EXTENDED METHANE MITIGATION CAPACITY OF A MID-SEASON DRAINAGE BEYOND THE RICE GROWING SEASON: A CASE IN SPAIN

Martínez-Eixarch M.[1]*, Manuel Beltrán-Miralles[2], Sébastien Guéry[3], Carles Alcaraz[1]

1 IRTA - Institute of Agrifood Research and Technology, Marine and Continental Waters Program,43540 Sant Carles de la Ràpita, Catalonia (Spain)

2 Gabinete de Iniciativas Europeas, S.A. C/ Arquitectura 5, planta 4, módulo 2, 41015, Sevilla (Spain).

3 Optimización de Riegos y Agronomía, S.L.U. C/ Arquitectura 5, planta 4, módulo 2, 41015, Sevilla (Spain).

*Corresponding author: maite.martinezeixarch@irta.cat

ORCID:

Maite Martínez-Eixarch: 0000-0002-7352-8522

Carles Alcaraz: 0000-0002-2147-4796

Acknowledgements

This work has been supported and funded by Mars Food, Herba Ricemills (Ebro Foods) and Danone Specialized Nutrition in the frame of the ORYZONTE project.

The authors acknowledge the support of the CERCA Programme / Generalitat de Catalunya. The technical support of the rice growing company Instituto Hispánico del Arroz S.A. (HISPARROZ) is also acknowledged.

ABSTRACT

Rice cultivation is a major source of methane (CH_4) emissions. Intermittent irrigation systems in rice cultivation, such as the mid-season drainage (MSD), are effective strategies to mitigate CH_4 emissions during the growing season, though reduction rates are variable and dependent on the crop context. Aeration periods induce alteration of soil CH_4 dynamics that can be prolonged after flooding recovery. However, whether these changes persist beyond the growing season remains underexplored.

A field experiment was conducted in Spain to study the effect of MSD implemented during the rice growing season on greenhouse gas (GHG) emissions in relation to the standard permanently flooded water management (PFL). Specifically, the study aimed at 1) assessing the CH_4 mitigation capacity of MSD in the studied area, and 2) testing the hypothesis that the mitigating effect of MSD can be extended into the following winter flooded fallow season. Year-round GHG sampling was conducted, seasonal and annual cumulative emissions of CH_4 and N_2O as well as the global warming potential were calculated, and grain yield measured. MSD reduced growing season CH_4 emissions by *ca.* 80% without yield penalties. During the flooded fallow season, MSD reduced CH_4 emissions by *ca.* 60%, despite both fields being permanently flooded. The novelty of our observations lies in the amplified mitigation capacity of MSD by extending the CH_4 mitigation effect to the following flooded winter fallow season. This finding becomes especially relevant in rice systems with flooded winter fallow season given the large contribution of this season to the annual CH_4 emissions.

Key words: greenhouse gas emission; paddy rice; water management; intermittent irrigation; mitigation measure; winter fallow

Introduction

Paddy rice cultivation is one of the main sources of agricultural CH_4 emissions (Saunois et al., 2016) being water management a key driver of greenhouse gas (GHG) emissions. Irrigation systems based on a single or multiple drying periods, such as the mid-season drainage (MSD) or the alternate wetting and drying system (AWD), are effective water saving measures to face the projected water scarcity (Javadinejad et al., 2021) that can also effectively reduce CH_4 emissions and the global warming potential (GWP) during the rice growing season (Carrijo et al., 2017; Liu et al., 2019; Martínez-Eixarch et al., 2021a).

In a previous study in Spain, the implementation of AWD during the vegetative growth stage of rice (Martínez-Eixarch et al., 2021a) significantly reduced CH_4 emissions not only during the aeration periods but also after flooding recovery in the subsequent reproductive and maturity stages. Such a prolonged interruption of the CH_4 emissions beyond AWD implementation, suggested, firstly, a prolonged lag phase of methanogenesis (Linquist et al., 2015) persisting after flooding recovery; and secondly, that aeration periods could have altered the structure and functioning of methanogenic communities, as already reported in rice (Ji et al., 2015; Reim et al., 2017) and lake sediments (Conrad et al., 2014). The interruption of CH_4 emission after flooding recovery has only been reported within the same growing season while few studies have examined whether it could persist in the subsequent post-harvest season. If this happened this way, the mitigation capacity of water-saving irrigation practices could be boosted at no grain yield cost. To our knowledge, there is only one single study assessing this response (LaHue et al., 2016) which concluded in a lack of effect.

