Yield-scaled global warming potential of two irrigation management systems in a highly productive rice system

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ABSTRACT: Water management impacts both methane (CH_4) and nitrous oxide (N_2O) emissions from rice paddy fields. Although controlled irrigation is one of the most important tools for reducing CH_4 emission in rice production systems it can also increase N_2O emissions and reduce crop yields. Over three years, CH_4 and N_2O emissions were measured in a rice field in Uruguay under two different irrigation management systems, using static closed chambers: conventional water management (continuous flooding after 30 days of emergence, CF30); and an alternative system (controlled deficit irrigation allowing for wetting and drying, AWDI). AWDI showed mean cumulative CH_4 emission values of 98.4 kg CH_4 ha^{-1}, 55 % lower compared to CF30, while no differences in nitrous oxide emissions were observed between treatments ($p > 0.05$). No yield differences between irrigation systems were observed in two of the rice seasons ($p > 0.05$) while AWDI promoted yield reduction in one of the seasons ($p < 0.05$). When rice yield and greenhouse gases (GHG) emissions were considered together, the AWDI irrigation system allowed for lower yield-scaled total global warming potential (GWP). Higher irrigation water productivity was achieved under AWDI in two of the three rice seasons. These findings suggest that AWDI could be an option for reducing GHG emissions and increasing irrigation water productivity. However, AWDI may compromise grain yield in certain years, reflecting the importance of the need for fine tuning of this irrigation strategy and an assessment of the overall tradeoff between relationships in order to promote its adoption by farmers.

Keywords: greenhouse gases, emissions, methane, nitrous oxide, mitigation

Introduction

Methane (CH_4) is the dominant greenhouse gas (GHG) produced in irrigated paddy rice fields, contributing approximately 15-20 % to annual global CH_4 emissions (Jacobson, 2005; Hadi et al., 2010). Flooded soils generate anaerobic conditions favoring the production of CH_4 as an end product from organic matter degradation (Conrad, 2002). Water management is one of the most important tools for achieving high levels of production as well as a promising option for the mitigation of CH_4. Changes in water management such as intermittent irrigation and mid-season drainage are effective options for the mitigation of CH_4 in rice fields (Hadi et al., 2010; Itoh et al., 2011; Jain et al., 2013; Minamikawa and Sakai, 2006; Tyagi et al., 2010; Yagi et al., 1997). However, these practices of alternate anaerobic and aerobic cycling can stimulate the emission of another GHG, nitrous oxide (N_2O), via denitrification and nitrification, respectively. Therefore, an optimum emission trade-off that minimizes emissions of both gases is highly desirable (Itoh et al., 2011; Zou et al., 2005). Furthermore, drainage systems are also important for conserving water and improving rice yields (Xu et al., 2007).

In Uruguay, rice yields are among the highest in the world, averaging 8000 kg ha^{-1}. Any alternative water management practice intended to reduce GHG emissions and to save water should not be detrimental to maintaining high rice yields. In dry-seeded rice systems, delaying permanent flooding during the vegetative stage of growth as much as possible is considered an acceptable practice aimed at minimizing GHG emissions and increasing water productivity. However, this water management system can induce crop water stress that can negatively affect the final rice yield (Dunn and Gaydon, 2011).

A large proportion of the world's rice is grown under continuous anaerobic conditions; thus, there is a lack of reports regarding the integrated effects of GHG emissions, water consumption and productivity on direct-seeded, delayed-flood rice production systems.

Based on this, the aim of this study was to compare the effect of conventional water management with continuous flooding after 30 days of emergence (CF30) with an alternative system of controlled deficit irrigation allowing for wetting and drying (AWDI) on GHG emissions, water productivity, and paddy rice yields in Uruguay.

Materials and Methods

Site description

A three-year experiment was conducted over the following consecutive rice (*Oryza sativa*) growing seasons: 2010-2011; 2011-2012; and 2012-2013, from October to March, in fields cultivated with a cultivar of indica origin, named El Paso 144, in the department of Treinta y Tres in the southeast of Uruguay, (33°14' S, 54°23' W, 21 m.a.s.l.). The soil was a Typic Argiudoll loamey clay. The main properties of the soil for the three rice growing seasons are described in Table 1.

