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1 **Greenhouse gas emissions as affected by different water management practices in temperate**  
2 **rice paddies**

3 Matteo Peyron<sup>1</sup>, Chiara Bertora<sup>1\*</sup>, Simone Pelissetti<sup>1</sup>, Daniel Said-Pullicino<sup>1</sup>, Luisella Celi<sup>1</sup>,  
4 Eleonora Miniotti<sup>1,2</sup>, Marco Romani<sup>2</sup>, Dario Sacco<sup>1</sup>

5

6 <sup>1</sup>*Dept. of Agricultural, Forest and Food Sciences, University of Turin, Grugliasco, Italy.*

7 <sup>2</sup>*Rice Research Centre, Ente Nazionale Risi, Castello d'Agogna, Italy.*

8

9 \*Corresponding author: Chiara Bertora, Dept. of Agricultural, Forest and Food Sciences, University  
10 of Turin, Largo Paolo Braccini 2, 10095 Grugliasco (TO), Italy, chiara.bertora@unito.it

11

12

13 **Abstract**

14 The mitigation of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions from rice paddy fields is  
15 pivotal in minimizing the impact of rice production on global warming. The large majority of the  
16 world rice is cropped in continuously flooded paddies, where soil anaerobic conditions lead to the  
17 production and emission of significant amounts of CH<sub>4</sub>. In this work we evaluated the effectiveness  
18 of water management techniques alternative to the conventional flooding on the mitigation of CH<sub>4</sub>  
19 emissions from paddy soils, and verified whether any concurrent increase in N<sub>2</sub>O emissions can  
20 totally or partially offset their environmental benefit. Two alternative water management systems  
21 were compared to the conventional continuous flooding system (WFL): dry seeding with delayed  
22 flooding (DFL) and intermittent irrigation (DIR). Methane and N<sub>2</sub>O emissions were monitored at

23 field-scale over two years including both rice cropping and fallow seasons, using non-steady-state  
24 closed chamber approach. The DFL system resulted in a 59 % decrease (average of the two  
25 measured years) in total CH<sub>4</sub> emissions with respect to WFL, while DIR annulled CH<sub>4</sub> emissions.  
26 The effect of CH<sub>4</sub> mitigation of DFL with respect to WFL was mainly concentrated within the  
27 vegetative stage, while any significant flux from DIR was recorded throughout the growing and  
28 non-growing season. However, DIR resulted in the highest emission peaks and cumulative fluxes of  
29 N<sub>2</sub>O, almost totally occurred during the vegetative stage. In contrast, DFL and WFL showed N<sub>2</sub>O  
30 emissions that were 77 and 93% lower with respect to DIR, respectively. Total annual fluxes  
31 suggest that the adoption of alternative water management practices that involve dry seeding and  
32 subsequent delayed flooding or intermittent irrigation can contribute to significantly reduce the  
33 global warming potential of rice cropping systems by 56 and 83 %, respectively with respect to  
34 continuous flooding.

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37

38 **Keywords:** Methane; Nitrous oxide; Continuous flooding; Dry seeding; Intermittent irrigation;  
39 Global warming potential; Water management; Rice paddy.

40

#### 41 **Highlights**

- 42 • GWP in continuously flooded paddy was on average 9.65 Mg CO<sub>2</sub>eq ha<sup>-1</sup> y<sup>-1</sup>
- 43 • Intermittent irrigation decreased GWP by 83 % compared to continuous flooding
- 44 • Delayed flooding decreased GWP by 56 % compared to continuous flooding
- 45 • CH<sub>4</sub> is the major contributor to GWP for continuous (98%) and delayed (92%) flooding
- 46 • For intermittent irrigation, N<sub>2</sub>O composes 100% of GWP

47 **1. Introduction**

48 Agriculture greatly contributes to anthropogenic greenhouse gas (GHG) emissions and this role is  
49 expected to remain pivotal throughout the 21<sup>st</sup> century. Annual GHG emissions from agricultural  
50 production, mainly methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), were estimated at 5.0–5.8 Gt CO<sub>2</sub>-eq y<sup>-1</sup>  
51 <sup>1</sup>for the 2000–2010 period (Faostat, 2013; Tubiello et al., 2013), accounting for approximately 10–  
52 12% of global anthropogenic emissions. Paddy rice cultivation is a major source of global CH<sub>4</sub>  
53 emissions, estimated to contribute around 11% of the overall CH<sub>4</sub> emissions (493–723 Mt CO<sub>2</sub>-eq  
54 y<sup>-1</sup>) in 2010 (Smith et al. 2014).

55 Methane fluxes from paddy fields are the net balance among the main processes of methanogenesis,  
56 (responsible for CH<sub>4</sub> production), methanotrophy (responsible for CH<sub>4</sub> consumption), and emission  
57 from soil to atmosphere (Wassmann and Aulakh, 2000). As plants develops during its growing  
58 cycle, diffusion through aerenchyma becomes the dominant process, responsible for more than 90%  
59 emitted, while ebullition and diffusion through flooded water provide minor contributions (Le Mer  
60 and Roger, 2001). Methane emissions are reported to covary with crop growth and maximum  
61 emissions peaks are normally observed in close proximity of rice panicle initiation (Gogoi *et al.*  
62 2005; Pittelkow *et al.* 2013).

63

64 Over 75% of the world rice is produced in paddies that are continuously flooded for most of the  
65 cropping season (Van der Hoek et al., 2001). Waterlogging has several agronomic advantages: it  
66 mainly limits variations in soil moisture and temperature, and depresses soil-borne disease and  
67 weed growth. Nevertheless, flooding drastically reduces the diffusion of atmospheric O<sub>2</sub> into the  
68 soil, therefore promoting methanogenesis. This microbial process, in fact, requires strict  
69 anaerobiosis and low oxydo-reduction potentials, distinctive traits of flooded paddies (Le Mer and  
70 Roger, 2001).

71 Alternative irrigation systems limiting the presence of a permanent water layer in field have been  
72 recently introduced, primarily for water-saving purposes in areas where scarcity is a crucial issue;  
73 additionally, these techniques can also be effective at enhancing the diffusion of O<sub>2</sub> into the soil  
74 therefore mitigating CH<sub>4</sub> production (Xu et al., 2015, Yang et al., 2012, Sass and Fisher, 1997).  
75 Furthermore, since water management affects availability of methanogenic substrates, interfering  
76 with straw decomposition, any limitation in water permanence in field, especially at the beginning  
77 of the cropping season, can also indirectly reduce CH<sub>4</sub> emissions by containing the presence of  
78 methanogenic substrates (Watanabe *et al.*, 2009).

79 However, water management practices that limit CH<sub>4</sub> production are generally prone to  
80 concurrently enhance N<sub>2</sub>O emissions (Zou et al., 2005). Frequent alternations in soil redox  
81 conditions as a result of dry–wet transitions are known to substantially increase N<sub>2</sub>O by favouring  
82 both nitrification and denitrification processes responsible for N<sub>2</sub>O production. This circumstance  
83 can substantially offset the advantages of CH<sub>4</sub> mitigation achieved by introducing drainage periods  
84 (Zou et al., 2007; Wang et al., 2011).

85 Water management in rice cropping systems therefore plays a key role in determining the trade-off  
86 between CH<sub>4</sub> and N<sub>2</sub>O emissions. The development of effective mitigation strategies aimed at  
87 minimizing the global warming potential (GWP) of rice cropping systems must therefore consider  
88 the emissions of both gases.

89 Only few studies have evaluated the effects of dry seeding and alternative irrigation practices  
90 (Pittelkow et al., 2014, Simmonds et al., 2015) on the overall GHG emissions from temperate paddy  
91 fields with respect to the conventional continuously flooded cultivation system.

92 In Europe, as in most temperate countries, two irrigation practices were introduced during the last  
93 few decades as an alternative to the conventional water management that involves water seeding  
94 and continuous flooding until ripening stage, one month before harvest (hereafter identified as  
95 WFL). The first alternative consists of dry seeding and delayed flooding at tillering about one

96 month after seeding (hereafter termed DFL), while the second is based on dry seeding followed by  
97 intermittent irrigation (henceforth called DIR).

98 In 2014, the DFL cropping system involved 72,984 ha accounting for about 33% of the total area  
99 cultivated to rice in Italy (219,532 ha). Although the application of this system does not lead to a  
100 reduction in water use (Zhao et al., 2015), the delay in flooding can effectively limit the  
101 accumulation of phytotoxic substances (like phenolic acids, phenolic aldehydes and low molecular  
102 weight aliphatic acids) derived from straw fermentation, and reduce inhibition on plant growth  
103 (Pramanik et al., 2001).

104 The DIR cropping system has a rather limited relevance in Italy; it is highly functional in very  
105 permeable soils where scarce water availability does not provide for continuous flooding or in areas  
106 in proximity of inhabited areas as a mosquito control strategy (Mutero et al., 2000; Klinkenberg et  
107 al., 2003).

108 Building upon these considerations, we hypothesized that, with respect to continuously flooded  
109 systems, alternative water management practices that reduce the permanence of ponding water in  
110 temperate rice paddies may contribute to reduce CH<sub>4</sub> emissions, though this environmental benefit  
111 may be partially offset by a concurrent increase in N<sub>2</sub>O emissions. We tested this hypothesis at  
112 field-scale by evaluating variations in the annual emissions of CH<sub>4</sub> and N<sub>2</sub>O and their specific  
113 contribution to the GWP of three water management practices (WFL, DFL, DIR) over a two year  
114 experimental periods.

