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

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Abstract

The mitigation of methane (CH_4) and nitrous oxide (N_2O) emissions from rice paddy fields is pivotal in minimizing the impact of rice production on global warming. The large majority of the world rice is cropped in continuously flooded paddies, where soil anaerobic conditions lead to the production and emission of significant amounts of CH_4. In this work we evaluated the effectiveness of water management techniques alternative to the conventional flooding on the mitigation of CH_4 emissions from paddy soils, and verified whether any concurrent increase in N_2O emissions can totally or partially offset their environmental benefit. Two alternative water management systems were compared to the conventional continuous flooding system (WFL): dry seeding with delayed flooding (DFL) and intermittent irrigation (DIR). Methane and N_2O emissions were monitored at field-scale over two years including both rice cropping and fallow seasons, using non-steady-state closed chamber approach. The DFL system resulted in a 59 % decrease (average of the two measured years) in total CH_4 emissions with respect to WFL, while DIR annulled CH_4 emissions. The effect of CH_4 mitigation of DFL with respect to WFL was mainly concentrated within the vegetative stage, while any significant flux from DIR was recorded throughout the growing and non-growing season. However, DIR resulted in the highest emission peaks and cumulative fluxes of N_2O, almost totally occurred during the vegetative stage. In contrast, DFL and WFL showed N_2O emissions that were 77 and 93% lower with respect to DIR, respectively. Total annual fluxes suggest that the adoption of alternative water management practices that involve dry seeding and subsequent delayed flooding or intermittent irrigation can contribute to significantly reduce the global warming potential of rice cropping systems by 56 and 83 %, respectively with respect to continuous flooding.

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

Highlights

- GWP in continuously flooded paddy was on average 9.65 Mg CO_2eq ha^{-1} y^{-1}
- Intermittent irrigation decreased GWP by 83 % compared to continuous flooding
- Delayed flooding decreased GWP by 56 % compared to continuous flooding
- CH_4 is the major contributor to GWP for continuous (98%) and delayed (92%) flooding
- For intermittent irrigation, N_2O composes 100% of GWP

1. Introduction

Agriculture greatly contributes to anthropogenic greenhouse gas (GHG) emissions and this role is expected to remain pivotal throughout the 21st century. Annual GHG emissions from agricultural production, mainly methane (CH_4) and nitrous oxide (N_2O), were estimated at 5.0–5.8 Gt CO_2-eq y^{-1} for the 2000–2010 period (Faostat, 2013; Tubiello et al., 2013), accounting for approximately 10–12% of global anthropogenic emissions. Paddy rice cultivation is a major source of global CH_4 emissions, estimated to contribute around 11% of the overall CH_4 emissions (493–723 Mt CO_2-eq $y^{-}1$) in 2010 (Smith et al. 2014).

Methane fluxes from paddy fields are the net balance among the main processes of methanogenesis, (responsible for CH_4 production), methanotrophy (responsible for CH_4 consumption), and emission from soil to atmosphere (Wassmann and Aulakh, 2000). As plants develops during its growing cycle, diffusion through aerenchyma becomes the dominant process, responsible for more than 90% emitted, while ebullition and diffusion through flooded water provide minor contributions (Le Mer and Roger, 2001). Methane emissions are reported to covary with crop growth and maximum emissions peaks are normally observed in close proximity of rice panicle initiation (Gogoi *et al.* 2005; Pittelkow *et al.* 2013).

Over 75% of the world rice is produced in paddies that are continuously flooded for most of the cropping season (Van der Hoek et al., 2001). Waterlogging has several agronomic advantages: it mainly limits variations in soil moisture and temperature, and depresses soil-borne disease and weed growth. Nevertheless, flooding drastically reduces the diffusion of atmospheric O_2 into the soil, therefore promoting methanogenesis. This microbial process, in fact, requires strict anaerobiosis and low oxydo-reduction potentials, distinctive traits of flooded paddies (Le Mer and Roger, 2001).

Alternative irrigation systems limiting the presence of a permanent water layer in field have been recently introduced, primarily for water-saving purposes in areas were scarcity is a crucial issue; additionally, these techniques can also be effective at enhancing the diffusion of O_2 into the soil therefore mitigating CH_4 production (Xu et al., 2015, Yang et al., 2012, Sass and Fisher, 1997). Furthermore, since water management affects availability of methanogenic substrates, interfering with straw decomposition, any limitation in water permanence in field, especially at the beginning of the cropping season, can also indirectly reduce CH_4 emissions by containing the presence of methanogenic substrates (Watanabe *et al.*, 2009).

However, water management practices that limit CH_4 production are generally prone to concurrently enhance N_2O emissions (Zou et al., 2005). Frequent alternations in soil redox conditions as a result of dry–wet transitions are known to substantially increase N_2O by favouring both nitrification and denitrification processes responsible for N_2O production. This circumstance can substantially offset the advantages of CH_4 mitigation achieved by introducing drainage periods (Zou et al., 2007; Wang et al., 2011).

Water management in rice cropping systems therefore plays a key role in determining the trade-off between CH_4 and N_2O emissions. The development of effective mitigation strategies aimed at minimizing the global warming potential (GWP) of rice cropping systems must therefore consider the emissions of both gases.

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

In Europe, as in most temperate countries, two irrigation practices were introduced during the last few decades as an alternative to the conventional water management that involves water seeding and continuous flooding until ripening stage, one month before harvest (hereafter identified as WFL). The first alternative consists of dry seeding and delayed flooding at tillering about one month after seeding (hereafter termed DFL), while the second is based on dry seeding followed by intermittent irrigation (henceforth called DIR).

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

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

Building upon these considerations, we hypothesized that, with respect to continuously flooded systems, alternative water management practices that reduce the permanence of ponding water in temperate rice paddies may contribute to reduce CH_4 emissions, though this environmental benefit may be partially offset by a concurrent increase in N_2O emissions. We tested this hypothesis at field-scale by evaluating variations in the annual emissions of CH_4 and N_2O and their specific contribution to the GWP of three water management practices (WFL, DFL, DIR) over a two year experimental periods.

2. Materials and methods

2.1. Experimental site description

A two-year field experiment was conducted in 2012 to 2013 at the Italian Rice Research Centre (Ente Nazionale Risi) in Castello d'Agogna, near Pavia. The site is located in the western area of the plain of the river Po (NW Italy) within the Italian rice district. The soil of the experimental field was a Fluvaquentic Epiaquept coarse silty, mixed, mesic (Soil Survey Staff, 2014) having a loam topsoil (0-30 cm) and a silty loam plough pan (30-40 cm). The topsoil had a mean pH (H_2O) of 5.9, 9.5 g kg^{-1} organic C, 0.8 g kg-1 total N, and a cation exchange capacity of 10.2 cmol(+) kg^{-1}. Further details of the site's soil were provided elsewhere (Said-Pullicino et al., 2016).