Crop (1-2 years of rice) - pasture (3-4 years) rotations have been the predominant cropping system in Uruguay since the 1960s. This rotational system maintains or increases fertility and thus allows for up to 70 kg N ha^{-1} to be deployed which might, in turn, result in lower N_2O emissions (García-Préchac et al., 2004). In this study, rice was seeded at a density of 150 kg ha^{-1} after a three-year pasture.

Daily mean air temperature (measurements were taken at 9 a.m., 3 p.m. and 9 p.m.between 20 days before and 20 days after 50 % flowering) was 23 °C over the three seasons studied. The mean air temperature and daily rainfall in the three seasons are shown in Figures 1A and 1B, respectively.

Experimental layout

A complete randomized block design was used with two irrigation treatments in triplicate for three consecutive growing seasons. The two irrigation treatments were conventional water management (CF30) and an al-

Table 1 – Soil properties for the three rice growing seasons (October-March) in Treinta y Tres, Uruguay.

Season	pH (H$_2$O)	Organic matter	P Bray	Available K
		%	µg g^{-1}	meq 100 g^{-1}
1	6.0	2	5.0	0.12
2	5.5	2	5.0	0.18
3	6.3	2	2.2	0.16

ternative controlled irrigation system (AWDI). CF30 consisted of a continuous flooding treatment applied 30 days after plant emergence and a 10-cm water layer above the soil surface, maintained during the rest of the growing season until final drainage. This water management system is the one most frequently employed by Uruguayan rice producers. AWDI consisted of alternate wetting and drying irrigation where irrigation was given only at a certain number of days, after the soil had reached 50 % depletion of the water available in the root zone. This treatment also started at 30 days after plant emergence (DAE) and continued until the panicle initiation stage, around 70 DAE. At this stage, the plots were flooded with a 10-cm water layer similar to the CF30 system (Figure 2). Both treatments were direct-seeded and occasionally flushed during the first 30 days to prevent severe water stress depending on rainfall conditions. For both treatments, the irrigation end-point was set at 15 days after 50 % of flowering and plots were drained 15 days before harvesting. Each plot of 66 m² had an independent irrigation inlet where water inflow was measured using a water flow meter to record the amount of water used for irrigation.

Details of crop management activities are provided in Table 2.

Gas sampling and flux measurement

CH_4 and N_2O emissions were monitored using the static closed chamber technique as described for rice by
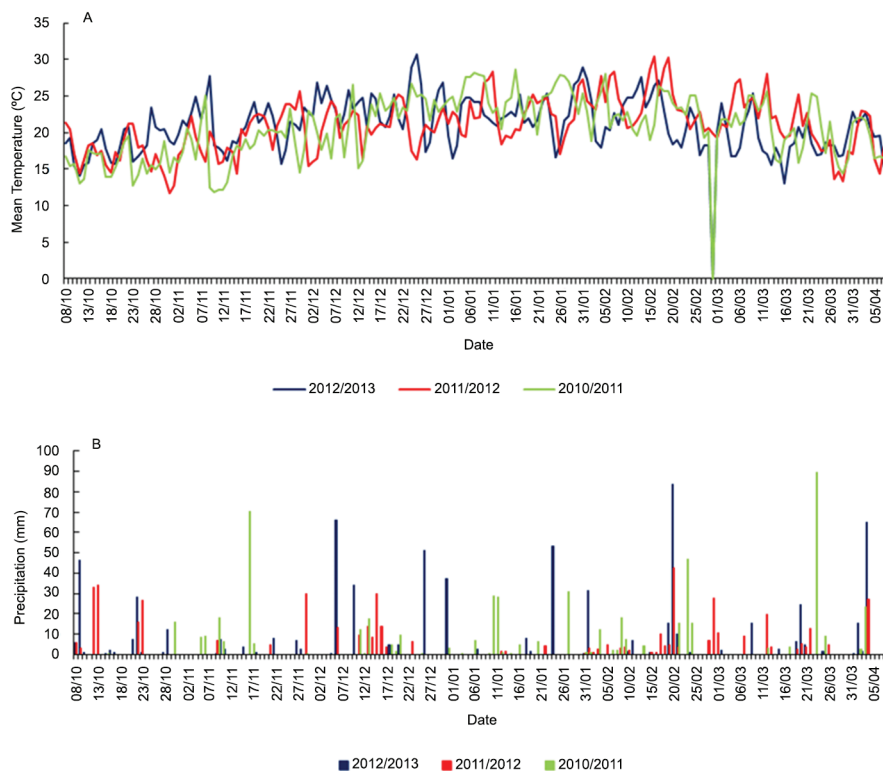