115

## 116 **2. Materials and methods**

### 117 *2.1. Experimental site description*

118 A two-year field experiment was conducted in 2012 to 2013 at the Italian Rice Research Centre  
119 (Ente Nazionale Risi) in Castello d'Agogna, near Pavia. The site is located in the western area of

120 the plain of the river Po (NW Italy) within the Italian rice district. The soil of the experimental field  
121 was a Fluvaquentic Epiaquept coarse silty, mixed, mesic (Soil Survey Staff, 2014) having a loam  
122 topsoil (0-30 cm) and a silty loam plough pan (30-40 cm). The topsoil had a mean pH (H<sub>2</sub>O) of 5.9,  
123 9.5 g kg<sup>-1</sup> organic C, 0.8 g kg<sup>-1</sup> total N, and a cation exchange capacity of 10.2 cmol(+) kg<sup>-1</sup>.  
124 Further details of the site's soil were provided elsewhere (Said-Pullicino et al., 2016).  
125 The climate is temperate subcontinental, with a mean annual temperature of 12.7 °C and a mean  
126 annual precipitation of 704 mm (average of last 20 years), characterized by two main rainfall  
127 periods in spring (April–May) and autumn (September–November). In 2012 and 2013, mean annual  
128 air temperature was 13.0 °C, while during the growing season the mean temperature was 22.7 °C  
129 (Figure 1). The annual cumulative rainfall over the experimental period was 623 and 756 mm in  
130 2012 and 2013, respectively, with around 70% occurring during intercropping periods between  
131 October and May (Figure 1). In both years, cropping seasons (May–September) were characterized  
132 by several rainfall events during early crop establishment, and limited rainfall thereafter until  
133 harvest. In 2013, the exceptionally high precipitations during March–May (379 mm) led to a delay  
134 in soil tillage and seeding operations by approximately 15 days.

135

## 136 2.2. *Experimental treatments*

137 Field treatments involved the comparison of three water management practices including water  
138 seeding and continuous flooding (WFL), dry seeding with flooding at tillering stage (DFL), and dry  
139 seeding with intermittent irrigation (DIR). The experimental site was divided into six 20×80 m  
140 plots, two for each of the three water management systems compared.

141 As explained by Miniotti et al. (2016), plots were kept adjacent, as described by de Vries et al.  
142 (2010), in order to ensure distinct water regimes and were separated by means of lateral levees (50  
143 cm above soil surface) coupled with two-side canals (20-25 cm deep), in order to maintain each plot  
144 hydraulically independent. All plots were maintained with the same water regime during both years  
145 of the study.

146 Variability in the two directions of the field was explored using position as covariates (x between  
147 treatments and y along the plot). X resulted to be not significant with very few exceptions where  
148 significance was close to 0.05, showing that no clear trends of variability exist on the field in this  
149 direction.

150 The four chamber for gaseous emission measurements were placed in one plot for each treatment,  
151 about 1 m apart from each other. Based on the “detailed soil survey, consisting of the description of  
152 five soil profiles opened in adjacent fields, as well as 108 soil cores sampled over the whole  
153 experimental site (1.2 ha)” (Miniotti et al. 2016) chambers were placed in the different treatments  
154 with the purpose of obtaining great soil homogeneity among and within treatments.

155 The Gladio variety was considered for the present study.

156 All plots involved spring tillage and straw incorporation with ploughing and disking (2<sup>nd</sup> April 2012  
157 and 9<sup>th</sup> May 2013), followed by laser levelling and the final seedbed preparation by rotary  
158 harrowing, and were seeded with long-grain, type B rice (*Oryza sativa* L. cv. Gladio; 160 kg ha<sup>-1</sup>)  
159 (Table 1). During winter all plots were maintained dried following typical practices of the region.

160 In WFL treatment, pinpoint flooding method was applied (Hardke and Scott, 2013), following  
161 typical practices of the region. In detail, after pre-seeding fertilization and flooding, rice was  
162 broadcasting water seeded (after 1-day water imbibition of seeds). The field was seeded on 28<sup>th</sup>  
163 May 2012 and 7<sup>th</sup> June 2013. During the seedling stage, soil was drained for few days up to one  
164 week. This is necessary for the radicle to penetrate the soil and anchor the seedling. At the end of  
165 this period, irrigation is re-established. However, during the subsequent 10-15 days, the soil is  
166 maintained saturated and not flooded, and irrigation stopped 2-3 times for the application of post-  
167 emergence treatments for weed and pest control. One day after the first top-dressing fertilization at  
168 first tillering stage, flooding was restored and a permanent ponding water depth of 5-20 cm was  
169 maintained until the field was drained approximately one month prior to harvest, except for one  
170 short mid-season drainage event (approximately 5 days) in correspondence with the second top-  
171 dressing fertilization at panicle initiation stage (Figure 2).

172 In the dry seeded plot (DFL), drill seeding into dry soil (2-3 cm deep with a 12 cm row spacing)  
173 was carried out on the 15<sup>th</sup> May 2012 and 28<sup>th</sup> May 2013 by means of a Maschio Gaspardo DC  
174 3000 COMBI seeding machine. Field flooding occurred approximately one month later, at first  
175 tillering stage, after the herbicide treatments and the first top-dressing fertilization. During the  
176 season water level was kept around 5-20 cm, except for one short mid-season drainage event in  
177 correspondence with the second top-dressing fertilization event at panicle initiation stage, and  
178 drained one month before harvest, that occurred in September 28<sup>th</sup>, 2012 and October 3<sup>th</sup>, 2013, as  
179 for WFL plots.

180 In the DIR treatment, dry seeding was carried out on May 15<sup>th</sup>, 2012 and May 28<sup>th</sup>, 2013 as  
181 described for the DFL treatment. During the growing season, the DIR plots were intermittently  
182 watered by surface irrigation when soil water potential at 10 cm approached -30 kPa. Irrigation was  
183 applied 9 times with an average interval of 8.1 days in 2012, and 12 times with an average interval  
184 of 7.5 days in 2013 without maintaining flooding

185 Nitrogen fertilizer was applied as urea at an annual dose of 160 kg N ha<sup>-1</sup> split between basal,  
186 tillering, panicle differentiation and booting stages as described in Table 2. Although the same total  
187 amount of urea was applied in the three treatments, splitting among the different stages was slightly  
188 different to maximize plant N uptake and limit losses. In WFL N was applied in three field  
189 distributions: the first before rice seeding (60 kg N ha<sup>-1</sup>), the second at beginning of tillering (60 kg  
190 N ha<sup>-1</sup>) and the third during panicle initiation (40 kg N ha<sup>-1</sup>).

191 In DFL N fertilization was managed, similarly to WFL, splitting the total amount of 160 kg ha<sup>-1</sup> in  
192 three interventions: 40 kg N ha<sup>-1</sup> before seeding and two top-dressing applications of 70 and 50 kg  
193 N ha<sup>-1</sup>; a lower amount of N with respect to WFL was applied before seeding for preventing losses  
194 via NH<sub>3</sub> volatilization.

195 In DIR, fertilization was planned slightly differently: we applied the same amount of urea (160 kg  
196 N ha<sup>-1</sup>) but split in four distributions, in order to increase N use efficiency. In detail, we decided a  
197 fourth fertilization at booting stage as necessary for maximizing productive performances of the

198 system. In dry conditions a significant amount of N is lost by nitrification, increasing split  
199 applications could improve Nitrogen Use Efficiency (NUE) (Raun et al., 2002).

200 Weeds and pests were controlled as needed, following recommended practices for the region.

201

202

### 203 2.3. Gaseous emissions

204 Emissions of CH<sub>4</sub> and N<sub>2</sub>O were measured from March 21<sup>th</sup> 2012 to March 21<sup>th</sup> 2014, for a total of  
205 110 sampling dates, split into the first year, thereafter called “2012” (from March 21<sup>th</sup> 2012 to  
206 March 21<sup>th</sup> 2013) and the second year, thereafter called “2013” (from March 21<sup>th</sup> 2013 to March  
207 21<sup>th</sup> 2014).

208 Measurements covered both the intercropping periods (35 measurements events, sum of the two  
209 years) and the growing seasons (38 measurements events in 2012 and 37 in 2013), these last  
210 subdivided into three main phenological stages: the vegetative stage (from germination to panicle  
211 initiation; 15 measurement events in 2012, 17 in 2013), the reproductive stage (from panicle  
212 initiation to flowering; 11 measurement events in 2012, 9 in 2013), and the ripening stage (from  
213 flowering to senescence; 12 measurement events in 2012, 11 in 2013) (Meijide *et al.*, 2013).

214 Sampling frequency was intensified in correspondence with fertilization, irrigation, flooding and  
215 drainage, when higher fluxes were expected. During autumn and winter, sampling frequency was  
216 progressively reduced as gaseous fluxes declined.

217 All gas-sampling events occurred around midday (11:00–14:00 h) to minimize variability due to  
218 diurnal variations in gaseous fluxes, as also applied by Pittelkow et al (2013).

219 Emissions were measured by means of a non-steady-state closed chamber technique (Livingston  
220 and Hutchinson, 1995) with four replicates per treatment. In March 2012, stainless steel anchors (75  
221 × 36 cm) were inserted into the soil up to a depth of 40 cm and left throughout the two years except  
222 for the time period between tillage and seeding during which they were removed to allow for soil

223 management. Wooden boards were adopted to access the anchors during sampling to avoid soil  
224 compaction or crop disturbance.