The climate is temperate subcontinental, with a mean annual temperature of 12.7 °C and a mean annual precipitation of 704 mm (average of last 20 years), characterized by two main rainfall periods in spring (April–May) and autumn (September–November). In 2012 and 2013, mean annual air temperature was 13.0 °C, while during the growing season the mean temperature was 22.7 °C (Figure 1). The annual cumulative rainfall over the experimental period was 623 and 756 mm in 2012 and 2013, respectively, with around 70% occurring during intercropping periods between October and May (Figure 1). In both years, cropping seasons (May–September) were characterized by several rainfall events during early crop establishment, and limited rainfall thereafter until harvest. In 2013, the exceptionally high precipitations during March–May (379 mm) led to a delay in soil tillage and seeding operations by approximately 15 days.

2.2. Experimental treatments

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

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

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

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

The Gladio variety was considered for the present study.

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

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

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

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

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

In DFL N fertilization was managed, similarly to WFL, splitting the total amount of 160 kg ha^{-1} in three interventions: 40 kg N ha^{-1} before seeding and two top-dressing applications of 70 and 50 kg N ha^{-1}; a lower amount of N with respect to WFL was applied before seeding for preventing losses via NH_3 volatilization.

In DIR, fertilization was planned slightly differently: we applied the same amount of urea (160 kg N ha^{-1}) but split in four distributions, in order to increase N use efficiency. In detail, we decided a fourth fertilization at booting stage as necessary for maximizing productive performances of the system. In dry conditions a significant amount of N is lost by nitrification, increasing split applications could improve Nitrogen Use Efficency (NUE) (Raun et al., 2002).

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

2.3. Gaseous emissions

Emissions of CH_4 and N_2O were measured from March 21th 2012 to March 21th 2014, for a total of 110 sampling dates, split into the first year, thereafter called “2012” (from March 21th 2012 to March 21th 2013) and the second year, thereafter called “2013” (from March 21th 2013 to March 21th 2014).

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

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

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

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

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

Headspace gas samples from inside the closed chambers were collected by propylene syringes at 0, 15, and 30 min after chamber closure. Thirty-millilitre air samples were collected and injected into 12-mL evacuated vials closed with butyl rubber septa (Exetainer® vial from Labco Limited, UK). Gas concentrations in collected samples were determined by gas chromatography by means of a fully automated gas chromatograph (Agilent 7890A with a Gerstel Maestro MPS2 auto sampler) equipped with electron capture, thermal conductivity and flame ionization detectors for the quantification of N_2O, CO_2 and CH_4, respectively.

Fluxes were calculated from the linear or nonlinear (Hutchinson and Mosier, 1981) increase in concentration (selected according to the emission pattern) in the chamber headspace with time, as suggested by Livingston and Hutchinson (1995). The MDF (Minimum Detectable Flux) varies in relation to the detection limit of the gas chromatograph and the chamber volume. The latter changed in time during the cropping season to accommodate for rice growth. Values for MDF ranged between 5-20 g N ha^{-1} d^{-1} for N_2O, 12-48 g C ha^{-1} d^{-1} for CH_4, and 2.62-10.61 kg C ha^{-1} d^{-1} for CO_2. Fluxes were set to zero if the change in gas concentration during chamber enclosure fell below the MDF.

Although the emphasis of this study was on CH_4 and N_2O emissions, CO_2 emission data determined simultaneously were also reported. However, during the cropping season, the presence of the rice plant inside the chamber meant that measured CO_2 fluxes also included a contribution from plant respiration. For this reason, we only investigated CO_2 emissions in the period between the establishment of flooding in WFL and that for DFL at tillering. During this period, the contribution of plant respiration to the total CO_2 emissions was assumed to be minor and of the same intensity across all treatments, and CO_2 fluxes were attributable to soil respiration alone.

Estimates of cumulative CH_4 and N_2O emissions for each plot were based on linear interpolation across sampling days. For both years, annual cumulative fluxes as well as those relative to the growing season and intercropping period, were calculated. Moreover, each growing season was further subdivided into the three above-mentioned phenological periods (vegetative stage, reproductive stage, and ripening stage). The Global Warming Potential (GWP) was also calculated to estimate the potential future impacts of emissions of different gases upon the climate system in a comparative way. The GWP is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of CO_2. For GWP estimation, we used the IPCC factors over the 100-year time scale in order to convert CH_4 and N_2O to CO_2 equivalents (25 and 298, respectively) (Smith et al., 2014).

2.4. Soil parameter measurements

Within the same experimental site, other concurrent parameters, ancillary to GHG emissions, were measured. Throughout the cropping seasons, soil redox potential (Eh) in each treatment was potentiometrically measured at a soil depth of 10 cm. Soil solutions were also collected on a weekly basis in correspondence with gas flux measurements by means of ceramic cups installed at 25 cm. All pore water samples were filtered through a 0.45 µm membrane filter and analysed for dissolved organic carbon (DOC) by high temperature combustion (VarioTOC, Elementar, Hanau, Germany), and nitrates (NO_3^-) by ion chromatography (Dionex 500, Sunnyvale, CA, USA).

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

2.5. Data analyses

Statistical effect of water management on cumulative fluxes of N_2O, CH_4 and CO_2 emissions and GWP was determined by one-way ANOVA. Before ANOVA application, Shapiro-Wilk test for normality and Levene test for homoscedasticity were applied. Years were independently analysed due to their heteroscedasticity. When ANOVA null hypothesis was rejected, treatment averages were separated by means of REGWQ (Ryan-Einot-Gabriel-Welch Q test) post hoc test. Correlations between daily CH_4 and N_2O emissions, Eh, DOC and NO_3^- were analysed for each treatment separately by means of Pearson correlation. We also investigated the correlation between CH_4 emissions and days of water permanence in fields by means of Pearson correlation. All statistical analyses were performed using the SPSS Statistics 21 (SPSS Inc., Chicago, IL).

3. Results

3.1. Methane emissions

In both years, CH_4 emissions from the WFL treatment started in correspondence with the days of drainage operated at seedling stage for root anchoring, and rapidly increased showing a first peak around the post-emergence weed and pest control treatments, that in both years were the highest peaks produced in the season (198 and 231 kg CO_2-eq ha^{-1} d^{-1} in 2012 and 2013, respectively) (Figure 3a). These peaks were followed by a great reduction of fluxes during the drainage period set up for allowing the fertilization at tillering stage, and subsequently increased again producing a second emission peak, few days before the panicle initiation stage (128 and 205 kg CO_2-eq ha^{-1} d^{-1} in 2012 and 2013, respectively). During the subsequent reproductive and ripening stages, emissions were spaced out by a great reduction of fluxes occurred during the drainage period around the third fertilization. Emissions drastically decreased after producing a singular high peak (22 and 134 kg CO_2-eq ha^{-1} d^{-1} in 2012 and 2013, respectively) few days after the final drainage before harvest. Throughout the fallow season in both years, CH_4 fluxes remained very low (<16 kg CO_2-eq ha^{-1} d^{-1}). In 2013, fluxes were generally higher than in 2012. Mean fluxes were 0.94 and 1.98 kg CO_2-eq ha^{-1} d^{-1} in 2012 and 2013, respectively.