Figure 1 –Daily mean air temperature (A) and rainfall (B) during the three crop seasons in Treinta y Tres, Uruguay.
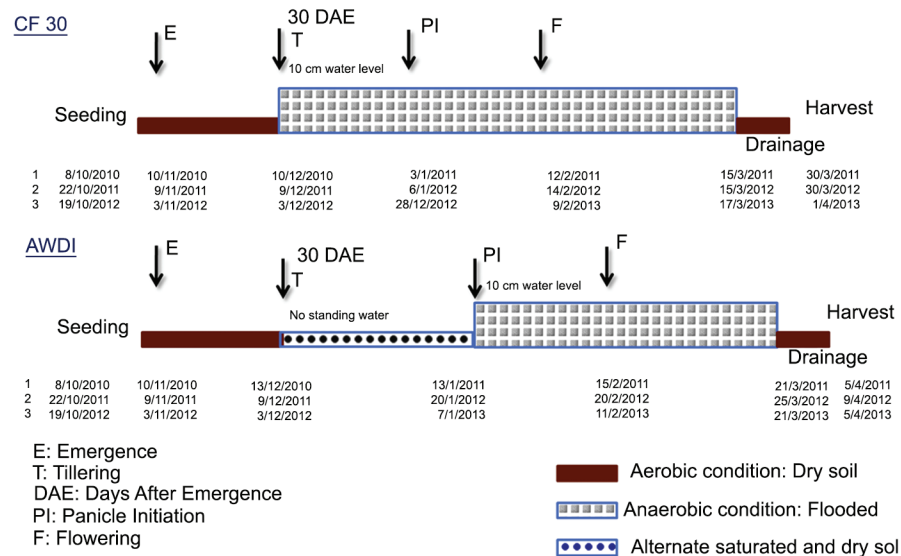
Figure 2 – Schematic of the rice crop cycle and irrigation treatments; CF30 = continuous flooding after 30 days of emergence; AWDI = controlled deficit irrigation allowing wetting and drying.

Table 2 – Seasonal sequence of rice crop management events during the three seasons in Treinta y Tres, Uruguay..

Crop management	Season 1	Season 2	Season 3
	DAE	DAE	DAE
Planting and fertilization (16 kg ha^{-1} N, 66 kg ha^{-1} P$_2$O$_5$, 18 kg ha^{-1} K$_2$O)	-33	-18	-15
Plant emergence	0 (10/11/2010)	0 (09/11/2001)	0 (03/11/2012)
Herbicide application	-11 and 9	-10 and 13	9 and 26
Fertilization at tillering (60 kg urea ha^{-1})[1]	33	30	30
Fertilization at panicle initiation (50 kg urea ha^{-1})	CF30: 54	CF: 58	CF:55
	AWDI: 64	AWDI: 72	AWDI: 65
Flooding	CF30: 33	CF30: 30	CF30: 30
	AWDI: 64	AWDI: 72	AWDI: 65

[1]Urea was applied in dry soil before flooding in CF30 (continuous flooding after 30 days of emergence) and before the first irrigation in AWDI (controlled deficit irrigation allowing wetting and drying); DAE= days after emergence.