225 During each measurement event, a rectangular stainless steel chamber (75 × 36 × 20 cm high) was  
226 sealed to each anchor by means of a water-filled channel and included the growing rice plants  
227 within when present. Chambers were covered with a 5 cm thick light-reflective insulation to limit  
228 temperature variations inside the chamber during flux measurements, and were equipped with a  
229 pressure vent valves designed according to Hutchinson and Mosier (1981), a battery-operated fan to  
230 ensure sufficient mixing of headspace air, and a gas sampling port. When necessary, steel chamber  
231 extensions (15 cm high) were added between the anchor and the chamber in order to accommodate  
232 the rice plant throughout the entire cropping season (maximum of four, around harvest).

233 Headspace gas samples from inside the closed chambers were collected by propylene syringes at 0,  
234 15, and 30 min after chamber closure. Thirty-millilitre air samples were collected and injected into  
235 12-mL evacuated vials closed with butyl rubber septa (Exetainer<sup>®</sup> vial from Labco Limited, UK).  
236 Gas concentrations in collected samples were determined by gas chromatography by means of a  
237 fully automated gas chromatograph (Agilent 7890A with a Gerstel Maestro MPS2 auto sampler)  
238 equipped with electron capture, thermal conductivity and flame ionization detectors for the  
239 quantification of N<sub>2</sub>O, CO<sub>2</sub> and CH<sub>4</sub>, respectively.

240 Fluxes were calculated from the linear or nonlinear (Hutchinson and Mosier, 1981) increase in  
241 concentration (selected according to the emission pattern) in the chamber headspace with time, as  
242 suggested by Livingston and Hutchinson (1995). The MDF (Minimum Detectable Flux) varies in  
243 relation to the detection limit of the gas chromatograph and the chamber volume. The latter changed  
244 in time during the cropping season to accommodate for rice growth. Values for MDF ranged  
245 between 5-20 g N ha<sup>-1</sup> d<sup>-1</sup> for N<sub>2</sub>O, 12-48 g C ha<sup>-1</sup> d<sup>-1</sup> for CH<sub>4</sub>, and 2.62-10.61 kg C ha<sup>-1</sup> d<sup>-1</sup> for CO<sub>2</sub>.

246 Fluxes were set to zero if the change in gas concentration during chamber enclosure fell below the  
247 MDF.

248 Although the emphasis of this study was on CH<sub>4</sub> and N<sub>2</sub>O emissions, CO<sub>2</sub> emission data determined  
249 simultaneously were also reported. However, during the cropping season, the presence of the rice  
250 plant inside the chamber meant that measured CO<sub>2</sub> fluxes also included a contribution from plant  
251 respiration. For this reason, we only investigated CO<sub>2</sub> emissions in the period between the  
252 establishment of flooding in WFL and that for DFL at tillering. During this period, the contribution  
253 of plant respiration to the total CO<sub>2</sub> emissions was assumed to be minor and of the same intensity  
254 across all treatments, and CO<sub>2</sub> fluxes were attributable to soil respiration alone.

255 Estimates of cumulative CH<sub>4</sub> and N<sub>2</sub>O emissions for each plot were based on linear interpolation  
256 across sampling days. For both years, annual cumulative fluxes as well as those relative to the  
257 growing season and intercropping period, were calculated. Moreover, each growing season was  
258 further subdivided into the three above-mentioned phenological periods (vegetative stage,  
259 reproductive stage, and ripening stage). The Global Warming Potential (GWP) was also calculated  
260 to estimate the potential future impacts of emissions of different gases upon the climate system in a  
261 comparative way. The GWP is a relative measure of how much heat a greenhouse gas traps in the  
262 atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the  
263 amount of heat trapped by a similar mass of CO<sub>2</sub>. For GWP estimation, we used the IPCC factors  
264 over the 100-year time scale in order to convert CH<sub>4</sub> and N<sub>2</sub>O to CO<sub>2</sub> equivalents (25 and 298,  
265 respectively) (Smith et al., 2014).

266

#### 267 *2.4. Soil parameter measurements*

268 Within the same experimental site, other concurrent parameters, ancillary to GHG emissions, were  
269 measured. Throughout the cropping seasons, soil redox potential (Eh) in each treatment was  
270 potentiometrically measured at a soil depth of 10 cm. Soil solutions were also collected on a weekly  
271 basis in correspondence with gas flux measurements by means of ceramic cups installed at 25 cm.  
272 All pore water samples were filtered through a 0.45 µm membrane filter and analysed for dissolved

273 organic carbon (DOC) by high temperature combustion (VarioTOC, Elementar, Hanau, Germany),  
274 and nitrates ( $\text{NO}_3^-$ ) by ion chromatography (Dionex 500, Sunnyvale, CA, USA).

275 Although seasonal trends in these parameters over the two cropping seasons were presented  
276 elsewhere (Said-Pullicino et al.,2016), we used these data to explore correlations with GHG fluxes.

277

### 278 *2.5. Data analyses*

279 Statistical effect of water management on cumulative fluxes of  $\text{N}_2\text{O}$ ,  $\text{CH}_4$  and  $\text{CO}_2$  emissions and  
280 GWP was determined by one-way ANOVA. Before ANOVA application, Shapiro-Wilk test for  
281 normality and Levene test for homoscedasticity were applied. Years were independently analysed  
282 due to their heteroscedasticity. When ANOVA null hypothesis was rejected, treatment averages  
283 were separated by means of REGWQ (Ryan-Einot-Gabriel-Welch Q test) post hoc test. Correlations  
284 between daily  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions, Eh, DOC and  $\text{NO}_3^-$  were analysed for each treatment  
285 separately by means of Pearson correlation. We also investigated the correlation between  $\text{CH}_4$   
286 emissions and days of water permanence in fields by means of Pearson correlation. All statistical  
287 analyses were performed using the SPSS Statistics 21 (SPSS Inc., Chicago, IL).

288

## 289 **3. Results**

### 290 *3.1. Methane emissions*

291 In both years,  $\text{CH}_4$  emissions from the WFL treatment started in correspondence with the days of  
292 drainage operated at seedling stage for root anchoring, and rapidly increased showing a first peak  
293 around the post-emergence weed and pest control treatments, that in both years were the highest  
294 peaks produced in the season (198 and 231  $\text{kg CO}_2\text{-eq ha}^{-1} \text{d}^{-1}$  in 2012 and 2013, respectively)  
295 (Figure 3a). These peaks were followed by a great reduction of fluxes during the drainage period set  
296 up for allowing the fertilization at tillering stage, and subsequently increased again producing a  
297 second emission peak, few days before the panicle initiation stage (128 and 205  $\text{kg CO}_2\text{-eq ha}^{-1} \text{d}^{-1}$   
298 in 2012 and 2013, respectively). During the subsequent reproductive and ripening stages, emissions

299 were spaced out by a great reduction of fluxes occurred during the drainage period around the third  
300 fertilization. Emissions drastically decreased after producing a singular high peak (22 and 134 kg  
301 CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup> in 2012 and 2013, respectively) few days after the final drainage before harvest.  
302 Throughout the fallow season in both years, CH<sub>4</sub> fluxes remained very low (<16 kg CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup>  
303 <sup>1</sup>). In 2013, fluxes were generally higher than in 2012. Mean fluxes were 0.94 and 1.98 kg CO<sub>2</sub>-eq  
304 ha<sup>-1</sup> d<sup>-1</sup> in 2012 and 2013, respectively.

305 In the DFL treatment, CH<sub>4</sub> emissions started one week after water establishment (Figure 3b), and  
306 subsequently increased until the panicle initiation stage. In 2012 emissions showed the highest peak  
307 (101 kg CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup>) around panicle initiation, followed by an alternation between emission  
308 peaks and drastic reductions of flux- the main one during the drainage period around the second  
309 top-dressing fertilization- similarly to that observed for WFL; as observed for WFL, DFL produced  
310 a high emission peak (93 kg CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup>) few days after the final drainage. Differently from  
311 what observed for WFL, in 2013, fluxes were generally lower than in 2012, showing a first  
312 emission peak (68 kg CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup>) during the reproductive stage, approximately 10 days after  
313 panicle initiation, and a second more intense event (76 kg CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup>) few days after the final  
314 drainage. In both years mean CH<sub>4</sub> fluxes (0.59 and 0.54 kg CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup> in 2012 and 2013,  
315 respectively) were lower than those obtained for WFL. Methane emissions during the fallow period  
316 were even lower than those measured in WFL and did not exceed 1.60 kg CO<sub>2</sub>-eq ha<sup>-1</sup> d<sup>-1</sup>.

317 Fluxes of CH<sub>4</sub> from DIR treatment were generally negligible throughout the experimental period  
318 (both cropping and fallow periods) (Figure 3c).

319 When cumulating fluxes per phenological stages, as shown in Figure 4, it is evident that the almost  
320 totality of fluxes occurred during the growing season. In 2012, cumulative CH<sub>4</sub> emissions produced  
321 by WFL were statistically higher than those by DFL during the vegetative stage, although this  
322 period lasted ten days less, while any difference could not be detected during the other phenological  
323 stages. On the contrary, in 2013, WFL induced CH<sub>4</sub> emissions significantly greater than DFL not

324 only during vegetative stage (ten days longer) but also during the reproductive stage (having  
325 approximately the same duration).