In the DFL treatment, CH_4 emissions started one week after water establishment (Figure 3b), and subsequently increased until the panicle initiation stage. In 2012 emissions showed the highest peak (101 kg CO_2-eq ha^{-1} d^{-1}) around panicle initiation, followed by an alternation between emission peaks and drastic reductions of flux- the main one during the drainage period around the second top-dressing fertilization- similarly to that observed for WFL; as observed for WFL, DFL produced a high emission peak (93 kg CO_2-eq ha^{-1} d^{-1}) few days after the final drainage. Differently from what observed for WFL, in 2013, fluxes were generally lower than in 2012, showing a first emission peak (68 kg CO_2-eq ha^{-1} d^{-1}) during the reproductive stage, approximately 10 days after panicle initiation, and a second more intense event (76 kg CO_2-eq ha^{-1} d^{-1}) few days after the final drainage. In both years mean CH_4 fluxes (0.59 and 0.54 kg CO_2-eq ha^{-1} d^{-1} in 2012 and 2013, respectively) were lower than those obtained for WFL. Methane emissions during the fallow period were even lower than those measured in WFL and did not exceed 1.60 kg CO_2-eq ha^{-1} d^{-1}.

Fluxes of CH_4 from DIR treatment were generally negligible throughout the experimental period (both cropping and fallow periods) (Figure 3c).

When cumulating fluxes per phenological stages, as shown in Figure 4, it is evident that the almost totality of fluxes occurred during the growing season. In 2012, cumulative CH_4 emissions produced by WFL were statistically higher than those by DFL during the vegetative stage, although this period lasted ten days less, while any difference could not be detected during the other phenological stages. On the contrary, in 2013, WFL induced CH_4 emissions significantly greater than DFL not only during vegetative stage (ten days longer) but also during the reproductive stage (having approximately the same duration).

3.2. Nitrous oxide emissions

Except for some minor peaks of low intensity (< 17 kg CO_2-eq ha^{-1} d^{-1}) after ploughing (only in 2012) and near the beginning of the cropping season in correspondence with the fertilization at tillering stage (in both years), N_2O fluxes in WFL were generally below the detection limit throughout the experimental period (Figure 3a). In 2013, the N_2O emissions in DFL treatment happened at the same time than in WFL, but with higher values, while peaks (of low intensity, always < 30 kg CO_2-eq ha^{-1} d^{-1}) were more frequent in 2012, in particular between ploughing and seeding and just after harvest (Figure 3b).

The DIR treatment showed the highest N_2O emissions in both years with respect to the other treatments (Figure 3c). Maximum fluxes generally coincided with N fertilization events and water irrigations (Figure 3c). In both cropping seasons, the highest fluxes (329 and 357 kg CO_2-eq ha^{-1} d^{-1} in 2012 and 2013, respectively) were observed about 2-3 days after the tillering fertilization. These peaks were observed only in DIR treatment despite the fact that this treatment received a lower amount of N fertilizer at the stage with respect to the other two treatments (Table 2). Another 2-3 peaks with lower intensity were also observed in correspondence with panicle formation fertilization, and with rainfall or irrigation events. No emissions were detected after the booting stage fertilization.

The greatest proportion of the cumulative N_2O emissions occurred during the vegetative stage (Figure 5) that comprehended all the fertilization events. In this period, cumulative fluxes were significantly higher in DIR with respect to the other treatments in both years. In 2013 alone, significantly higher emissions in DIR were also observed in the reproductive stage. Across treatments, no N_2O emissions were detected during the winter fallow period in 2013, while, as already described, some sporadic pulse-like peaks were observed during the spring of 2012 following mechanical operation for tillage and crop residue incorporation (Figure 3).

3.3. Carbon dioxide emissions

Cumulative emissions of CO_2 for the period between the establishment of flooding in WFL and that at tillering stage in DFL were calculated for each of the three treatments (Figure 4). Cumulative emissions of CO_2 at the beginning of the cropping season were generally lower in 2013 with respect to 2012. In fact, for WFL and DFL treatments we observed 60% lower emissions in 2013 with respect to 2012, while in DIR the reduction was equivalent to 76%. However, in both years, cumulative emissions were significantly lower for WFL with respect to DFL and DIR treatments.

3.4. Annual cumulative emissions and global warming potential

Although the annual pattern of CH_4 emissions in WFL was rather similar in both years, higher annual cumulative emissions were produced in 2013 than in 2012 (11.7 and 7.4 Mg CO_2-eq ha^{-1} yr^{-1}, respectively; Figure 7). Emissions were mainly concentrate during the growing season, 99.7% in 2012 and 96.5 in 2013 (7.37 and 11.27 Mg CO_2-eq ha^{-1} yr^{-1}, respectively). Annual cumulative CH_4 fluxes obtained for DFL were 4.4 and 3.4 Mg CO_2-eq ha^{-1} yr^{-1} in 2012 and 2013, respectively, while cumulative emissions in DIR treatment were zero for both years (Figure 7). We found significant differences in cumulative emissions across the treatments (Figure 7); in both years, where CH_4 emissions were significantly lower in DFL than in WFL.

In WFL treatment, N_2O cumulative emissions were 0.217 Mg CO_2-eq ha^{-1} yr^{-1} in 2012 and 0.017 Mg CO_2-eq ha^{-1} yr^{-1} in 2013. In DFL, the nitrous oxide cumulative values were 0.672 Mg CO_2-eq ha^{-1} yr^{-1} in 2012 and 0,066 Mg CO_2-eq ha^{-1} yr^{-1} in 2013. The annual cumulative flux of N_2O emissions from DIR treatment was 2.1 Mg CO_2-eq ha^{-1} yr^{-1} in 2012 and 1.2 Mg CO_2-eq ha^{-1} yr^{-1} in 2013 (Figure 7).

Statistical analysis on cumulative N_2O fluxes in 2012 and 2013 outlined higher emissions in DIR system than in WFL and DFL treatments, among which no statistical differences were found (Figure 7).

For each treatment, we calculated the GWP due to annual emissions of both CH_4 and N_2O over the two years (Table 3). Throughout the experimental period, CH_4 represents the main contributor to the total GWP in both WFL and DFL treatments accounting for 97-100% and 87-98%, respectively. In contrast, CH_4 emissions were absent in the DIR treatment where N_2O represented the only contributor to the total GWP. Among all treatments, WFL showed the highest annual GWP over both years with values ranging from 7.6 to 11.7 Mg CO_2-eq ha^{-1} yr^{-1}. A significantly lower GWP was obtained for the DFL treatment over both years. On average, this water management resulted in a 56% decrease in the GWP with respect to WFL (33 and 71% less in 2012 and 2013, respectively). Lowest annual GWP was obtained for the DIR treatment with values ranging between 1.2-2.1 Mg CO_2-eq ha^{-1} yr^{-1}, corresponding to a 73-90% decrease with respect to WFL.