Butterbach-Bahl et al. (2015). The assembly consisted of permanently installed stainless steel bases, 40 cm in diameter and 20 cm in height that were left in the place inserted 10 cm into the soil and enclosing approximately 12-14 rice plants. At each sampling date, acrylic boxes of 60 cm in height were placed on the bases and a water-seal was established to provide air-tight conditions. The chamber was equipped with a battery-operated circulating fan which was turned on 5 min before measurements to ensure complete gas mixing and a device to equilibrate pressure between the inside and the outside of the chamber. Gas samples from the chamber headspace were drawn using 25 mL plastic syringes at 0, 30 and 60 min for CH$_4$ and at 0, 15 and 30 min for N$_2$O, carefully flushing the syringe three times before two replicates were stored in evacuated 12-mL glass vials with screw caps and septum until analysis. Two chambers were installed in each plot. Chamber temperature, floodwater depths and headspace heights were recorded and used to calculate gas flux rates from the soil surface to the chamber atmosphere assuming a linear increase in gas concentration over time. The frequency of flux measurements was generally every seven days which has been determined to be an accurate approach for estimating seasonal CH$_4$ emissions from rice systems (Minamikawa et al., 2012). Gas flux measurements were taken between 10h00 and 11h30 a.m., as recommended by Minamikawa et al. (2012). The CH$_4$ concentrations were analyzed on a GC-2014 gas chromatograph (Shimadzu Scientific) with a Porapak Q column equipped with an FID (flame ionization) detector. The N$_2$O analysis was carried out on a gas chromatograph with an electronic capture detector (ECD), as described in Perdomo et al. (2009).

Overall gas emissions during the cropping season (from plant emergence to harvest) were calculated by integrating the fluxes over time. Seasonal CH$_4$ and N$_2$O

were estimated by adding all mass flux values for the experimental period. The net gas mass flux between the two measurement dates was calculated taking the mean flux values of the two dates multiplied by the number of days between these dates (Bowden et al., 1990). Total Global Warming Potential (GWP) was calculated in terms of CO_2 equivalents (CO_2 eq) over a 100-year time horizon using a radiative forcing potential of 298 for N_2O and 25 for CH_4 (Solomon et al., 2007). Yield-scaled GWP refers to GWP divided by grain yield in order to determine an agricultural efficiency value (Groenigen et al., 2010).

Soil and plant measurements

Water applied in the rice field under AWDI was based on cumulative crop evapotranspiration (ETm). The Penman-Monteith equation (FAO 56PM – Allen et al., 1998) was used to estimate potential evapotranspiration (ETo). The ETm was calculated multiplying ETo by an initial corrected crop coefficient value for rice (K_c) of 0.8 and a medium value of 1.2. Irrigation water was applied when cumulative ETm was equal to 50 % depletion of the available water in the root zone. Precipitation data was registered at a meteorological station located at the experimental field and the soil water content was measured hourly every day in situ using a frequency domain reflectometry device (FDR), Decagon EC5, with 5-cm rod length, at a soil depth of 0-10. Irrigation water productivity and total water productivity were estimated by dividing the grain yield by irrigation water applied and by rainfall plus irrigation water applied, respectively.

Redox potential was measured weekly during 2012-13 season, using a Horiba D-52 manual platinum electrode which performs instantaneous value measurements. The measurements were taken between rows with a 10 cm depth and five replicates for each plot. Rice yields were assessed by crop-cut sampling in each plot using a 3 × 2 m sampling frame. Reported grain yield refers to the weight of rough rice adjusted to 14 % grain moisture content.

Statistical analysis

Differences for seasonal cumulative CH_4 and N_2O emissions, GWP, grain yield, and yield-scaled GWP were compared between irrigation treatments using a linear Mixed Model. Irrigation treatment by cropping season interaction was considered a fixed-effect, while blocks and cropping season were included as random effects. If a significant interaction per cropping season was present, an analysis by cropping season was conducted to detect differences between treatments. The level of significance was determined as $p < 0.05$.

Results and Discussion

Water use and water productivity

Table 3 shows variations in water consumption and water productivity. Significantly lower amounts of irrigation water were used in AWDI for seasons 1 and 3 (2010-2011 and 2012-2013). Season 3 required less amounts of irrigations during the period between planting and final flooding due to regular rainfall. Season 1 was characterized by a shortage of rainy days during the above-mentioned period with the intermediate occurrence of an event of heavy rainfall (above 60 mm), while the rainfall pattern in season 2 was of a more irregular nature, no rainfall after seeding followed by some days of rain.