We conducted a one-year field experiment in a rice growing area in Southern Spain, aiming at 1) assessing the mitigation capacity of a mid-season drainage on both seasonal and annual CH_4 emissions, and 2) testing the hypothesis that the mitigating effect of MSD implemented in the growing season can be extended to the following winter flooded fallow season.

Material and methods

A field experiment was conducted covering the whole rice cropping period, including the growing (June to October 2019) and fallow (October 2019 to June 2020) seasons. The fallow season included a flooded (October to January) and an unflooded (January to May) period. Two adjacent commercial rice fields of 1.2 ha each were selected to study two water treatments: 1) control (permanently flooded over the growing and fallow seasons, PFL) and 2) mid-season drainage implemented in the growing season and fallow season with permanent flooding from October to January (MSD). PFL represented the standard water management, and it included a short aeration period early in the growing season of 2 days in which water table dropped to –15 cm. MSD consisted of a drainage period in the vegetative stage of approximately 4.5 days, in which the water level dropped to – 28.7 ± 0.01 cm, and then the flooding was recovered. Thereafter, during the ripening stage, the MSD field was emptied with the objective of implementing a second aeration period prior to harvest to let the water table drop at ca. – 15 cm; however, the rainfalls only allowed water layer to drop from 15.3 ± 0.01 cm to 0 ± 0.01 cm (Table 1). Apart from these two drying periods, water level was maintained at 5 to 10 cm over the vegetative and reproductive stages in both MSD and PFL fields. In the winter fallow season, both PFL and MSD fields remained flooded from harvest until January 15th (flooded fallow season). Thereafter, the irrigation was cut, and both fields were left to progressively drain (unflooded fallow season). Crop management in the two fields were the same and it was based on the standard practices in the area (Table 1). In each field, three different subplots of 154 x 7.5 m were harvested separately. The harvest and grain moisture in each of them was measured to calculate grain yield at 14 % of moisture (kg of paddy rice ha^{-1}).

Water level was continuously monitored with sensors (Meter Hydros 21 and Entelechy EnviroPro EP100G-08 in MSD and PFL plots, respectively PFL).

Greenhouse gas (GHG) emissions were monitored using static gas chambers on a weekly or bi-weekly basis during flooded periods and every two days during draining periods. Gas sampling was consistently conducted from 10 am to 2 pm to avoid diurnal variations of emissions and in clear sunny days, thus avoiding cloudy, rainy, or windy days. Three floating chambers per treatment were installed and removed every sampling day. Chambers were equipped with two ports for the insertion of a thermometer, to monitor headspace temperature, and a syringe for gas extraction. The basis of the chamber structure was covered by removable foam for its buoyancy on the flooded rice fields, in order to avoid both soil disturbance and gas exchange between the headspace and the exterior. When the fields were dry, foams were removed and chambers were carefully placed on the soil, with humid towels around the base to prevent gas exchange. Wooden boards were used to access the chamber without disturbing the soil. In each sampling event, chambers were installed in the field for 30 minutes and 4 gas samples were extracted every 10 minutes. Each gas sample was transferred to an overpressured 12.5 mL vial.

Concentrations of GHG were measured by gas chromatography (FID, Trace GC 2000, Thermo Finnigan, Germany). Gas concentration of each sample was corrected by temperature measured in the headspace of the chamber according to the ideal gas law. The emission rates in each chamber was calculated from the slope of the linear regression between gas concentration and the time interval of sampling. Only linear regressions with $R^2>0.70$ were accepted. Cumulative GHG emissions between two consecutive sampling events were calculated assuming constant emission rates between them and then, they were all summed to calculate the seasonal cumulative CH_4 and N_2O emissions. Global warming potential was calculated summing the warming effect of CH_4 and N_2O, which is 28 and 268 times higher than that of CO_2 (IPCC, 2013), respectively, and given in CO_2-equivalent units. Further details on GHG sampling, concentration analyses, calculations of the emission rates and the seasonal and annual cumulative emissions are referred in Martínez-Eixarch et al. (2018). The effect of water treatment on emission rates, cumulative seasonal and annual GHG emissions and the GWP was tested with ANOVA. Statistical analyses were run with SPSS statistics software (IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY: IBM Corp).