326

### 327 3.2. Nitrous oxide emissions

328 Except for some minor peaks of low intensity ( $< 17 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ d}^{-1}$ ) after ploughing (only in  
329 2012) and near the beginning of the cropping season in correspondence with the fertilization at  
330 tillering stage (in both years),  $\text{N}_2\text{O}$  fluxes in WFL were generally below the detection limit  
331 throughout the experimental period (Figure 3a). In 2013, the  $\text{N}_2\text{O}$  emissions in DFL treatment  
332 happened at the same time than in WFL, but with higher values, while peaks (of low intensity,  
333 always  $< 30 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ d}^{-1}$ ) were more frequent in 2012, in particular between ploughing and  
334 seeding and just after harvest (Figure 3b).

335 The DIR treatment showed the highest  $\text{N}_2\text{O}$  emissions in both years with respect to the other  
336 treatments (Figure 3c). Maximum fluxes generally coincided with N fertilization events and water  
337 irrigations (Figure 3c). In both cropping seasons, the highest fluxes ( $329$  and  $357 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ d}^{-1}$   
338 in 2012 and 2013, respectively) were observed about 2-3 days after the tillering fertilization. These  
339 peaks were observed only in DIR treatment despite the fact that this treatment received a lower  
340 amount of N fertilizer at the stage with respect to the other two treatments (Table 2). Another 2-3  
341 peaks with lower intensity were also observed in correspondence with panicle formation  
342 fertilization, and with rainfall or irrigation events. No emissions were detected after the booting  
343 stage fertilization.

344 The greatest proportion of the cumulative  $\text{N}_2\text{O}$  emissions occurred during the vegetative stage  
345 (Figure 5) that comprehended all the fertilization events. In this period, cumulative fluxes were  
346 significantly higher in DIR with respect to the other treatments in both years. In 2013 alone,  
347 significantly higher emissions in DIR were also observed in the reproductive stage. Across  
348 treatments, no  $\text{N}_2\text{O}$  emissions were detected during the winter fallow period in 2013, while, as

349 already described, some sporadic pulse-like peaks were observed during the spring of 2012  
350 following mechanical operation for tillage and crop residue incorporation (Figure 3).

351

352

### 353 *3.3. Carbon dioxide emissions*

354 Cumulative emissions of CO<sub>2</sub> for the period between the establishment of flooding in WFL and that  
355 at tillering stage in DFL were calculated for each of the three treatments (Figure 4). Cumulative  
356 emissions of CO<sub>2</sub> at the beginning of the cropping season were generally lower in 2013 with respect  
357 to 2012. In fact, for WFL and DFL treatments we observed 60% lower emissions in 2013 with  
358 respect to 2012, while in DIR the reduction was equivalent to 76%. However, in both years,  
359 cumulative emissions were significantly lower for WFL with respect to DFL and DIR treatments.

360

### 361 *3.4. Annual cumulative emissions and global warming potential*

362 Although the annual pattern of CH<sub>4</sub> emissions in WFL was rather similar in both years, higher  
363 annual cumulative emissions were produced in 2013 than in 2012 (11.7 and 7.4 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup>  
364 <sup>1</sup>, respectively; Figure 7). Emissions were mainly concentrate during the growing season, 99.7% in  
365 2012 and 96.5 in 2013 (7.37 and 11.27 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup>, respectively). Annual cumulative CH<sub>4</sub>  
366 fluxes obtained for DFL were 4.4 and 3.4 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> in 2012 and 2013, respectively, while  
367 cumulative emissions in DIR treatment were zero for both years (Figure 7). We found significant  
368 differences in cumulative emissions across the treatments (Figure 7); in both years, where CH<sub>4</sub>  
369 emissions were significantly lower in DFL than in WFL.

370 In WFL treatment, N<sub>2</sub>O cumulative emissions were 0.217 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> in 2012 and 0.017  
371 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> in 2013. In DFL, the nitrous oxide cumulative values were 0.672 Mg CO<sub>2</sub>-eq  
372 ha<sup>-1</sup> yr<sup>-1</sup> in 2012 and 0,066 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> in 2013. The annual cumulative flux of N<sub>2</sub>O  
373 emissions from DIR treatment was 2.1 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> in 2012 and 1.2 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> in  
374 2013 (Figure 7).

375 Statistical analysis on cumulative N<sub>2</sub>O fluxes in 2012 and 2013 outlined higher emissions in DIR  
376 system than in WFL and DFL treatments, among which no statistical differences were found  
377 (Figure 7).

378 For each treatment, we calculated the GWP due to annual emissions of both CH<sub>4</sub> and N<sub>2</sub>O over the  
379 two years (Table 3). Throughout the experimental period, CH<sub>4</sub> represents the main contributor to  
380 the total GWP in both WFL and DFL treatments accounting for 97-100% and 87-98%, respectively.  
381 In contrast, CH<sub>4</sub> emissions were absent in the DIR treatment where N<sub>2</sub>O represented the only  
382 contributor to the total GWP. Among all treatments, WFL showed the highest annual GWP over  
383 both years with values ranging from 7.6 to 11.7 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup>. A significantly lower GWP  
384 was obtained for the DFL treatment over both years. On average, this water management resulted in  
385 a 56% decrease in the GWP with respect to WFL (33 and 71% less in 2012 and 2013, respectively).  
386 Lowest annual GWP was obtained for the DIR treatment with values ranging between 1.2-2.1 Mg  
387 CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup>, corresponding to a 73-90% decrease with respect to WFL.

388

### 389 3.5. Correlation analyses

390 Emissions of CH<sub>4</sub> from WFL and DFL treatments were positively correlated with topsoil DOC  
391 concentrations and negatively correlated with Eh and, to a lesser extent, also with NO<sub>3</sub><sup>-</sup>  
392 concentrations in the case of WFL (Table 4). In contrast, CH<sub>4</sub> emissions from the DIR treatment  
393 were found to be only negatively correlated to soil Eh values. Moreover, CH<sub>4</sub> emissions in DFL  
394 were weakly correlated to N<sub>2</sub>O emissions. On the other hand, N<sub>2</sub>O emissions were strongly and  
395 positively correlated to NO<sub>3</sub><sup>-</sup> concentrations in DFL and DIR treatments, while only weakly  
396 correlated to DOC concentrations in WFL. Table 5 reports the average values of Eh and topsoil  
397 DOC and NO<sub>3</sub><sup>-</sup> concentrations (mean of two years) at different stages of the cropping season for the  
398 three treatments.

399 We also found a significant correlation ( $r = 0.87$ ,  $P(r) = 0.023$ ,  $n = 6$ ) between cumulative CH<sub>4</sub>  
400 emissions and days of water permanence in the fields (Table 1).

401

## 402 **4. Discussion**

### 403 *4.1. Effect of water management practices on CH<sub>4</sub> emissions*

404 This two-year field study provided further evidence that water management practices adopted  
405 during the growing season may have an important effect on controlling CH<sub>4</sub> emissions in temperate  
406 rice cropping systems. The conventional system based on water seeding and pinpoint flooding  
407 clearly promoted the highest CH<sub>4</sub> fluxes, while any reduction in the permanence of ponding water  
408 in the field proved to be effective in mitigating CH<sub>4</sub> emissions to different extents, depending on the  
409 chosen alternative water practice. In particular, dry seeding and delayed flooding resulted in a 59%  
410 decrease (average of the two measured years) of total CH<sub>4</sub> emissions with respect to the  
411 conventional water seeded treatment, while the adoption of intermittent irrigation totally prevented  
412 CH<sub>4</sub> emissions. Measured CH<sub>4</sub> emissions were in good agreement with results obtained for other  
413 temperate and non-temperate rice paddy fields (Table 6). Pittelkow *et al.* (2014) observed a  
414 significant reduction (47%) in CH<sub>4</sub> emissions with dry seeding with respect to continuous flooding  
415 in temperate paddy fields. Similarly, Zhang *et al.* (2012), Yang *et al.* (2012), and Pandey *et al.*, 2014  
416 report how dry seeding and intermittent irrigation may effectively mitigate CH<sub>4</sub> emissions by 83%  
417 and 71% respectively with respect to conventional water management.

418 The establishment of strictly anaerobic soil conditions ( $< -200$  mV) is a prerequisite for  
419 methanogenic activity (Xu *et al.*, 2003; Rath *et al.*, 1999; Pittelkow *et al.*, 2013), and the strong  
420 positive correlation between cumulative CH<sub>4</sub> emissions and soil flooding days suggests that the  
421 permanence of ponding water in the fields may control CH<sub>4</sub> production. Under continuous flooding  
422 we recorded on average about 104 days of soil submergence, while with the adoption of dry seeding  
423 flooding days were reduced by 22% (about 23 days less) that more than halved total CH<sub>4</sub> emissions.  
424 Furthermore, limiting soil submergence through intermittent irrigation maintained oxic soil

425 conditions over most of the cropping season (Eh values were generally always > 0 mV) and  
426 effectively eliminated CH<sub>4</sub> emissions. The influence of soil water regime on the redox status was  
427 confirmed by the significant negative correlation between redox potential and CH<sub>4</sub> emission found  
428 for all treatments (Table 5). The activity of methanogens is related to the presence of organic  
429 substrates that may serve as electron donors. Water management practices may influence the  
430 degradation of crop residues, an important C source for CH<sub>4</sub> production, incorporated into the soil  
431 between one cropping season and the other.