Seasonal patterns of CH_4 emissions

For all years and irrigation treatments, a similar seasonal CH_4 emission pattern was observed (Figure 3A and 3B). CH_4 emission increased gradually over time after flooding and reached an expressive peak in the late reproductive stage of the crop (before and around flowering in CF30 and around and after flowering in AWDI) after which emissions gradually declined until field drainage or harvesting. An exception to this behavior was observed in the 2010-2011 season for CF30 where a significant drop in CH_4 emission was recorded around 98 DAE. The highest CH_4 emission rates for CF30 ranged from 3948 to 4766 g $ha^{-1} d^{-1}$, significantly higher ($p = 0.0016$) than for AWDI, which ranged from 2105 to 3189 g $ha^{-1} d^{-1}$ (Figure 3A and 3B). After the beginning of the flooding, CH_4 emissions achieved a peak between seven and nine weeks after flooding in CF30 and around six weeks after flooding in AWDI. Total CH_4 emissions during the cropping period from CF30 were 208.2, 249.4 and 248.8 kg CH_4 ha^{-1} and from AWDI were 93.3,

Table 3 – Rice crop water consumption and productivity for the three seasons and for the two irrigation systems evaluated, in Treinta y Tres, Uruguay.

Season	Treatment	Irrigation water applied[1]	Total water input[2]	Irrigation water productivity	Total water productivity
		——————————— m^3 ha^{-1} ———————————		——————————— kg m^3 ———————————	
1	CF 30	11208[a]	15905[a]	1.01[a]	0.71[a]
	AWDI	7708[b]	12666[b]	1.35[b]	0.81[a]
2	CF 30	8278[a]	11657[a]	1.23[a]	0.82[a]
	AWDI	7017[a]	10667[a]	1.25[a]	0.87[a]
3	CF 30	6072[a]	11103[a]	1.65[a]	0.88[a]
	AWDI	4776[b]	10622[b]	2.00[b]	0.89[a]

[1]As interaction between season and treatment was significant, the analysis was performed by season; Different letters indicate differences between treatments ($p < 0.05$); [2]Irrigation water applied + rainfall; CF30 = continuous flooding after 30 days of emergence; AWDI = controlled deficit irrigation allowing wetting and drying.
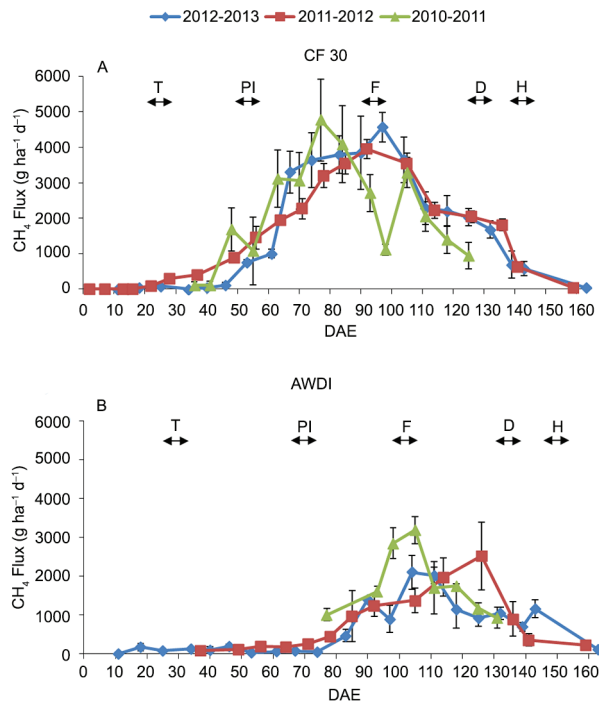
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Figure 3 – Evolution of CH4 fluxes in the three rice crop seasons for the two irrigation treatments; A) CF30 (continuous flooding after 30 days of emergence); B) AWDI (controlled deficit irrigation allowing wetting and drying); Points are average fluxes and error bars represent the standard error of six replicates; DAE = days after emergence; Dates of tillering (T), panicle initiation (PI), flowering (F), drainage (D) and harvesting (H) are indicated.
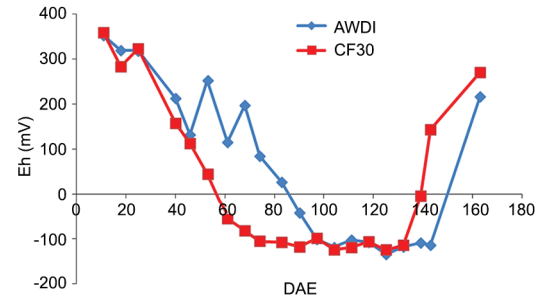