Results and discussion

Methane emissions under PFL, i.e., the standard water management (Table 2), were lower than those previously reported in Spain in the growing season (Seiler et al., 1983; Martínez-Eixarch et al., 2018) and during the whole annual rice cropping cycle (Martínez-Eixarch et al., 2021b). The lower emissions herein reported could be explained by the larger clay and sulphate soil content (Table 1) since both factors are negatively related to CH_4 emissions (Brye et al., 2016; Martínez-Eixarch et al., 2021).

In the growing season (Fig. 1), MSD significantly ($F_{1,8.2}$, $P < 0.05$) reduced cumulative CH_4 emissions by 80 % (Table 2) without any effect on grain yield ($\mu \pm SE = 10.4 \pm 2.9$ T ha^{-1} and 10.2 ± 5.1 T ha^{-1}, in MSD and PFL, respectively). Emissions rates of CH_4 in MSD were interrupted after the first drainage and remained low thereafter, resulting in significant ($F_{1,13.1}$, $P < 0.05$) lower mean rates (0.11 ± 0.03 mg CH_4 m^{-2} h^{-1} vs. 0. 50 ± 0.11 mg CH_4 m^{-2} h^{-1}). It is worthy to remark the substantial reduction observed, which is comparable to that observed in another rice growing area in Spain (Martínez-Eixarch et al. (2021a). Such a large reduction is placed in the uppermost range of reductions induced by intermittent irrigation systems with minimum yield losses reviewed by Carrijo et al. (2017) and Liu et al. (2019).

In the winter flooded fallow season (Fig. 1), CH_4 emission rates followed the same temporal pattern in both treatments but they were significantly lower ($F_{1,5.6}$, $P < 0.05$) in MSD throughout the flooded period (1.46 ± 0.70 mg CH_4 m^{-2} h^{-1} vs. 4.07 ± 1.05 mg CH_4 m^{-2} h^{-1}). As a result of this, cumulative CH_4 emissions during the fallow season were reduced by 61.8 % in relation to PFL, though non-significantly ($F_{1,\ 3.0}$, $P > 0.05$) (Table 2). Therefore, the mitigation effect of MSD implemented in the growing season persisted in the subsequent flooded fallow season.

During the aeration periods, O_2 diffusion inhibits CH_4 production (Conrad 2020). The reduced CH_4 emission rates observed after the implementation of MSD could have been driven by alterations in soil structure induced by the draining periods. For example, short aerations can increase soil hardness (Norton et al., 2017) and decrease soil macroporosity (Diel et al., 2019), thus limiting CH_4 diffusion to the atmosphere. Yet, this effect is more accentuated in clay-rich soils (Diel et al., 2019), such as that in our study (*ca*. 70 % of clay), fact that could explain the contrasting results with LaHue et al. (2016), who found no extended effect of AWD in the following fallow season in a paddy soil with lower clay content (45 %).Another plausible reason explaining the mitigation of CH_4 is an altered composition and activity of the methanogenic communities induced by short-term drying effects (Krüger et al., 2005; Conrad et al., 2014; Reim et al., 2017) that could have reduced CH_4 production. These biogeochemical responses to MSD could have persisted not only in after field reflooding within the growing season, thus explaining the large mitigation of CH_4 during the growing season, but also in the following winter flooded fallow season.

From February onwards, when both fields were drained, CH_4 emissions were interrupted in both treatments. Overall, annual CH_4 cumulative emissions in MSD were reduced by 63.3 % in comparison to PFL (Table 2). Additionally, it is worthy to remark the substantial reduction observed (*ca.* 80%), which is comparable to that observed in another rice growing area in Spain (Martínez-Eixarch et al. (2021a). Such a large reduction is placed in the uppermost range of reductions induced by intermittent irrigation systems with minimum yield losses reviewed by Carrijo et al. (2017) and Liu et al. (2019).

Emission rates of N_2O were not significantly affected by the water management in either the growing ($F_{1,0.01}$, $P > 0.05$) or fallow ($F_{1,0.89}$, $P > 0.05$) seasons (Table 2). Therefore, the decreased CH_4 emissions induced by MSD were not offset by N_2O, which is in line with Linquist et al. (2015) and Martínez-Eixarch et al., (2021a) but in contrast with Kritee et al., (2018). The resulting annual GWP was reduced by 59.7% (Table 2).