432 The significant reduction in CH<sub>4</sub> emissions in the dry seeded with respect to the water seeded  
433 treatment was, thus, not only related to the different soil redox status during the first part of the  
434 growing season, but also to a reduced availability of labile organic matter after the onset of field  
435 flooding. With dry seeding, labile organic matter incorporated into the soil with crop residues in  
436 spring was partially degraded under aerobic conditions when the field was still drained. The rapid  
437 mineralization of the readily available organic matter pool under oxic conditions, consequently,  
438 resulted in a lower substrate availability for methanogens after flooding (Pandey et al., 2014). The  
439 significantly higher CO<sub>2</sub> emissions measured for the dry seeded with respect to the water-seeded  
440 treatment during the beginning of the cropping season (Figure 6) lends support to this interpretation.

441 Important differences in cumulative CH<sub>4</sub> emissions from the continuously flooded treatment were  
442 also observed between the two years of study. Although the annual trends in CH<sub>4</sub> emissions were  
443 fairly similar in both years, cumulative emissions in 2013 were about 58% higher with respect to  
444 2012 (Figure 7), and differences in flux intensity were particularly strong, due to higher emission  
445 fluxes during the beginning of the cropping season (Figure 3). This was mainly attributed to a  
446 different timing in crop residue management operations with respect to field flooding between the  
447 two years that could have influenced organic matter availability for the soil microbial biomass. In  
448 fact, whereas soil tillage and residue incorporation was performed 53 days before field flooding in  
449 2012, heavy rainfall in 2013 delayed these operations leading to residue incorporation only 27 days

450 before flooding. These induced higher emissions, significantly greater than those measured from  
451 DFL, not only during vegetative stage, but also during the subsequent reproductive stage.

452 Many studies reported CH<sub>4</sub> emission covaried with crop growth under permanent flooding  
453 conditions, showing low emission at early period of plant growth and the highest peaks during  
454 reproductive stage, as a function of CH<sub>4</sub> transportation through rice aerenchyma (Gogoi *et al.*, 2005;  
455 Pittelkow *et al.*, 2013; Bayer *et al.* 2015). Nevertheless, in our study, besides the peaks around  
456 panicle initiation stage, we observed a first period of intense flux at very early stages of crop  
457 growth, within 3 weeks from seeding, during the period of post-emergence treatments for weed and  
458 pest control. During these weeks, soil microporosity is not completely saturated and it is likely that  
459 CH<sub>4</sub> produced in saturated soil zones escaped from soil to atmosphere mainly via diffusion through  
460 aerated microsites.

#### 461 462 *4.2. Effect of water management practices on N<sub>2</sub>O emissions*

463 Water management practices that were effective in mitigating CH<sub>4</sub> emissions resulted in a  
464 significant increase in N<sub>2</sub>O emissions. In fact, the intermittently irrigated system showed the highest  
465 N<sub>2</sub>O emission peaks and cumulative fluxes, while dry seeding and continuous flooding reduced  
466 total emissions by 77 and 93%, respectively (Figure 7). Soil water content is recognised as one of  
467 the major factors influencing N cycling in soil, in particular N<sub>2</sub>O production (Davidson *et al.*, 2000).  
468 Clayton *et al.* (1997) report maximum N<sub>2</sub>O emissions at a water-filled pore space in the range of 65-  
469 90%. Under drier soil conditions, the oxidative process of nitrification dominates, and NO is the  
470 major gaseous N oxide produced. With increasing moisture contents, nitrification is inhibited while  
471 denitrification prevails with the production of N<sub>2</sub>O as the dominant end product. Under anaerobic  
472 conditions resulting from water saturation, denitrification prevails and much of the N<sub>2</sub>O produced  
473 during this process is further reduced to N<sub>2</sub> by denitrifiers before it escapes from the soil (Davidson  
474 *et al.*, 2000). The intermittent irrigation treatment presumably experienced important variations in

475 soil moisture status due to the frequent irrigation events, consequently resulting in the highest N<sub>2</sub>O  
476 emissions (Figure 7) that were also strongly correlated to soil NO<sub>3</sub><sup>-</sup> concentrations (Table 5)  
477 produced by nitrification and representing the major substrate for denitrifiers (Pathak et al., 2002).  
478 In contrast, maintaining the soil under anoxic conditions for most of the cropping season in both  
479 water and dry seeded flooded treatments probably inhibited nitrification, favoured complete  
480 denitrification, and limited N<sub>2</sub>O exchange between soil and the atmosphere (Pathak et al., 2002).

481 In our study, N<sub>2</sub>O emission peaks observed under intermittent irrigation were strongly linked to N  
482 fertilization events. Furthermore, whereas pre-seeding fertilization events did not induce important  
483 N<sub>2</sub>O emissions, peak fluxes were recorded after the two midseason top-dressing distributions. In  
484 particular, we observed highest emission peaks in correspondence with the irrigation event that  
485 occurred 3-5 days after the second urea distribution. Mineral N fertilization provides a readily  
486 available N pool for nitrification and denitrification, and, when this coincides with significant  
487 changes in soil moisture status, important amounts of applied N may be rapidly lost as N<sub>2</sub>O to the  
488 atmosphere before being further reduced to N<sub>2</sub>. These conditions determined the crucial  
489 contribution of punctual and considerable releases of N<sub>2</sub>O in correspondence with the period  
490 between top-dressing fertilizer application and subsequent irrigation, to the total cumulative N<sub>2</sub>O  
491 emissions over the cropping season. This aspect highlights the importance of minimizing time  
492 between fertilization and re-establishment of waterlogging for the mitigation of N<sub>2</sub>O emissions.  
493 Other factors could have influenced the contribution of N<sub>2</sub>O emissions in proximity of first fertilizer  
494 N application. The presence of labile C from incorporated crop residues, together with the choice of  
495 incorporating N fertilizer, could have in fact favoured complete denitrification (heterotrophic) as  
496 well as enhanced biotic N immobilization that competes with nitrification and denitrification (Said-  
497 Pullicino et al., 2014). This could explain the low N<sub>2</sub>O emissions measured in correspondence with  
498 the first fertilization even in mid-May. Also, the rapid uptake of applied N by the crop at panicle  
499 initiation stage (Hashim et al., 2015) could have strongly limited the availability of mineral N for

500 microbial processes, and be responsible for the lower N<sub>2</sub>O emissions observed for the last  
501 topdressing fertilization event at the beginning of August with respect to the first topdressing event.  
502 The total amount of N<sub>2</sub>O emissions accounted for 2.16 % (3.47 kg N ha<sup>-1</sup>) of applied N in the  
503 intermittently irrigated system (160 kg N ha<sup>-1</sup>), while significantly lower amounts of N were lost in  
504 the dry seeded and water seeded flooded treatments (0.49 % and 0.16 % respectively).

505

#### 506 *4.3. Trade-off between CH<sub>4</sub> e N<sub>2</sub>O emissions and GWP*

507 The GWP was used as an indicator that takes into consideration both CH<sub>4</sub> and N<sub>2</sub>O emissions as a  
508 function of the different irrigation systems considered in this study, and highlighting their relative  
509 incidence to the overall GHG emissions (Figure 7).

510 In 2012 and 2013 growing seasons we found that the continuous flooding treatment recorded the  
511 highest GWP, confirmed by statistical analysis (on average 9.7 Mg CO<sub>2</sub>-eq ha<sup>-1</sup>yr<sup>-1</sup>), with CH<sub>4</sub>  
512 emissions accounting for approximately 99% of the total GWP. Adoption of dry seeding and  
513 delayed flooding resulted in a mean decrease in GWP by 56% (4.3 Mg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup>) compared  
514 to WFL. In this system, CH<sub>4</sub> was still the major contributor to the GWP with N<sub>2</sub>O representing 9%  
515 of total emissions. This difference between conventional treatment and dry seeding underlined how  
516 delaying field flooding by one month at the beginning of the cropping season could effectively half  
517 the GWP even if the decrease in CH<sub>4</sub> emissions was partially offset by a slight increase in N<sub>2</sub>O  
518 emissions.

519 Managing paddy fields under intermittent irrigation resulted in the lowest GWP with respect to the  
520 other treatments. The total amount of emissions from this system was 1.6 Mg CO<sub>2</sub>-eq ha<sup>-1</sup>yr<sup>-1</sup>,  
521 showing how intermittent irrigation can effectively reduce the emissions by 83% (average of two  
522 years). In this system, N<sub>2</sub>O was the only contributor to the overall emissions. In our GWP  
523 calculation, we considered only the emissions of CH<sub>4</sub> and N<sub>2</sub>O, while C losses as CO<sub>2</sub> and possible

524 changes in soil organic C contents were not taken into account, since they occur over periods longer  
525 than those spent for the current study. We suppose that water management practices involving  
526 intermittent irrigation would result in a decrease in soil organic C contents in the long-term, due to  
527 faster organic matter turnover and lower C inputs in the form of straw and below ground residues as  
528 a result of lower biomass yields and reduced rooting depth (Miniotti *et al.*, 2016).

529

## 530 **5. Conclusions**

531 Our two-year field study investigated the implications of water management practices on GHG  
532 emissions from temperate rice cropping systems in northern Italy. Two alternative irrigation  
533 systems limiting the establishment of anoxic soil conditions to different extents by reducing the  
534 permanence of ponding water in field were compared to the conventional continuous flooding  
535 irrigation regime, in terms of CH<sub>4</sub> and N<sub>2</sub>O emissions during both growing and non-growing  
536 seasons. Obtained results identified the effective period of water permanence in field as the main  
537 factor driving CH<sub>4</sub> emissions. On the contrary, N<sub>2</sub>O emissions appeared to be primarily driven by  
538 alternate aerobic-anaerobic conditions in the soil in proximity of N fertilizer distribution.