Figure 4 – Soil redox potential (10 cm depth) over time for rice crop season 2012-13 for the two irrigation treatments; Eh = soil redox potential; DAE = days after emergence; AWDI = controlled deficit irrigation allowing wetting and drying; CF30 = continuous flooding after 30 days of emergence.

Table 4 — Seasonal CH_4 and N_2O emissions and rice grain yield for two irrigation systems and three seasons, in Treinta y Tres, Uruguay.

Season	Treatment	CH_4[1]	N_2O[2]	Grain yield
			kg ha^{-1}	
1	CF30	208.2[a]	0.3	11171[a]
	AWDI	93.3[a]	0.4	10170[a]
2	CF30	249.4[a]	1.0	10387[a]
	AWDI	106.3[b]	1.2	8700[b]
3	CF30	248.8[a]	0.6	9803[a]
	AWDI	95.7[b]	1.9	8992[a]

[1]As interaction between season and treatment was significant, the analysis was performed by season; Different letters indicate differences between treatments ($p < 0.05$); [2]Seasonal N_2O emissions were not different ($p > 0.05$); CF30 = continuous flooding after 30 days of emergence; AWDI = controlled deficit irrigation allowing wetting and drying.

106.3 and 95.7 kg CH_4 ha^{-1} (Table 4). Significantly lower fluxes were observed in season two and in season three for AWDI, accounting for a 57 and 62 % reduction, respectively (Table 4). Even considering only the period when both irrigation treatments were flooded (from panicle initiation to drainage), the fluxes were significantly higher for CF30. Our estimates are consistent over the three seasons and comparable to previously published rates from rice fields from temperate countries. Reports from continuously irrigated systems include the following values of kg CH_4 ha^{-1}: 634 (Hadi et al., 2010); 250 (Cicerone et al., 1992); 112-404 (Schütz et al., 1989); 200-500 (Gutierrez et al., 2013) from Japan, California, Italy and South Korea, respectively. Two continuously irrigated systems (direct-seeded, delayed flood) similar to ours have reported values of 270 kg CH_4 ha^{-1} (Rogers et al., 2012) and 340-423 kg CH_4 ha^{-1} (Moterle et al., 2013) from rice fields in Arkansas, USA, and southern Brazil, respectively.

Soil redox potential (Eh) was measured in the third year of the experiment. This parameter showed a different pattern under both water treatments (Figure 4). In CF30, soil redox potential was above + 300 mV before flooding and then decreased sharply to a level of -100 mV within about 30 days after flooding (Figure 4).

On the other hand, Eh values for AWDI gradually decreased to 100 mV until 46 DAE. This was followed by transient increases and decreases in the redox potential during intermittent drainage until the field was continuously flooded with standing water and Eh values turned negative (Figure 4). This soil Eh fluctuation between 10 and 70 DAE corresponds with the minimal CH_4 flux detected in AWDI fields. This is expected because the soil Eh did not decline in this period to within an appropriate range favorable for the activity of methanogens. As a consequence, CH_4 emission from AWDI was delayed compared to CF30. Soil water content variations reflected soil redox potential fluctuations (data not shown). As many previous studies have reported, the seasonal gradual CH_4 emission pattern has been ascribed to the progressive development of anaerobic soil conditions during flooding, reaching a maximum around flowering due to the higher availability of substrates in the rice rhizosphere for methanogens responsible for CH_4 production and followed by a decrease in CH_4 efflux at the ripening stage of the crop due to reduced photosynthetic activity (Mitra et al., 2005; Pittelkow et al., 2013; Towprayoon et al., 2000; Wassmann et al., 2002). The absence of an emission peak early in the cultivation season in this study could be