3.5. Correlation analyses

Emissions of CH_4 from WFL and DFL treatments were positively correlated with topsoil DOC concentrations and negatively correlated with Eh and, to a lesser extent, also with NO_3^- concentrations in the case of WFL (Table 4). In contrast, CH_4 emissions from the DIR treatment were found to be only negatively correlated to soil Eh values. Moreover, CH_4 emissions in DFL were weakly correlated to N_2O emissions. On the other hand, N_2O emissions were strongly and positively correlated to NO_3^- concentrations in DFL and DIR treatments, while only weakly correlated to DOC concentrations in WFL. Table 5 reports the average values of Eh and topsoil DOC and NO_3^- concentrations (mean of two years) at different stages of the cropping season for the three treatments.

We also found a significant correlation ($r = 0.87$, $P(r) = 0.023$, $n = 6$) between cumulative CH_4 emissions and days of water permanence in the fields (Table 1).

4. Discussion

4.1. Effect of water management practices on CH_4 emissions

This two-year field study provided further evidence that water management practices adopted during the growing season may have an important effect on controlling CH_4 emissions in temperate rice cropping systems. The conventional system based on water seeding and pinpoint flooding clearly promoted the highest CH_4 fluxes, while any reduction in the permanence of ponding water in the field proved to be effective in mitigating CH_4 emissions to different extents, depending on the chosen alternative water practice. In particular, dry seeding and delayed flooding resulted in a 59% decrease (average of the two measured years) of total CH_4 emissions with respect to the conventional water seeded treatment, while the adoption of intermittent irrigation totally prevented CH_4 emissions. Measured CH_4 emissions were in good agreement with results obtained for other temperate and non-temperate rice paddy fields (Table 6). Pittelkow *et al.* (2014) observed a significant reduction (47%) in CH_4 emissions with dry seeding with respect to continuous flooding in temperate paddy fields. Similarly, Zhang et al. (2012), Yang et al. (2012), and Pandey et al., 2014 report how dry seeding and intermittent irrigation may effectively mitigate CH_4 emissions by 83% and 71% respectively with respect to conventional water management.

The establishment of strictly anaerobic soil conditions (< –200 mV) is a prerequisite for methanogenic activity (Xu et al., 2003; Rath et al., 1999; Pittelkow et al., 2013), and the strong positive correlation between cumulative CH_4 emissions and soil flooding days suggests that the permanence of ponding water in the fields may control CH_4 production . Under continuous flooding we recorded on average about 104 days of soil submergence, while with the adoption of dry seeding flooding days were reduced by 22% (about 23 days less) that more than halved total CH_4 emissions. Furthermore, limiting soil submergence through intermittent irrigation maintained oxic soil conditions over most of the cropping season (Eh values were generally always > 0 mV) and effectively eliminated CH_4 emissions. The influence of soil water regime on the redox status was confirmed by the significant negative correlation between redox potential and CH_4 emission found for all treatments (Table 5). The activity of methanogens is related to the presence of organic substrates that may serve as electron donors. Water management practices may influence the degradation of crop residues, an important C source for CH_4 production, incorporated into the soil between one cropping season and the other.

The significant reduction in CH_4 emissions in the dry seeded with respect to the water seeded treatment was, thus, not only related to the different soil redox status during the first part of the growing season, but also to a reduced availability of labile organic matter after the onset of field flooding. With dry seeding, labile organic matter incorporated into the soil with crop residues in spring was partially degraded under aerobic conditions when the field was still drained. The rapid mineralization of the readily available organic matter pool under oxic conditions, consequently, resulted in a lower substrate availability for methanogens after flooding (Pandey et al., 2014). The significantly higher CO_2 emissions measured for the dry seeded with respect to the water-seeded treatment during the beginning of the cropping season (Figure 6) lends support to this interpretation.

Important differences in cumulative CH_4 emissions from the continuously flooded treatment were also observed between the two years of study. Although the annual trends in CH_4 emissions were fairly similar in both years, cumulative emissions in 2013 were about 58% higher with respect to 2012 (Figure 7), and differences in flux intensity were particularly strong, due to higher emission fluxes during the beginning of the cropping season (Figure 3). This was mainly attributed to a different timing in crop residue management operations with respect to field flooding between the two years that could have influenced organic matter availability for the soil microbial biomass. In fact, whereas soil tillage and residue incorporation was performed 53 days before field flooding in 2012, heavy rainfall in 2013 delayed these operations leading to residue incorporation only 27 days before flooding. These induced higher emissions, significantly greater than those measured from DFL, not only during vegetative stage, but also during the subsequent reproductive stage.

Many studies reported CH_4 emission covaried with crop growth under permanent flooding conditions, showing low emission at early period of plant growth and the highest peaks during reproductive stage, as a function of CH_4 transportation through rice aerenchyma (Gogoi *et al.*, 2005; Pittelkow *et al*, 2013; Bayer *et al.* 2015). Nevertheless, in our study, besides the peaks around panicle initiation stage, we observed a first period of intense flux at very early stages of crop growth, within 3 weeks from seeding, during the period of post-emergence treatments for weed and pest control. During these weeks, soil microporosity is not completely saturated and it is likely that CH_4 produced in saturated soil zones escaped from soil to atmosphere mainly via diffusion through aerated microsites.

4.2. Effect of water management practices on N_2O emissions

Water management practices that were effective in mitigating CH_4 emissions resulted in a significant increase in N_2O emissions. In fact, the intermittently irrigated system showed the highest N_2O emission peaks and cumulative fluxes, while dry seeding and continuous flooding reduced total emissions by 77 and 93%, respectively (Figure 7). Soil water content is recognised as one of the major factors influencing N cycling in soil, in particular N_2O production (Davidson et al., 2000). Clayton et al. (1997) report maximum N_2O emissions at a water-filled pore space in the range of 65-90%. Under drier soil conditions, the oxidative process of nitrification dominates, and NO is the major gaseous N oxide produced. With increasing moisture contents, nitrification is inhibited while denitrification prevails with the production of N_2O as the dominant end product. Under anaerobic conditions resulting from water saturation, denitrification prevails and much of the N_2O produced during this process is further reduced to N_2 by denitrifiers before it escapes from the soil (Davidson et al., 2000). The intermittent irrigation treatment presumably experienced important variations in soil moisture status due to the frequent irrigation events, consequently resulting in the highest N_2O emissions (Figure 7) that were also strongly correlated to soil NO_3^- concentrations (Table 5) produced by nitrification and representing the major substrate for denitrifiers (Pathak et al., 2002). In contrast, maintaining the soil under anoxic conditions for most of the cropping season in both water and dry seeded flooded treatments probably inhibited nitrification, favoured complete denitrification, and limited N_2O exchange between soil and the atmosphere (Pathak et al., 2002).