Conclusions

The present study confirms the capacity of MSD to effectively mitigate CH_4 emissions in the rice growing season without yield penalties (Liu et al., 2019). The novelty of our observations lies in the prolonged mitigation capacity of an intermittent irrigation system, MSD, in the following flooded winter fallow season. The herein reported *ca*. 60 % reduction of the fallow CH_4 emissions becomes especially relevant in rice systems with post-harvest management consisting in maintaining the fields flooded and incorporating rice straw into the soil, given the large contribution of this season to the annual CH_4 emissions (Fitzgerald et al., 2000; Martínez-Eixarch et al., 2021b). Despite the promising results herein presented, we are aware that the experimental design, consisting in one single year of study in one unique location, limits their representativeness and generalizability. Nevertheless, in the view of the potentially impactful finding of an amplified mitigating effect of MSD on annual CH_4 emissions, we strongly suggest that further research should be conducted, with special emphasis on the underlying soil microbial processes.

Declarations

This work has been supported and funded by Mars Food, Herba Ricemills (Ebro Foods) and Danone Specialized Nutrition in the frame of the ORYZONTE project.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

Brye, K.R., Nalley, L.L., Tack, J.B., Dixon, B.L., Barkley, A.P., Rogers, C.W., Smartt, A.D., Norman, R.J., Jagadish, K.S.V., 2016. Factors affecting methane emissions from rice production in the Lower Mississippi river valley, USA. Geoderma Regional 7, 223-229.

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.

Conrad, R., 2020. Methane Production in Soil Environments—Anaerobic Biogeochemistry and Microbial Life between Flooding and Desiccation. Microorganisms 8, 881.

Conrad, R., Ji, Y., Noll, M., Klose, M., Claus, P., Enrich-Prast, A., 2014. Response of the methanogenic microbial communities in Amazonian oxbow lake sediments to desiccation stress. Environmental Microbiology 16, 1682-1694.

Diel, J., Vogel, H.-J., Schlüter, S., 2019. Impact of wetting and drying cycles on soil structure dynamics. Geoderma 345, 63-71.

Fitzgerald, G.J., Scow, K.M., Hill, J.E., 2000. Fallow season straw and water management effects on methane emissions in California rice. Global Biogeochemical Cycles 14, 767-776.

Ji, Y., Scavino, A.F., Klose, M., Claus, P., Conrad, R., 2015. Functional and structural responses of methanogenic microbial communities in Uruguayan soils to intermittent drainage. Soil Biology and Biochemistry 89, 238-247.

Kritee, K., Nair, D., Zavala-Araiza, D., Proville, J., Rudek, J., Adhya, T.K., Loecke, T., Esteves, T., Balireddygari, S., Dava, O., Ram, K., S. R., A., Madasamy, M., Dokka, R.V., Anandaraj, D., Athiyaman, D., Reddy, M., Ahuja, R., Hamburg, S.P., 2018. High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. Proceedings of the National Academy of Sciences 115, 9720-9725.

Javadinejad, S., Eslamian, S., Ostad-Ali-Askari, K., 2021. The analysis of the most important climatic parameters affecting performance of crop variability in a changing climate. International journal of hydrology science and technology 11, 1-25.

Krüger, M., Frenzel, P., Kemnitz, D., Conrad, R., 2005. Activity, structure and dynamics of the methanogenic archaeal community in a flooded Italian rice field. FEMS Microbiology Ecology 51, 323-331.

LaHue, G.T., Chaney, R.L., Adviento-Borbe, M.A., Linquist, B.A., 2016. Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. Agriculture, Ecosystems & Environment 229, 30-39.

Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A., Chaney, R.L., Nalley, L.L., da Rosa, E.F., van Kessel, C., 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Global Change Biology 21, 407-417.

Liu, X., Zhou, T., Liu, Y., Zhang, X., Li, L., Pan, G., 2019. Effect of mid-season drainage on CH_4 and N_2O emission and grain yield in rice ecosystem: A meta-analysis. Agricultural Water Management 213, 1028-1035.

Martínez-Eixarch, M., Alcaraz, C., Guàrdia, M., Català-Forner, M., Bertomeu, A., Monaco, S., Cochrane, N., Oliver, V., Teh, Y.A., Courtois, B., 2021a. Multiple environmental benefits of alternate wetting and drying irrigation system with limited yield impact on European rice cultivation: the Ebre Delta case. Agricultural Water Management.

