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Irrigation management strategies to increase water productivity in *Oryza sativa* (rice) in Uruguay

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ABSTRACT

Traditional rice irrigation systems in Uruguay are fully irrigated and early continuously flooded irrigation accounts for a high volume of water used. The purpose of this study was to determine irrigation techniques that increase irrigation water productivity (WPi) allowing a reduction in water input without negatively affecting grain yield in Uruguay. Ten experiments were conducted over a six-year period from 2009 to 2015, in three experimental units located among the major rice growing regions. Treatments included: early continuous flooding (C), alternate wetting and drying (AWD), intermittent flooding until panicle initiation (IP) and intermittent flooding during all crop growth period (I). All treatments were planted on dry soil. In treatment C flooding started 15–20 days after emergence and a water layer of 10 cm above the soil surface was maintained throughout all the crop cycle. In treatments IP and I, the water level alternated between 10 cm and 0 cm and was re-established when the soil was still saturated. The AWD treatment allowed the soil to dry periodically (water depletion of 50% of soil available water) until panicle initiation. IP and I over three seasons led to significant savings in irrigation water inputs in the North and Central regions (averaged 35% or - 3986 $m^3\,ha^{-1}$) in relation to C. In the East region, AWD allowed for a 29%(-2067 $m^3\,ha^{-1}$) water saving in relation to the control over four seasons but determined a significant yield loss of 1339 kg rice ha^{-1} (15% reduction) in relation to C. WPi was increased by 0.25 kg m^{-3} (23%) in IP and 0.68 kg m^{-3} (62%) in I, in relation to the control C. Whole grain percentage was significantly reduced with I in the North region only. Techniques that maintained the soil water at saturated conditions like intermittent flooding, allowed a reduction of water input with no significant effects on grain yield, which led to a significant increase in WPi.

1. Introduction

Continuously flooded rice is the largest irrigated crop in the world with a higher water demand in relation to other cereal crops (Pimentel et al., 2004) and the major staple food crop with 54 kg consumed per person annually (FAOSTAT, 2018). Increasing grain yields and maintaining grain quality while reducing water use, is a great challenge for the rice sector globally. Rising global food demand will increase water use requirements and competition for this resource that is becoming increasingly scarce in some parts of the world (Tuong and Bouman, 2003; Rijsberman, 2006; Mekonnen and Hoekstra, 2016). This can be attributed to competition from other sectors, environmental concerns, and climate change predictions, like increased occurrence of drought periods, aquifer over-extraction, loss of water quality by sewage, chemical pollution, and salinization (Meybeck et al., 1996; Bouman et al., 2007a; Siebert et al., 2010; Reba et al., 2013; Famiglietti, 2014). Climate change predictions by many models are indicating increases in temperature, more weather variability (Stocker et al., 2013) and higher frequency, duration and severity of water shortages (Spinoni et al., 2014) which would limit water availability for irrigation and rice production in the future (Peng et al., 2004; Lobell, 2007; Wassmann et al., 2009a, 2009b; Gaydon et al., 2010; Lyman et al., 2013).

Rice is also the largest irrigated and water consumer crop in Uruguay. Early continuous flooding is the main irrigation technique implemented by farmers to secure the highest yields to maximize profit. Rice is planted on dry soil conditions, flooded from 15 to 25 days after emergence when rice plants have 3–5 leaves (V3 -V5 according to Counce et al. (2000)), and maintained with a water layer of 5–10 cm until 20 days before harvest. Rice grown in Uy requires from 8000 to 15,000 $m^3\,ha^{-1}$ of water (Battello et al., 2009; Böcking et al., 2008;

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Roel et al., 2011; Lavecchia et al., 2011; Riccetto et al., 2017). Several authors reported rice water requirements for growth within the range from 3550 to 7000 $m^3 ha^{-1}$ (Pringle, 1994; Tabbal et al., 2002; Bouman et al., 2007a; Massey et al., 2014). This information is in concordance with the data reported by Blanco et al. (1984), where only 45% or 6000 $m^3 ha^{-1}$ were evapotranspirated from the 13,300 $m^3 ha^{-1}$ irrigation water input for continuous flooded rice in Uruguay. Those results are also aligned with the ones reported by Böcking et al. (2008), where evapotranspiration ranged from 5500 to 6780 m^3 ha^{-1} in three studies conducted in the North of Uruguay. The main benefits of flooding the rice crops are related to more effective weed control, an increase in nutrient availability, lower disease incidence, and thermal insulation/protection from cold during microsporogenesis (Williams and Angus, 1994; Dunn and Gaydon, 2011). In some countries like Australia, a deep layer of water (0.20-0.25 m) is used during flowering to protect pollen from low temperature (Humphreys et al., 2006). Conversely, the application of deep-water layer during this critical period determined no differences in temperature within the canopy in Uruguay (Roel, 2005). Some potential disadvantages of the traditional continuously flooded (C) technique are associated with higher arsenic (As) accumulation in rice grain (Linquist et al., 2015; Carrijo et al., 2017; Yang et al., 2017; Carrijo et al., 2018; Seyfferth et al., 2018), and higher Green House Gas (GHG) emissions (Linquist et al., 2015; Tarlera et al., 2016; Seyfferth et al., 2018) in relation to alternative irrigation techniques like alternate wetting and drying (AWD).