In our study, N_2O emission peaks observed under intermittent irrigation were strongly linked to N fertilization events. Furthermore, whereas pre-seeding fertilization events did not induce important N_2O emissions, peak fluxes were recorded after the two midseason top-dressing distributions. In particular, we observed highest emission peaks in correspondence with the irrigation event that occurred 3-5 days after the second urea distribution. Mineral N fertilization provides a readily available N pool for nitrification and denitrification, and, when this coincides with significant changes in soil moisture status, important amounts of applied N may be rapidly lost as N_2O to the atmosphere before being further reduced to N_2. These conditions determined the crucial contribution of punctual and considerable releases of N_2O in correspondence with the period between top-dressing fertilizer application and subsequent irrigation, to the total cumulative N_2O emissions over the cropping season. This aspect highlights the importance of minimizing time between fertilization and re-establishment of waterlogging for the mitigation of N_2O emissions. Other factors could have influenced the contribution of N_2O emissions in proximity of first fertilizer N application. The presence of labile C from incorporated crop residues, together with the choice of incorporating N fertilizer, could have in fact favoured complete denitrification (heterotrophic) as well as enhanced biotic N immobilization that competes with nitrification and denitrification (Said-Pullicino et al., 2014). This could explain the low N_2O emissions measured in correspondence with the first fertilization even in mid-May. Also, the rapid uptake of applied N by the crop at panicle initiation stage (Hashim et al., 2015) could have strongly limited the availability of mineral N for microbial processes, and be responsible for the lower N_2O emissions observed for the last topdressing fertilization event at the beginning of August with respect to the first topdressing event. The total amount of N_2O emissions accounted for 2.16 % (3.47 kg N ha^{-1}) of applied N in the intermittently irrigated system (160 kg N ha^{-1}), while significantly lower amounts of N were lost in the dry seeded and water seeded flooded treatments (0.49 % and 0.16 % respectively).

4.3. Trade-off between CH_4 e N_2O emissions and GWP

The GWP was used as an indicator that takes into consideration both CH_4 and N_2O emissions as a function of the different irrigation systems considered in this study, and highlighting their relative incidence to the overall GHG emissions (Figure 7).

In 2012 and 2013 growing seasons we found that the continuous flooding treatment recorded the highest GWP, confirmed by statistical analysis (on average 9.7 Mg CO_2-eq $ha^{-1}yr^{-1}$), with CH_4 emissions accounting for approximately 99% of the total GWP. Adoption of dry seeding and delayed flooding resulted in a mean decrease in GWP by 56% (4.3 Mg CO_2-eq ha^{-1} yr^{-1}) compared to WFL. In this system, CH_4 was still the major contributor to the GWP with N_2O representing 9% of total emissions. This difference between conventional treatment and dry seeding underlined how delaying field flooding by one month at the beginning of the cropping season could effectively half the GWP even if the decrease in CH_4 emissions was partially offset by a slight increase in N_2O emissions.

Managing paddy fields under intermittent irrigation resulted in the lowest GWP with respect to the other treatments. The total amount of emissions from this system was 1.6 Mg CO_2-eq $ha^{-1}yr^{-1}$, showing how intermittent irrigation can effectively reduce the emissions by 83% (average of two years). In this system, N_2O was the only contributor to the overall emissions. In our GWP calculation, we considered only the emissions of CH_4 and N_2O, while C losses as CO_2 and possible changes in soil organic C contents were not taken into account, since they occur over periods longer than those spent for the current study. We suppose that water management practices involving intermittent irrigation would result in a decrease in soil organic C contents in the long-term, due to faster organic matter turnover and lower C inputs in the form of straw and below ground residues as a result of lower biomass yields and reduced rooting depth (Miniotti *et al.,* 2016).

5. Conclusions

Our two-year field study investigated the implications of water management practices on GHG emissions from temperate rice cropping systems in northern Italy. Two alternative irrigation systems limiting the establishment of anoxic soil conditions to different extents by reducing the permanence of ponding water in field were compared to the conventional continuous flooding irrigation regime, in terms of CH_4 and N_2O emissions during both growing and non-growing seasons. Obtained results identified the effective period of water permanence in field as the main factor driving CH_4 emissions. On the contrary, N_2O emissions appeared to be primarily driven by alternate aerobic-anaerobic conditions in the soil in proximity of N fertilizer distribution.

Our results suggest that dry seeding treatment and intermittent irrigation was the best solution in terms of GHG mitigation, decreasing the GWP by around 83 %, with respect to water seeding and continuous flooding. Moreover dry seeding and flooding at tillering stage treatment could simultaneously mitigate CH_4 and modestly increase N_2O emissions (overall GWP decreased of 56 %) compared with conventional system.

Since CH_4 was undeniably the major contributor to GWP and an effective CH_4 attenuation has been obtained by decreasing the permanence of ponding water in field, future efforts towards GHG mitigation could be addressed to identify agronomic practices that can effectively shorten periods of soil anoxic conditions.

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Figure captions

Figure 1. Seasonal variations in precipitation and temperature during the experimental period. Precipitations refer to three days accumulation.

Figure 2. Timing of crop management for the three experimental treatments. Dates are average of the two years 2012 and 2013.

Figure 3. Seasonal variation in CH_4 and N_2O emissions fluxes over two years as a function of water management practices involving (a) water seeding and continuous flooding (WFL), (b) dry seeding and flooding at tillering stage (DFL), and (c) dry seeding and rotational irrigation (DIR). Grey shaded areas represent the presence of flooding water. The two-year studied period was subdivided into: intercropping periods (IC), vegetative stages (from germination to panicle initiation, VE), reproductive stages (from panicle initiation to flowering, RE) and ripening stages (from flowering to senescence, RI), as reported at the top of the graph.

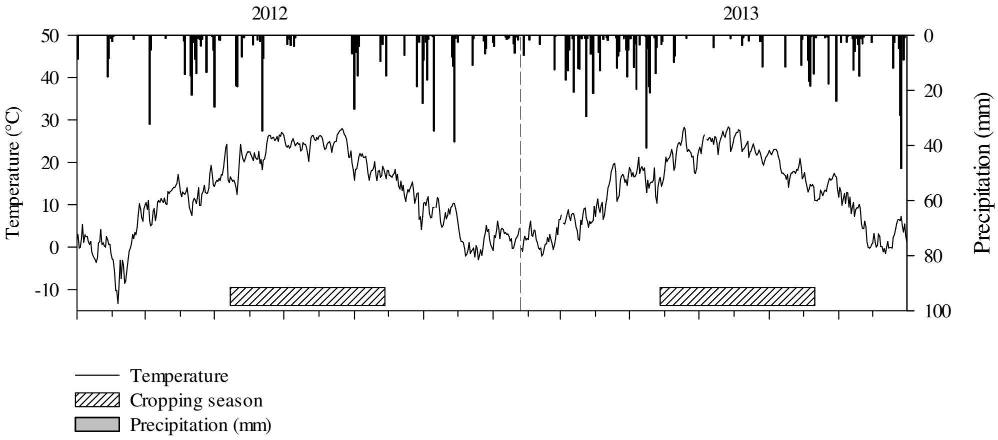
Figure 4. Cumulative CH_4 emissions for continuous flooding (WFL), dry seeding (DFL) and intermittent irrigation (DIR) systems over different phenological stages for both years. The cropping period was subdivided into three stages: the vegetative stage (from germination to panicle initiation), the reproductive stage (from panicle initiation to flowering), and the ripening stage (from flowering to senescence). Fallow periods were defined as intercropping periods. Error bars represent the standard error of four replicates. Different letters represent significant differences among treatments at 0.05 probability level (REGWQ test).