539 Our results suggest that dry seeding treatment and intermittent irrigation was the best solution in  
540 terms of GHG mitigation, decreasing the GWP by around 83 %, with respect to water seeding and  
541 continuous flooding. Moreover dry seeding and flooding at tillering stage treatment could  
542 simultaneously mitigate CH<sub>4</sub> and modestly increase N<sub>2</sub>O emissions (overall GWP decreased of 56  
543 %) compared with conventional system.

544 Since CH<sub>4</sub> was undeniably the major contributor to GWP and an effective CH<sub>4</sub> attenuation has been  
545 obtained by decreasing the permanence of ponding water in field, future efforts towards GHG  
546 mitigation could be addressed to identify agronomic practices that can effectively shorten periods of  
547 soil anoxic conditions.

548

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553

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690

691 **Figure captions**

692

693 Figure 1. Seasonal variations in precipitation and temperature during the experimental period.

694 Precipitations refer to three days accumulation.

695

696 Figure 2. Timing of crop management for the three experimental treatments. Dates are average of

697 the two years 2012 and 2013.

698

699 Figure 3. Seasonal variation in CH<sub>4</sub> and N<sub>2</sub>O emissions fluxes over two years as a function of water

700 management practices involving (a) water seeding and continuous flooding (WFL), (b) dry seeding

701 and flooding at tillering stage (DFL), and (c) dry seeding and rotational irrigation (DIR). Grey

702 shaded areas represent the presence of flooding water. The two-year studied period was subdivided

703 into: intercropping periods (IC), vegetative stages (from germination to panicle initiation, VE),

704 reproductive stages (from panicle initiation to flowering, RE) and ripening stages (from flowering

705 to senescence, RI), as reported at the top of the graph.

706

707 Figure 4. Cumulative CH<sub>4</sub> emissions for continuous flooding (WFL), dry seeding (DFL) and

708 intermittent irrigation (DIR) systems over different phenological stages for both years. The

709 cropping period was subdivided into three stages: the vegetative stage (from germination to panicle

710 initiation), the reproductive stage (from panicle initiation to flowering), and the ripening stage (from

711 flowering to senescence). Fallow periods were defined as intercropping periods. Error bars

712 represent the standard error of four replicates. Different letters represent significant differences

713 among treatments at 0.05 probability level (REGWQ test).

714

715 Figure 5. Cumulative N<sub>2</sub>O emissions for continuous flooding (WFL), dry seeding (DFL) and  
716 intermittent irrigation (DIR) systems over different phenological stages for both years. The  
717 cropping period was subdivided into three stages: the vegetative stage (from germination to panicle  
718 initiation), the reproductive stage (from panicle initiation to flowering,) and the ripening stage (from  
719 flowering to senescence). Fallow periods were defined as intercropping periods. Error bars  
720 represent the standard error of four replicates. Different letters represent significant differences  
721 among treatments at 0.05 probability level (REGWQ test).

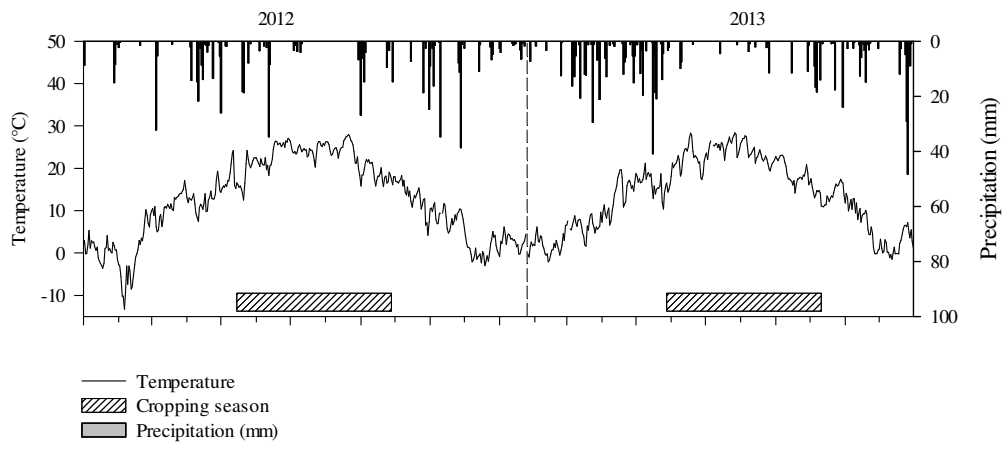
722

723 Figure 6. CO<sub>2</sub> cumulative emissions during the beginning of the cropping season between the  
724 establishment of flooding for WFL and that for DFL treatment (from May 25<sup>th</sup> to June 19<sup>th</sup> in 2012  
725 and from June 7<sup>th</sup> to June 21<sup>th</sup> in 2013) in WFL, DFL and DIR treatments. Treatments P(F) was  
726 equal to 0.000 in 2012 and 0.000 in 2013. Error bars represent the standard error of four replicates.  
727 Different letters represent significant differences among treatments in CO<sub>2</sub> emissions at 0.05  
728 probability level (REGWQ test).

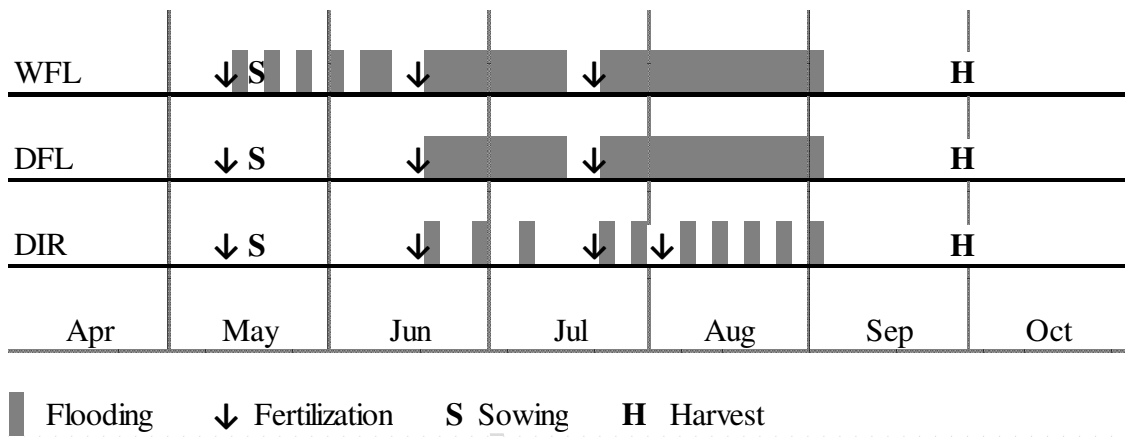
729

730 Figure 7. Yearly cumulative emissions of CH<sub>4</sub> and N<sub>2</sub>O for continuous flooding (WFL), dry seeding  
731 (DFL) and intermittent irrigation (DIR) systems during 2012 and 2013. Measured CH<sub>4</sub> emissions in  
732 DIR treatment were below detection limits in both years and therefore excluded from the analysis.  
733 Treatments P(F) was equal to 0.013 in 2012 and 0.004 in 2013 for CH<sub>4</sub>; 0.000 in 2012 and 0.000 in  
734 2013 for N<sub>2</sub>O. Error bars represent the standard error of four replicates. Different letters represent  
735 significant differences among treatments in N<sub>2</sub>O emission at 0.05 probability level (REGWQ test).  
736 Different italic letters represent significant differences among treatments in CH<sub>4</sub> emission at 0.05  
737 probability level (REGWQ test).