Martínez-Eixarch, M., Alcaraz, C., Viñas, M., Noguerol, J., Aranda, X., Prenafeta-Boldú, F.-X., Català-Forner, M., Fennessy, M.S., Ibáñez, C., 2021b. The main drivers of methane emissions differ in the growing and flooded fallow seasons in Mediterranean rice fields. Plant and Soil, 1-17.

Martínez-Eixarch, M., Alcaraz, C., Viñas, M., Noguerol, J., Aranda, X., Prenafeta-Boldú, F., la Vega Saldaña-De, J., Català, M., Ibáñez, C., 2018. Neglecting the fallow season can significantly underestimate annual methane emissions in Mediterranean rice fields. PloS one 13, e0198081-e0198081.

Norton, G.J., Shafaei, M., Travis, A.J., Deacon, C.M., Danku, J., Pond, D., Cochrane, N., Lockhart, K., Salt, D., Zhang, H., 2017. Impact of alternate wetting and drying on rice physiology, grain production, and grain quality. Field Crops Research 205, 1-13.

Reim, A., Hernández, M., Klose, M., Chidthaisong, A., Yuttitham, M., Conrad, R., 2017. Response of Methanogenic Microbial Communities to Desiccation Stress in Flooded and Rain-Fed Paddy Soil from Thailand. Front Microbiol 8, 785.

Saunois, M., Jackson, R.B., Bousquet, P., Poulter, B., Canadell, J.G., 2016. The growing role of methane in anthropogenic climate change. Environmental Research Letters 11, 120207.

Seiler, W., Holzapfel-Pschorn, A., Conrad, R., Scharffe, D., 1983. Methane emission from rice paddies. Journal of Atmospheric Chemistry 1, 241-268.

Figure captions

Fig 1. a. Methane (CH_4) emission rates (mg C-CH_4 m^{-2} h^{-1}) in control (PFL) and mid-season drainage (MSD) treatments over a) the whole rice cropping period and b) the growing season. Error bars indicate ± standard error of the mean. The rectangle in 1b indicates the period of mid-season drainage (from 10/7 to 18/7). Note the different scale of the values for Y-axis in both graphs.

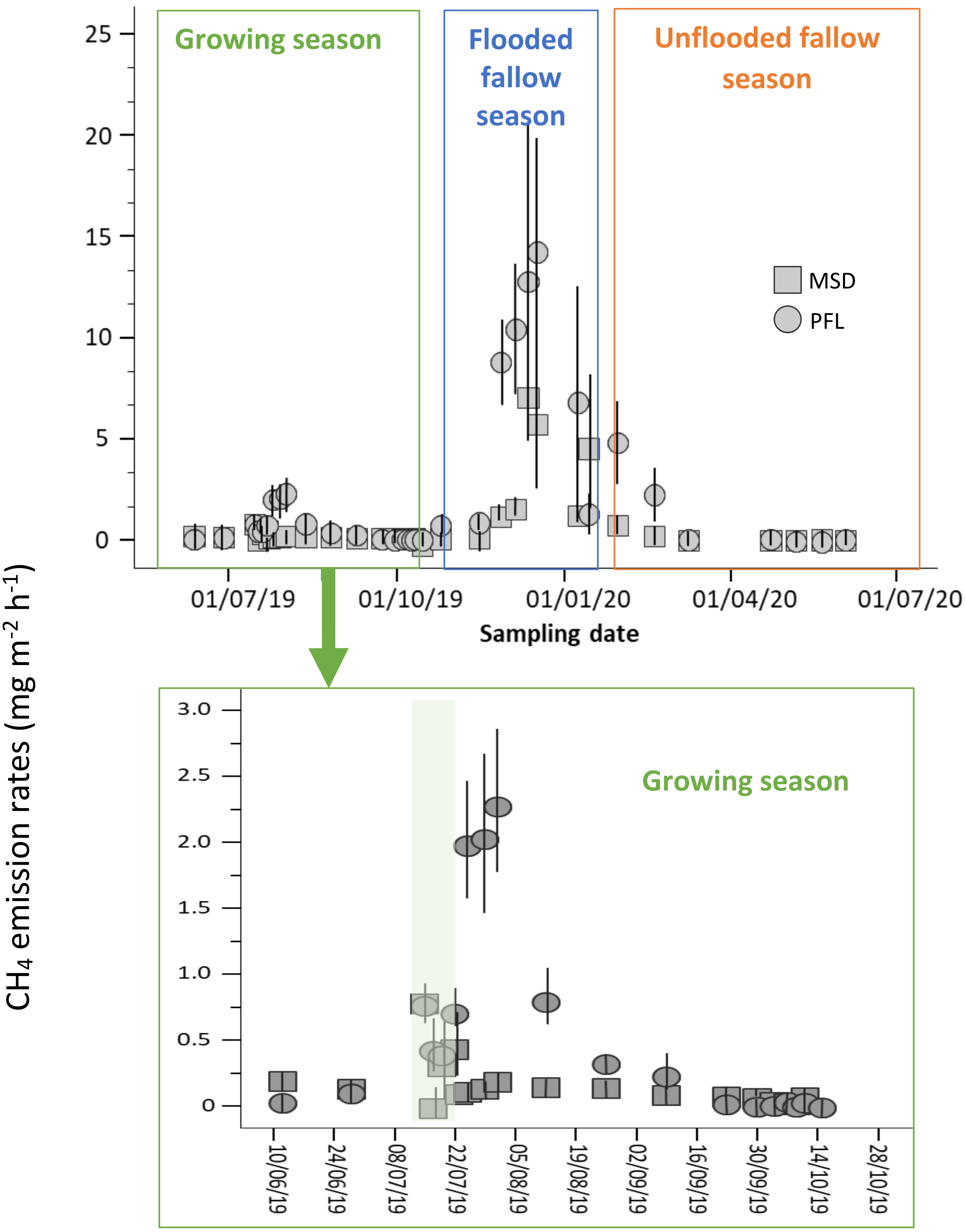
25
20
15
10
5
0
Growing season
Flooded fallow season
Unflooded fallow season
MSD
PFL
01/07/19
01/10/19
01/01/20
01/04/20
01/07/20
Sampling date
CH₄ emission rates (mg m⁻² h⁻¹)
3.0
2.5
2.0
1.5
1.0
0.5
0
Growing season
10/06/19
24/06/19
08/07/19
22/07/19
05/08/19
19/08/19
02/09/19
16/09/19
30/09/19
14/10/19
28/10/19