Figure 5. Cumulative N_2O emissions for continuous flooding (WFL), dry seeding (DFL) and intermittent irrigation (DIR) systems over different phenological stages for both years. The cropping period was subdivided into three stages: the vegetative stage (from germination to panicle initiation), the reproductive stage (from panicle initiation to flowering,) and the ripening stage (from flowering to senescence). Fallow periods were defined as intercropping periods. Error bars represent the standard error of four replicates. Different letters represent significant differences among treatments at 0.05 probability level (REGWQ test).

Figure 6. CO_2 cumulative emissions during the beginning of the cropping season between the establishment of flooding for WFL and that for DFL treatment (from May 25thto June 19th in 2012 and from June 7th to June 21th in 2013) in WFL, DFL and DIR treatments. Treatments P(F) was equal to 0.000 in 2012 and 0.000 in 2013. Error bars represent the standard error of four replicates. Different letters represent significant differences among treatments in CO_2 emissions at 0.05 probability level (REGWQ test).

Figure 7. Yearly cumulative emissions of CH_4 and N_2O for continuous flooding (WFL), dry seeding (DFL) and intermittent irrigation (DIR) systems during 2012 and 2013. Measured CH_4 emissions in DIR treatment were below detection limits in both years and therefore excluded from the analysis. Treatments P(F) was equal to 0.013 in 2012 and 0.004 in 2013 for CH_4; 0.000 in 2012 and 0.000 in 2013 for N_2O. Error bars represent the standard error of four replicates. Different letters represent significant differences among treatments in N_2O emission at 0.05 probability level (REGWQ test). Different italic letters represent significant differences among treatments in CH_4 emission at 0.05 probability level (REGWQ test).

Figure 1



2012
2013
50
40
30
20
10
0
-10
Temperature (°C)
0
20
40
60
80
100
Precipitation (mm)
Temperature
Cropping season
Precipitation (mm)

Figure 2

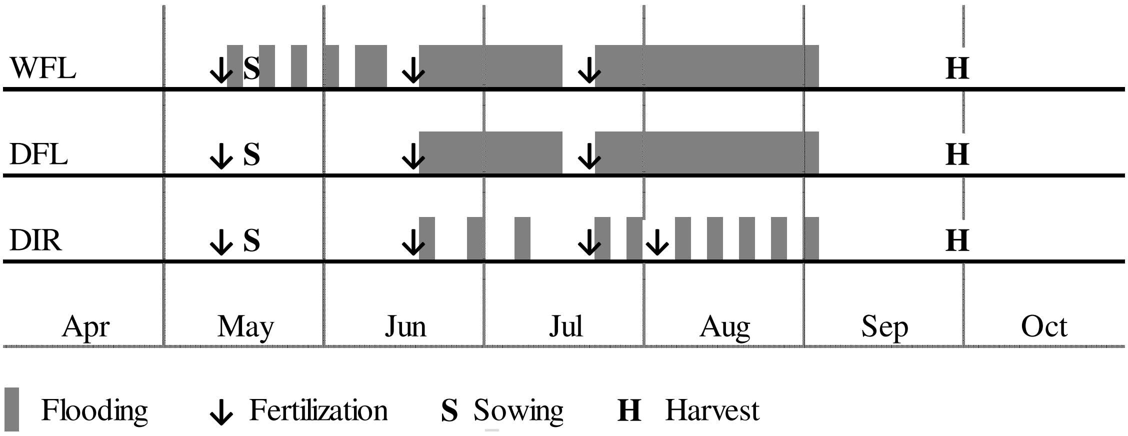
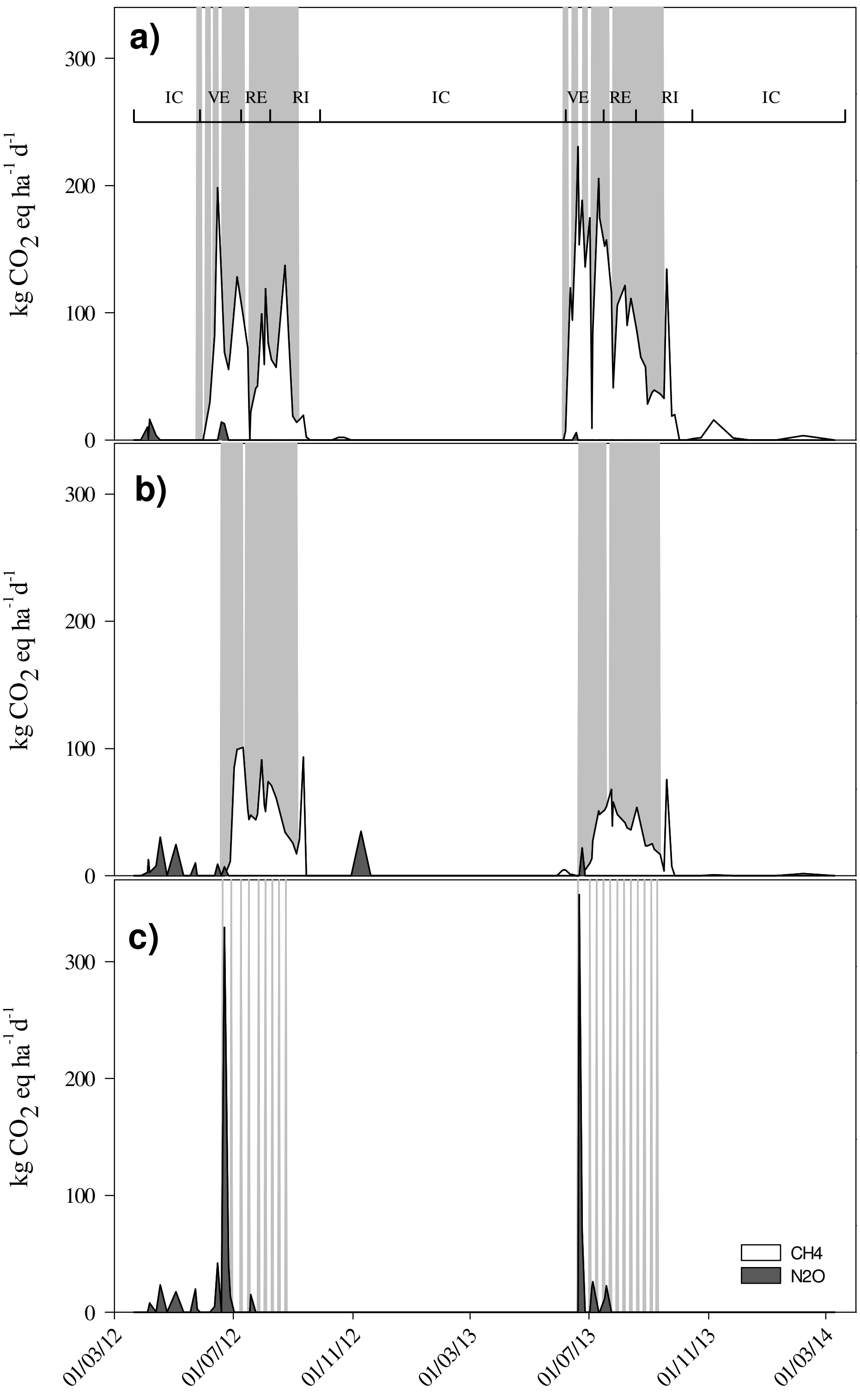
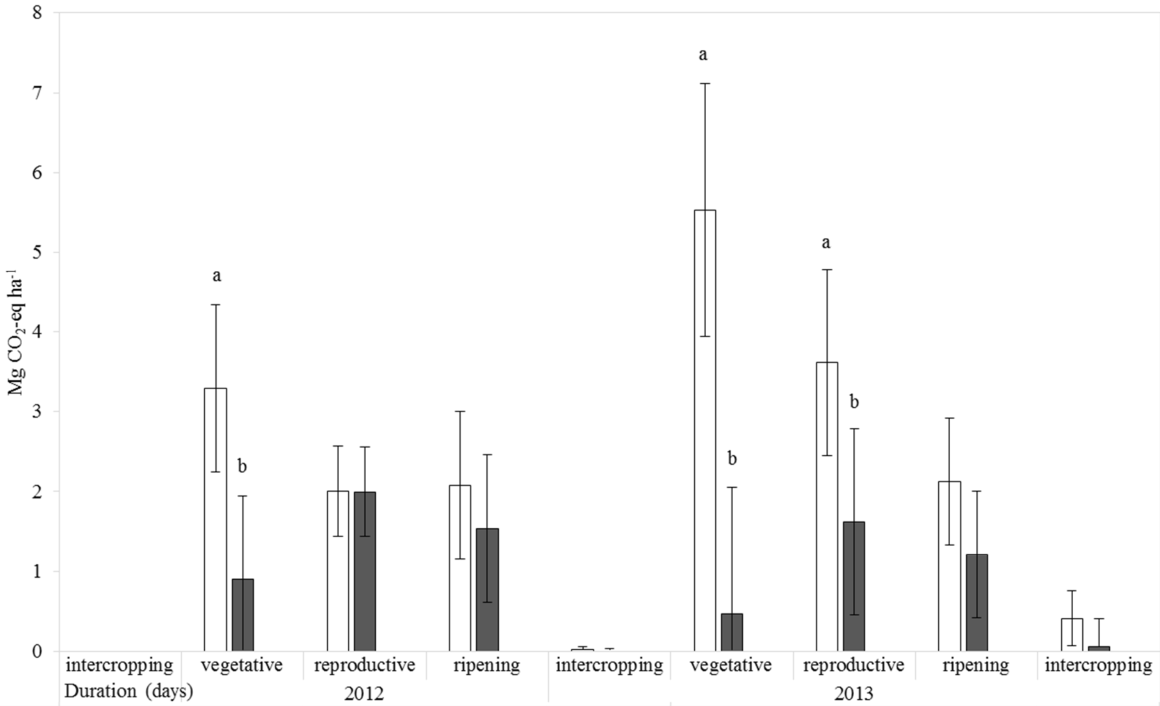