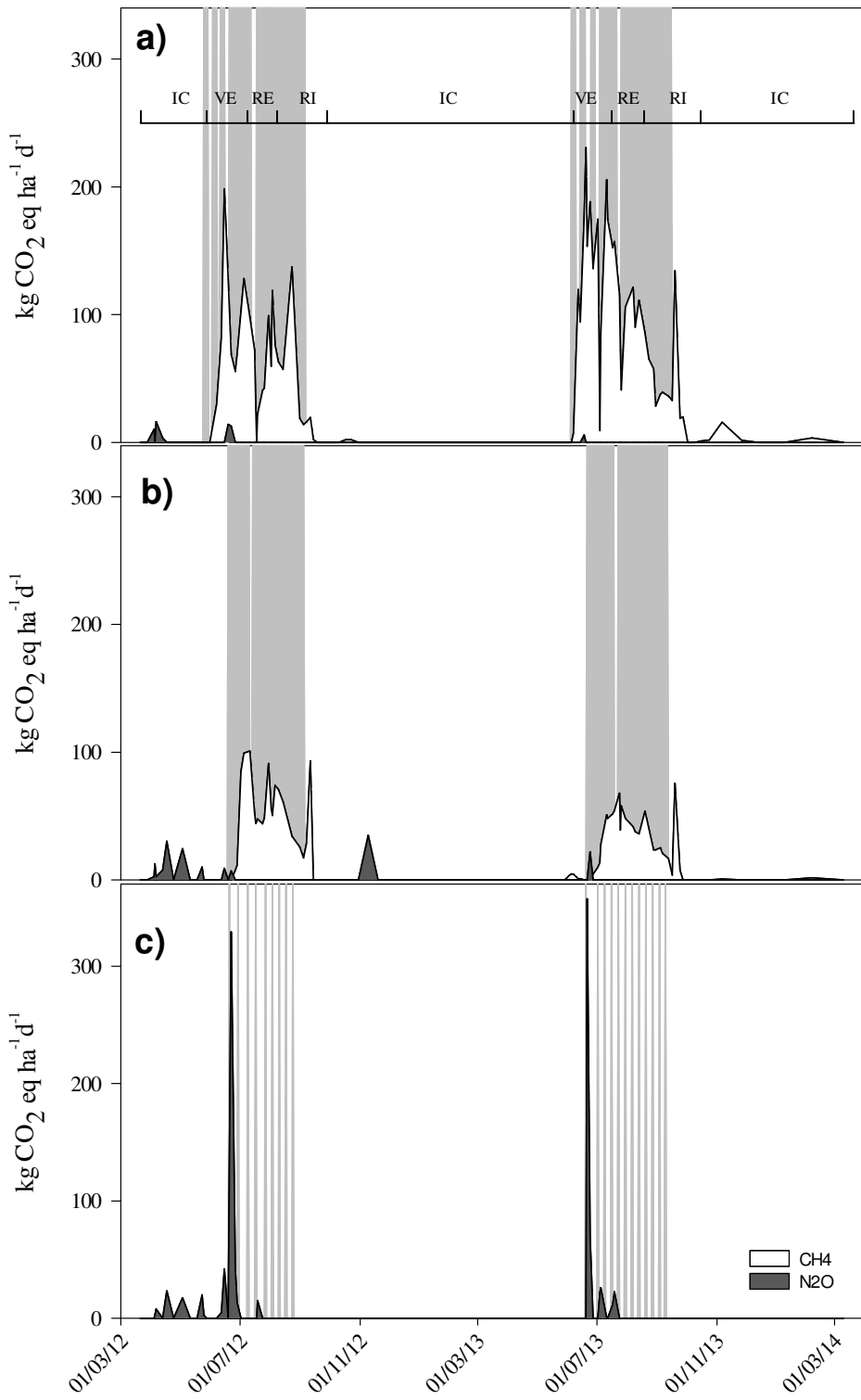
**Figure 1**



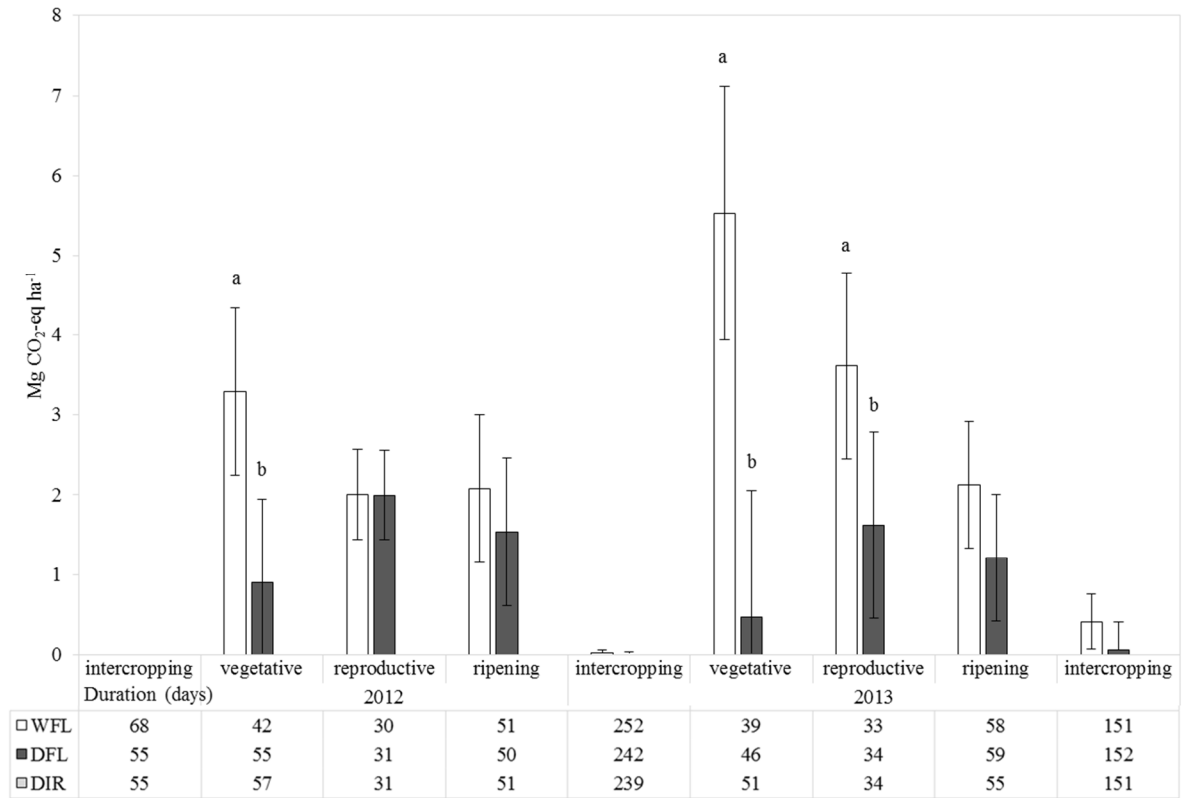
**Figure 2**



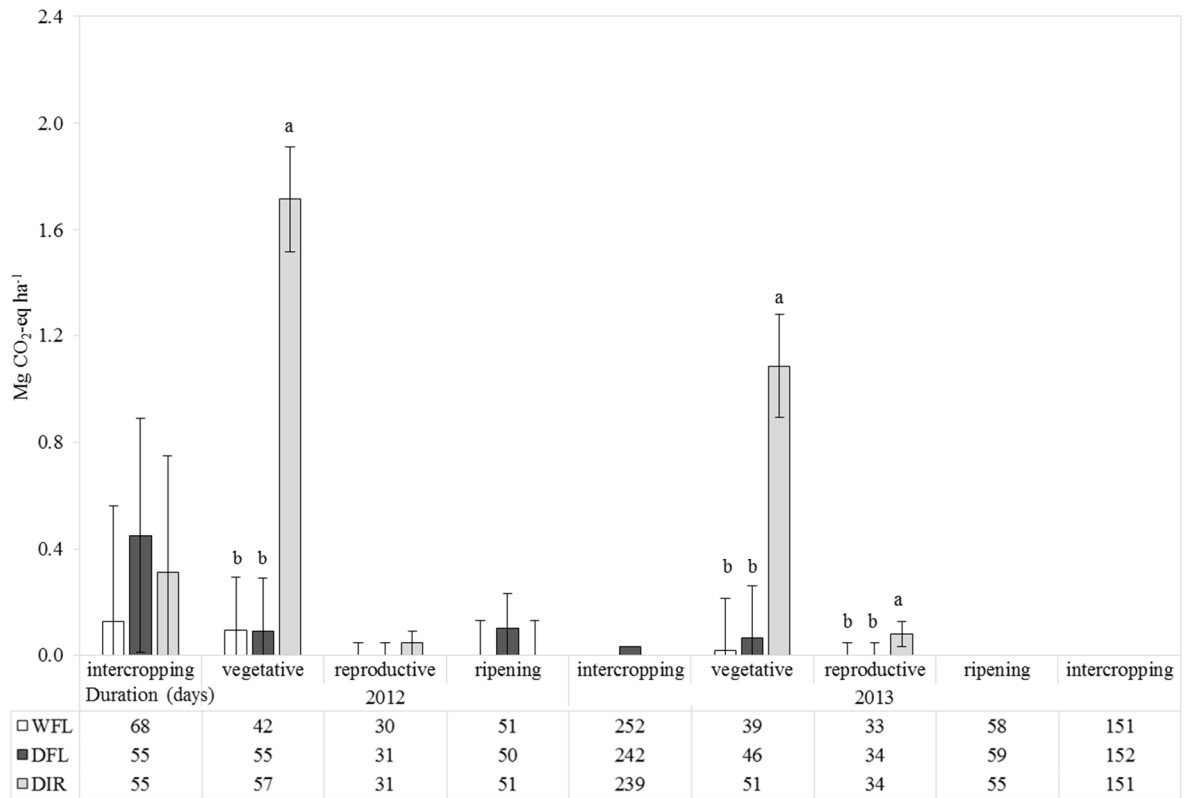
**Figure 3**



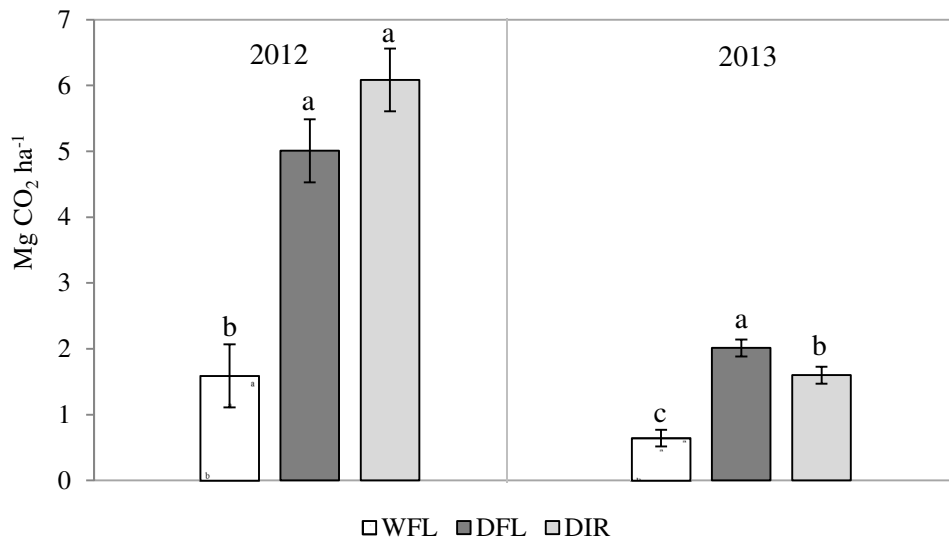
**Figure 4**



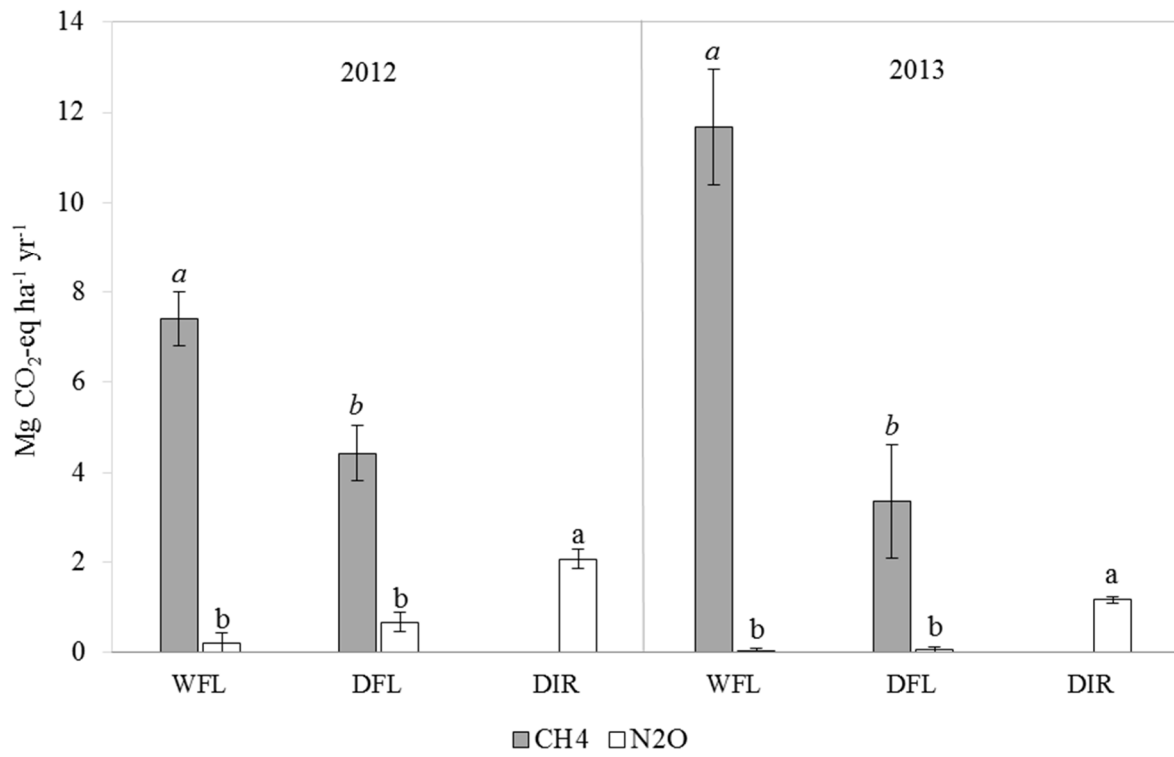
**Figure 5**



**Figure 6**



**Figure 7**



Management practice	WFL		DFL		DIR	
	2012	2013	2012	2013	2012	2013
Spring tillage	2-Apr	9-May	2-Apr	9-May	2-Apr	9-May
First N fertilization	24-May	4-Jun	14-May	27-May	14-May	27-May
Field flooding	25-May	5-Jun	19-Jun	21-Jun	-	-
Seeding	28-May	7-Jun	15-May	28-May	15-May	28-May
Post-emergence treatments	12-Jun	17-Jun	12-Jun	18-Jun	12-Jun	18-Jun
	18-Jun	2-Jul	18-Jun	19-Jun	18-Jun	19-Jun
Second N fertilization	19-Jun	3-Jul	18-Jun	20-Jun	18-Jun	19-Jun
Third N fertilization	17-Jul	25-Jul	13-Jul	22-Jul	16-Jul	15-Jul
Fourth N fertilization	-	-	-	-	2-Aug	5-Aug
Field drained prior to harvest	5-Sep	16-Sep	5-Sep	12-Sep	-	-
Harvest	28-Sep	3-Oct	28-Sep	3-Oct	1-Oct	15-Oct
Flood water in field (days)	104	104	79	84	-	-

Table 1. Crop management for the three experimental treatments in 2012 and in 2013 growing season.

	WFL (kg N ha <sup>-1</sup> )	DFL (kg N ha <sup>-1</sup> )	DIR (kg N ha <sup>-1</sup> )
Pre-seeding	60	40	50
Tillering	60	70	40
Panicle formation	40	50	40
Booting	-	-	30

Table 2. N fertilization in the three experimental treatments.

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Water management	GWP 2012 (Mg CO <sub>2</sub> eq ha <sup>-1</sup> y <sup>-1</sup> )	GWP 2013 (Mg CO <sub>2</sub> eq ha <sup>-1</sup> y <sup>-1</sup> )	GWP mean (Mg CO <sub>2</sub> eq ha <sup>-1</sup> y <sup>-1</sup> )
WFL	7.62 a	11.69 a	9.65 a
DFL	5.11 b	3.42 b	4.26 b
DIR	2.07 c	1.16 b	1.62 c
n	4	4	4
p(F)	0.000	0.000	0.000

Table 3. Annual and mean GWP for continuous flooding (WFL), dry seeding (DFL) and intermittent irrigation (DIR) systems. Different letters represent significant differences among treatments at 0.05 probability level (REGWQ test).

Water management		n	N <sub>2</sub> O	n	DOC	n	Eh	n	NO <sub>3</sub> <sup>-</sup>
WFL	CH <sub>4</sub>	110	0.037	46	0.725***	43	-0.417**	46	-0.361*
	N <sub>2</sub> O			45	0.296*	43	0.031	45	-0.076