Fig. 1

Table 1 Crop Management and soil traits of the rice fields with contrasting water management during the growing season: control (PFL, permanent flooding) and mid-season drainage (MSD).

Crop management	**Permanently flooded**	**Mid-season drainage**
Sowing date	02/06/19	02/06/19
Harvest	17/10/19	17/10/19
Fertilization rate	165 (KgN ha^{-1})	165 (KgN ha^{-1})
Straw incorporation	20/11/19	20/11/19
Water management during the growing season	Permanent flooding, with a short aeration period of < 2 days (10/7/19 – 13/7/19)	Two drainages: 10/7/19 – 18/7/19, 13/9/19 – 17/9/19
Water management during the winter fallow season	Permanent flooding: 15/11/19 - 15/01/20 Irrigation cut and fields progressively drained: 15/01/20	Permanent flooding: 15/11/19 - 15/01/20 Irrigation cut and fields progressively drained: 15/01/20
Soil traits		
Clay (%)	69	71
Sand (%)	4	3
Lime (%)	27	26
Soil organic matter (%)	3.03	3.06
Total Nitrogen (mg kg^{-1})	2584	2537
Sulphates (mg kg^{-1})	3109	3872
P (Olsen, mg kg^{-1})	36.9	40.6

Table 2 Cumulative seasonal (growing and fallow seasons) and annual GHG emissions (CH_4 and N_2O) and GWP (μ ± SE) in the studied water managements: PFL, permanent flooding over the growing and fallow season; MSD, mid-season drainage in the growing seasons + winter flooding. Units are given in kg CH_4, N_2O or CO_2-eq per ha.

		Growing	**Fallow**	**Annual**
CH_4	**MSD**	2.9 ± 0.2	66.0 ± 16.1	68.8± 16.4
	PFL	14.8 ± 0.5	173 ± 59.8	187.8 ± 57.8
N_2O	**MSD**	-0.06 ± 0.01	0.78 ± 1.3	0.72 ± 1.4
	PFL	-0.15 ± 0.05	0.16 ± 0.3	0.01 ± 0.3
GWP	**MSD**	64.8 ± 30.4	2054.5 ± 799.4	2119.3 ± 813.2
	PFL	374.4± 74.3	4887.1 ± 1730.8	5261.6 ± 1685.2