WFL
DFL
DIR
S
H
Apr
May
Jun
Jul
Aug
Sep
Oct
Flooding
Fertilization
S Sowing
H Harvest

Figure 3



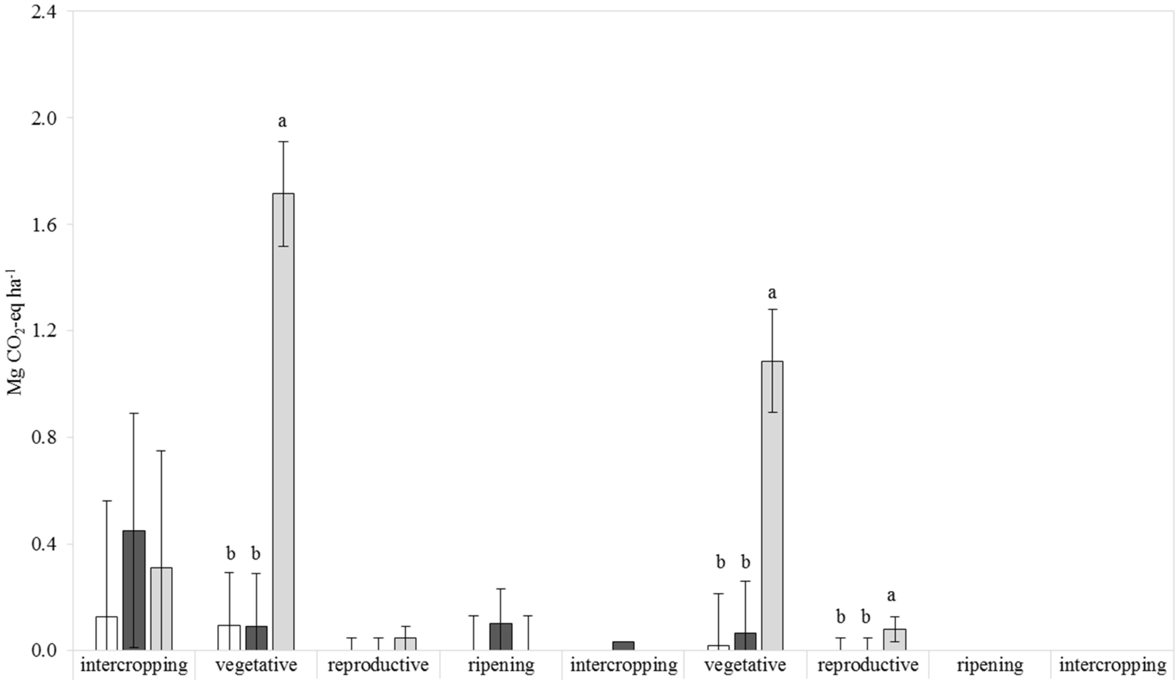
a)
b)
c)
IC
VE
RE
RI
IC
VE
RE
RI
IC
kg CO2 eq ha-1 d-1
kg CO2 eq ha-1 d-1
kg CO2 eq ha-1 d-1
300
200
100
0
CH4
N2O
01/03/12
01/07/12
01/11/12
01/03/13
01/07/13
01/11/13
01/03/14