DFL	CH <sub>4</sub>	110	-0.195*	34	0.552**	39	-0.574***	35	-0.313
	N <sub>2</sub> O			34	-0.028	39	0.127	35	0.942***
DIR	CH <sub>4</sub>	110	-0.030	35	0.231	41	-0.465**	34	-0.21
	N <sub>2</sub> O			35	0.051	41	-0.152	34	0.615***

Table 4. Correlations between CH<sub>4</sub> and N<sub>2</sub>O emission fluxes and dissolved organic carbon (DOC), redox potential (Eh) and nitrate in soil solution (NO<sub>3</sub><sup>-</sup>). \* =  $p < 0.05$ ; \*\* =  $p < 0.01$ ; \*\*\* =  $p < 0.001$ ; n represents the number of matching pairs.

Treatment	Stage	Eh (mV)			DOC (mg C l <sup>-1</sup> )			NO <sub>3</sub> <sup>-</sup> (mg N l <sup>-1</sup> )		
		Mean	SD	n	Mean	SD	n	Mean	SD	n
WFL	Vegetative	-287	121	14	26	10	14	0,1	0,2	15
	Reproductive	-342	63	15	22	4	9	0,0	0,0	9
	Ripening	-391	24	17	21	3	15	0,0	0,0	15
DFL	Vegetative	92	297	12	18	7	7	10,5	15,0	7
	Reproductive	-293	47	15	23	4	9	0,0	0,0	9
	Ripening	-380	28	17	25	3	15	0,1	0,0	15
DIR	Vegetative	347	80	16	12	4	9	22,8	15,5	9
	Reproductive	365	170	15	11	2	10	0,4	0,4	10
	Ripening	411	151	15	8	2	12	0,2	0,2	11

Table 5. Eh, DOC and NO<sub>3</sub><sup>-</sup> values for continuous flooding (WFL), dry seeding (DFL) and intermittent irrigation (DIR) systems. Vegetative stage is from germination to panicle initiation; reproductive stage is from panicle initiation to flowering; ripening stage is from flowering to senescence. Mean represents the average value of two growing seasons, SD represents standard deviation, n represents the number of sampling dates.

Study	Location	CH <sub>4</sub> (Mg CO <sub>2</sub> eq ha <sup>-1</sup> )		
		WFL	DFL	DIR
Pandey et al. (2014)	Vietnam	2.7	-	0.8
Zhang et al. (2012)	China	4.6	-	1.4
Yang et al. (2012)	China	4.1	-	0.6
Ko et al. (2002)	Korea	9.3	6.0	-
Setyanto et al. (2000)	Indonesia	6.4	-	-
Brodt et al. (2014)	California	6.5	-	-
Pittelkow et al. (2014)	California	8.4	4.4	-
Mejjide et al. (2011)	Italy	10.0	-	-
This study	Italy	9.6	3.9	0.0

Table 6. Reference studies providing methane field emission measurements from different environments. In all studies, CH<sub>4</sub> emissions were measured using the closed chamber method.