due to either the lack of organic amendment which has been reported to enhance CH_4 emission or to inadequate conditions for anaerobic methanogenesis during the 30-day delayed flooding due to posterior non-flooded fallow conditions (Itoh et al., 2011; Watanabe et al., 1999; Zhang et al., 2011). Alternate wet-dry conditions delayed the onset of CH_4 emission as compared to continuously flooded plots. This pattern of a retarded initiation of CH_4 emission has also been observed in mid-season and multiple drainage treatments (Itoh et al., 2011; Towprayoon et al., 2005; Tyagi et al., 2010). This decrease can be ascribed to temporary soil aeration generated due to partial drying of the soil that in turn suppresses methanogenic activity and may increase aerobic methanotrophic activity.

Seasonal patterns of N_2O emissions

Figures 5A and 5B shows the pattern of N_2O emission for both irrigation treatments in the three crop seasons. There was no clear seasonal pattern of N_2O emission, either for the different seasons or treatments. Until 30 DAE when CF30 was flooded, the two irrigation treatments behaved similarly and one or two peaks of N_2O fluxes were registered in all the seasons. These peaks of N_2O fluxes prior to permanent flooding could not be correlated with rain events but the highest flux peaked after flushing in season 2011-2012 (65 g N_2O ha^{-1} d^{-1}).

In AWDI, N_2O fluxes were detected until 90 DAE while in CF30 only until 60 DAE. The dry-wet alternation created a favorable environment for both nitrification and denitrification processes and probably enhanced soil available C released from organic matter and consequently denitrification activity that is mainly heterotrophic (Zou et al., 2007). The period when N_2O fluxes were registered was longer in AWDI while CH_4, on the contrary, was emitted during a shorter lapse in AWDI than in CF30 (Figures 3 and 5).

Once soils are waterlogged and negative redox potential values are reached (Figure 4), thermodynamics determines the sequential reduction of inorganic electron acceptors present such as nitrate, sulfate and iron (III) after which CH_4 production is initiated (Conrad, 2002; Kögel-Knaber et al., 2010). Therefore, N_2O emissions are not expected to occur under these anaerobic soil conditions that prevent nitrification and promote methanogenesis (Figures 3 and 5).

N_2O seasonal emissions were not significantly different under either treatment (Table 4). The sporadic behavior of N_2O fluxes has been acknowledged previously in different agricultural soils including rice systems (Perdomo et al., 2009; Pittelkow et al., 2013; Zhao et al., 2011). Numerous factors are involved in controlling N_2O emissions from soils, which contribute to the huge spatiotemporal variation in emissions in field trials. As a consequence of the spatiotemporal variation, it has been reported that the power of statistical tests of such experiments is low (Bakken et al., 2012).

Soil moisture conditions and fertilizer management practices are the main factors that determine N_2O emissions from paddy soils (Guo and Zhou, 2007). However, in our experiment the peaks of N_2O were not related to N-fertilizer application (Figure 5A and B). Although excess fertilizer N doses result in high emissions, N_2O emissions correlate poorly with the N fertilizer applied when they are within realistic ranges (Bakken et al., 2012). The demand-driven N supply minimizes the pool of excessive nitrogen in the soil and thus, reduces N_2O emissions. At tillering the rice crop was actively growing and consequently the amount of soil mineral N left for losses was reduced. Total N-fertilizer recovery in rice plants was 40 % when the fertilizer was split versus a single dose application (20 %) in the same rice field of this experiment (Irisarri et al., 2007). An inverse relationship between N_2O emission and N use efficiency had been clearly established previously (Dalal et al., 2003). The split fertilization used in this study, which is the recommended method of application for this crop in Uruguay, probably increased N use efficiency.