Figure 4



□WFL	68	42	30	51	252	39	33	58	151
■DFL	55	55	31	50	242	46	34	59	152
□DIR	55	57	31	51	239	51	34	55	151

Figure 5



Duration (days)	intercropping (2012)	vegetative (2012)	reproductive (2012)	ripening (2012)	intercropping (2013)	vegetative (2013)	reproductive (2013)	ripening (2013)	intercropping (2013)
WFL	68	42	30	51	252	39	33	58	151
DFL	55	55	31	50	242	46	34	59	152
DIR	55	57	31	51	239	51	34	55	151

Figure 6

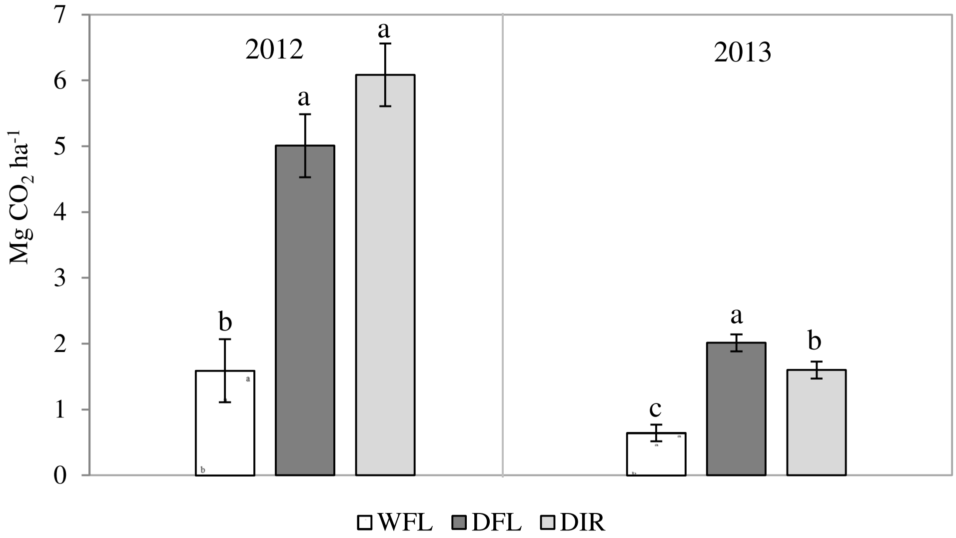
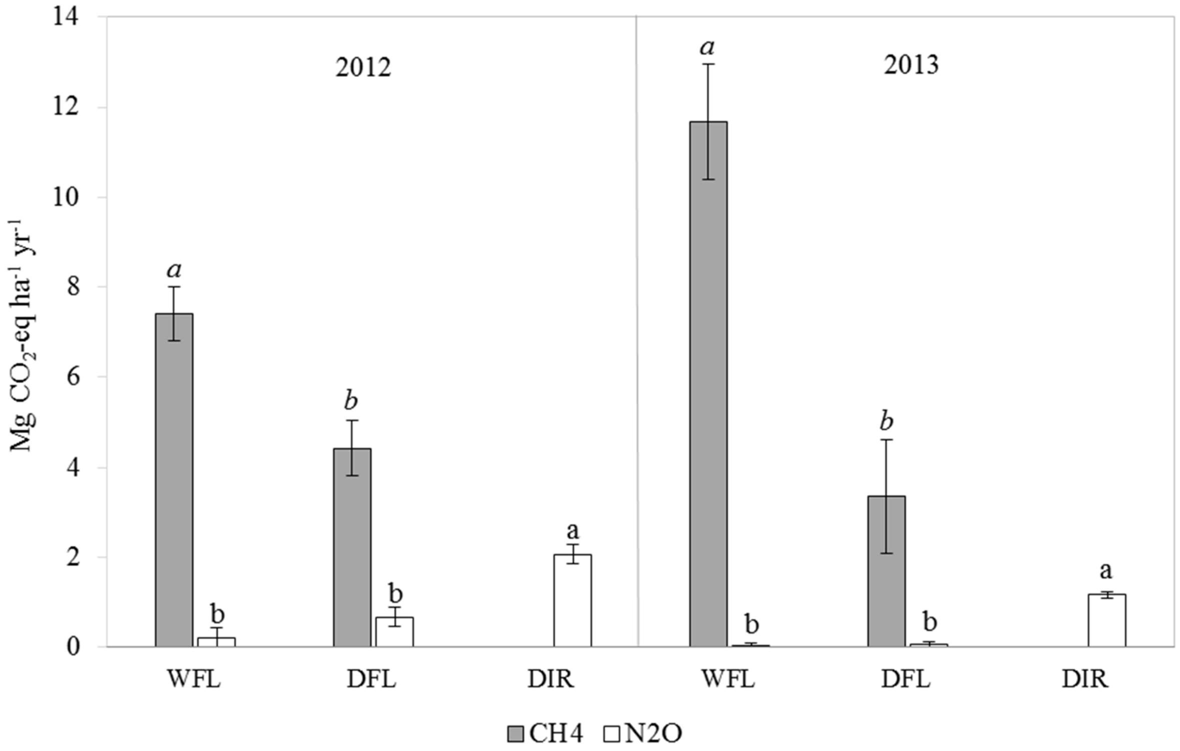


Figure 7



14
12
10
8
6
4
2
0
Mg CO_2-eq ha^{-1} yr^{-1}
2012
2013
a
b
a
b
b
b
a
b
b
a
WFL
DFL
DIR
WFL
DFL
DIR
CH4
N2O

Management practice	WFL 2012	WFL 2013	DFL 2012	DFL 2013	DIR 2012	DIR 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.

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	WFL (kg N ha^{-1})	DFL (kg N ha^{-1})	DIR (kg N ha^{-1})
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.

Water management	GWP 2012 ($Mg\ CO_2eq\ ha^{-1}\ y^{-1}$)	GWP 2013 ($Mg\ CO_2eq\ ha^{-1}\ y^{-1}$)	GWP mean ($Mg\ CO_2eq\ ha^{-1}\ y^{-1}$)
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_2O	n	DOC	n	Eh	n	NO_3^-
WFL	CH_4	110	0.037	46	0.725***	43	-0.417**	46	-0.361*
	N_2O			45	0.296*	43	0.031	45	-0.076
DFL	CH_4	110	-0.195*	34	0.552**	39	-0.574***	35	-0.313
	N_2O			34	-0.028	39	0.127	35	0.942***
DIR	CH_4	110	-0.030	35	0.231	41	-0.465**	34	-0.21
	N_2O			35	0.051	41	-0.152	34	0.615***

Table 4. Correlations between CH_4 and N_2O emission fluxes and dissolved organic carbon (DOC), redox potential (Eh) and nitrate in soil solution (NO_3^-). * = $p< 0.05$; ** = $p< 0.01$;*** = $p< 0.001$; n represents the number of matching pairs.

		Eh (mV)			DOC (mg C l^{-1})			NO_3^- (mg N l^{-1})		
Treatment	Stage	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 an NO_3^- 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 season, SD represents standard deviation, n represents the number of sampling dates.

Study	Location	WFL	DFL	DIR
			CH_4 (Mg CO_2 eq ha^{-1})	
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	-
Meijide 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_4 emissions were measured using the closed chamber method.