxygen quickly penetrates the soil, CH_4 oxidation 193 by methanotrophs (i.e., methane oxidizing bacteria) becomes largely favored over pro-194 duction by methanogens. The redox potential increases to values typical of aerated con-195 ditions and, in turn, methanogenesis stops. After re-flooding, CH₄ production and emis-196 sion initiate again only after low Eh conditions are reestablished, i.e., after another in-197 terval τ (see Figure 3). The mid-season drainage hence decreases the total amount of 198 CH_4 emitted throughout the season by reducing the time spent under favorable low re-199 dox potentials. A factor that was not explicitly included in our analysis is the negative 200 effect of the drainage on the development of the aerenchyma, which may lead to reduced 201 transport to the atmosphere (Kludze et al., 1993). This factor may result in a further 202 decrease in total CH_4 emissions. 203

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

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Figure 3. (a) Dynamics of redox potential Eh as affected by water management, continuous flooding and mid-season drainage. (b) CH₄ 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 CH₄ 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)).

²¹³ 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,

$$\eta(t_d) = \frac{E_{CF}^{TOT} - E_D^{TOT}(t_d)}{E_{CF}^{TOT}},$$
(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 CH₄ 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 241 and quantify their effects on CH_4 emissions, especially when combined with various wa-242 ter managements. Organic fertilizers (manure or rice straw) are in fact largely favored 243 over chemical ones, because of their slower N release and because they promote soil health 244 in the long term (Le Mer & Roger, 2001). Additionally, soil incorporation of rice straws 245 is a common practice for their disposal, as opposed to burning them (Islam et al., 2018). 246 As we have discussed above, organic amendment gives rise to seasonal pattern of CH_4 247 emissions characterized by two peaks (Figure 6(a)), originated by the decomposition of 248 the incorporated organic matter and of the labile C released by plants, respectively. As 249 a consequence, the dependence of the mitigation efficiency η on drainage timing also may 250 characterized by two local maxima, corresponding to the two peaks of emissions (Fig-251 ure 6(b)). 252

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

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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)).

²⁶¹ 5 Case studies

As an application of the above results, we analyze the experiments conducted by 262 Liao et al. (2020) and by Islam et al. (2018) aimed at comparing the role of different wa-263 ter managements on CH_4 emissions and rice yield. In the experiments by Liao et al. (2020) 264 organic amendment was not included, whereas in the ones by Islam et al. (2018) 10 t/ha⁻¹ 265 of rice straws were incorporated. While various water managements were tested in the 266 experiments, here we compare specifically the experiments conducted under a contin-267 uous flooding regime and with a single drainage. Full detailed about the experiments se-268 tups are provided in the corresponding references. 269

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

Symbol	Description	Units	Fig. 1-6*	No OM^{\star}	OM^{\ddagger}
	Rice	e growth			
r	Growth rate	d^{-1}	0.07	0.065	0.10
B_{max}	Intrinsic maximum biomass	${\rm g}~{\rm m}^{-2}$	780	1500	410
K_B	Related to initial biomass	-	88	150	50
	Redox	c 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 Org	anic 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	$\rm mgCH_4~g^{-1}~d^{-1}$	24	0.8	58
K_s	Emissions per unit C content and biomass	$\rm mgCH_4$ ha $\rm t^{-1}~g^{-1}~d^{-1}$	$1\cdot 10^3$	-	$12\cdot 10^3$

*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).

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5.1 No organic amendment

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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. CH₄ 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 278 in Figure 7(a). For continuously flooded conditions, CH_4 emissions begin after approx-279 imately 20 days from the beginning of the experiment and then peak at about day 70 280 $(20 \text{ mgCH}_4/\text{m}^2/\text{hr})$, after which they decline, as expected, until the end of the exper-281 iment at day 92. With a drainage at approximately day 37, the emissions follow a sim-282 ilar trajectory up to the drainage time, after which they are interrupted for about 20 days, 283 corresponding to the time τ needed for the soil redox potential to cross again the thresh-284 old Eh. After the interruption, labile C by plants and gas conductance had started to 285 decline, so CH₄ emissions remained limited until the end of the season. 286

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

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total amount of CH_4 emitted under continuous flooding and with application of a drainage, calculated from equation (11), are 765 and 432 mg CH_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 292 efficiency of drainage (Figure 7 (c)). The analysis reveals that the drainage was applied 293 too early in the season, way before the peak of emissions, so that CH_4 emissions were 294 interrupted when they were still low. The optimal drainage timing for this experimen-295 tal and environmental conditions is in fact day 58, for which the total methane emitted 296 is as low as 297 mgCH₄/m² and the efficiency is 0.62. Hence, for this rice cultivar, en-297 vironmental conditions and soil properties, proper planning and application of the drainage 298 at the optimal timing allows a further 20% reduction in total emissions throughout the 299 season. 300

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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.

 $_{307}$ CH₄ 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 mgCH₄/m²/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, orig-312 inated by organic matter incorporation, largely prevails over the emissions associated to 313 the rice growth season. Therefore, an early drainage, targeting the early emissions, would 314 be the most convenient choice, as discussed in Section 4. The drainage indeed was ap-315 plied at approximately day 27, during the first peak of emissions. Emissions dropped to 316 zero when the redox potential increased (above -100 mV) and started again after 10 days, 317 producing a second peak at day 55. Overall, much more CH₄ was emitted than with-318 out organic amendment. Under continuous flooding total emissions amounted to $6 \cdot 10^4$ 319

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 $mgCH_4/m^2$, 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 $2.3 \cdot 10^4 \text{ mgCH}_4/\text{m}^2$.

327 6 Conclusion

We introduced a mechanistic model of CH_4 emissions from rice paddies to inves-328 tigate the effect of drainage timing on the mitigation efficiency of the drainage. The model, 329 with only a few parameters that can be readily calibrated from experiments, was used 330 to explore the time evolution of CH_4 emissions as affected by the employment or not of 331 a single drainage, and provided the optimal drainage timing that maximizes the miti-332 gation efficiency of the drainage. The framework was applied to a set of experiments that 333 tested the effect of water management on CH_4 emissions from soils with and without or-334 ganic amendments (rice straw) and showed that a strategically applied drainage could 335 reduce emissions by more than 60%. These results highlight the need to carefully plan 336 the application of the drainage to effectively reduce emissions. 337

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 N₂O emissions (Pandey et al., 2014) and unsaturated con-

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ditions 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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