Global warming potential in relation to irrigation systems

When CH_4 and N_2O emissions are expressed as CO_2 equivalents, AWDI lowered GWP to 54 % (Table 5). The major contributor to GWP in CF30 and AWDI was CH_4 which represented above 96 % and between 95 and 81 % of total GWP across years, respectively (Table 5). This is in agreement with previous reports on paddy soils that have shown that N_2O emissions contribute much less to GWP than CH_4 (Itoh et al., 2011; Pittelkow et al., 2013). It has also been reported that simultaneous minimization of both CH_4 and N_2O emissions cannot be maintained due to redox potential changes (Johnson-Beebout et al., 2009).

In addition to concern over CH_4 emissions from rice fields, rice productivity needs also to be considered. Uruguayan rice yields are among the highest in the world and any change in water management strategy must make sure that this highly productive system is not negatively affected. As shown in Table 3, despite the fact that only in season 2 was the AWDI rice yield significantly lower in comparison to CF30; yield levels of AWDI were always lower. Yield-scaled GWP (Table 5) showed a reduction close to 50 % for AWDI vs. CF30 thus indicating a potential treatment for rice GHG mitigation.

Conclusions

The results of this study are among the first to report GWP and yield-scaled GWP for two irrigation treatments in a dry-seeded, highly productive rice system and underpin the importance of water-management strategies for the simultaneous achievement of high yields, efficient water use and contribution to global agricultural GHG mitigation.

AWDI can reduce GHG emissions and increase water productivity. However, AWDI may compromise

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Table 5 – Global Warming Potential (GWP) and Yield scaled GWP for the three rice seasons, in Treinta y Tres, Uruguay..

Season	Treatment	CH_4 GWP	N_2O GWP	GWP reduction	Yield scaled GWP	Yield scaled GWP reduction
		——————— kg CO_2 eq ha^{-1} ———————		%	kg CO_2 eq kg grain yield^{-1}	%
1	CF 30	5205	81		0.47	
	AWDI	2333	110	54	0.24	49
2	CF 30	6234	288		0.63	
	AWDI	2658	347	54	0.35	45
3	CF 30	6219	193		0.65	
	AWDI	2392	578	54	0.33	49

CF30 = continuous flooding after 30 days of emergence; AWDI = controlled deficit irrigation allowing wetting and drying.

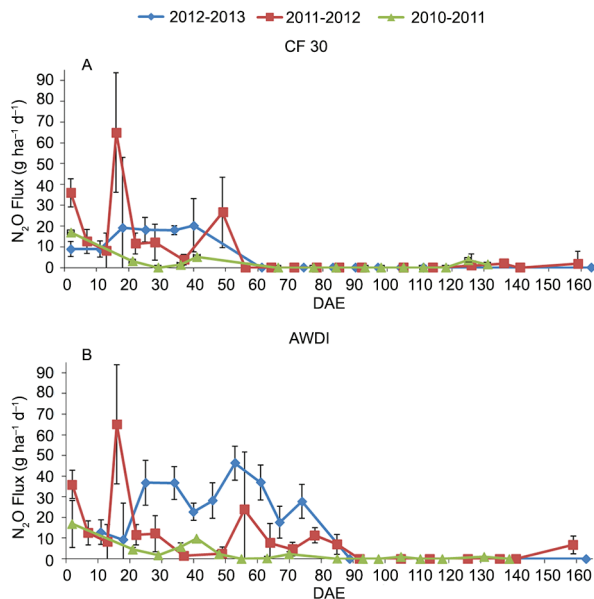Figure 5 – Evolution of N2O fluxes in the three rice seasons for the two irrigation systems; A) CF30 (continuous flooding after 30 days of emergence); B) AWDI (controlled deficit irrigation allowing wetting and drying); Points are average fluxes and error bars represent the standard error of six replicates. DAE= days after emergence.

grain yield, mainly in dryer seasons. Therefore, further AWDI irrigation strategies with less restrictive thresholds, (e.g. start of irrigation before reaching 50 % depletion of available water) should be explored in order to avoid yield penalties. In addition, the overall tradeoffs between productivity, GWP emissions, and water use should be assessed in order to provide rice farmers with decision tools for the adoption of alternative irrigations systems.

Acknowledgements

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