Uruguay has a subtropical to temperate climate with a great deal of secure water resources (river, streams, lagoon) and an average annual rainfall ranging from 1200 mm (Southwest) to 1600 mm (Northeast) (Castaño et al., 2011). Average rainfall during the rice growing season from October to March over a 17-year period (1988–2015) was 624 mm ranging from 301 to 934 mm per year (Carracelas et al., 2017; GYGA, 2019). Rainfall it is not evenly distributed during the crop season and for this reason rice cannot be grown without the addition of irrigation water in this country, as grain yields are highly penalized resulting in non-harvestable yields. All rice cultivated in Uruguay is irrigated during most of the crop cycle. There is an opportunity to optimize rainfall captured by implementing alternative techniques like intermittent irrigation (Massey et al., 2014; de Avila et al., 2015). The importance of studying and continuing to develop irrigation techniques that use less water while preserving crop yields in Uruguay are also driven by the desire to reduce irrigation pumping costs and promote expansion of rice crop area. Most of the water used to irrigate rice is pumped (56%) in Uruguay (DIEA MGAP, 2017) and the cost of energy is a pressing issue for farmers. Lowering the irrigation cost to increase profit and maintaining enough water to irrigate adequately to secure crop yield potential is one of the main drivers for the implementation of water saving techniques by farmers in Uruguay.

Water is a limiting factor for the expansion of rice and other crops. Dams built for irrigation purposes are the main water source (54%) (DIEA MGAP, 2017). Increasing water use efficiency and building new dams would contribute to an increase in irrigated area. Additionally, if more water is available to irrigate other cereal crops and pastures, this would create an opportunity for land owners to make more profit and reduce risk by diversification of their products. In drought years water stored in the reservoirs in Uruguay may not be enough to irrigate 100% of rice fields flooded during the entire growing season. New water management techniques have the potential to help farmers cope with water scarcity in dry years.

Worldwide, several water saving irrigation techniques have been implemented to reduce water input, reduce associated irrigation costs, or save water for other purposes (Bouman et al., 2007a) but they may have a negative impact on grain yield as rice is very susceptible to water stress (Tuong et al., 2005). Much of the research outputs has conflicting result in the impacts of alternative irrigation systems on grain yields. Rice yields can be reduced under non-saturated soil conditions (Bouman and Tuong, 2001; Tuong et al., 2005; Parent et al., 2010; Sudhir-Yadav et al., 2012), and this could be associated with the shallow rice root system (Parent et al., 2010) as well as other factors like diseases, weeds or nutrients. However, other studies reported a significant reduction in water input without affecting rice grain yield and therefore improving water productivity (Tabbal et al., 2002; Belder et al., 2004; Lampayan et al., 2005). It is imperative to research and find out the main factors affecting the success of these alternative irrigation techniques over a range of environmental, soil and management conditions specific to each country. Alternative irrigation techniques need to be locally adapted and developed to use less water and minimize off-site impacts while preserving grain yield and quality. Intermittent irrigation and safe alternate wetting and drying are a promising alternative irrigation technique, not only for reducing water input and to increase water productivity, but also to minimize water footprint, environmental impact, greenhouse gas emissions and food safety issues, especially the accumulation of heavy metals like Arsenic in grain (Linquist et al., 2015; Tarlera et al., 2016; Yang et al., 2017; Carrijo et al., 2017, 2018; Seyfferth et al., 2018).

This paper is an integrated analysis of different irrigation management practices in experiments conducted at different sites with different soil and slope situations representative of the three rice growing regions of Uruguay. The main objective of this research was to determine irrigation management practices and techniques that increase WP without negatively affecting grain yield. In addition, we were looking to identify an optimal irrigation management that could be implemented across all environments or if different techniques need to be developed for each region. This study tested the hypothesis that during the crop vegetative phase it is possible to adjust the traditional early irrigation flooding management, without affecting grain yield, reducing irrigation water input and consequently increasing water productivity (WPi and WPir). WPi can be defined as the kilograms of grain produced per m^3 of irrigation water inputs and WPir is rice yield over volume of water inputs by irrigation and rain (kg m^{-3}). Evapotranspiration water productivity (WP_{ET}) defined as rice yield over m^3 of evapotranspirated water, was also reported in this work (Bouman et al., 2007a).

2. Methods

2.1. Study site description

The Uruguayan rice sector is divided in three regions: East (118,391 ha), North (33 448 ha) and Central (12 618 ha) representing 72%, 20% and 8% of total annually rice planted area (DIEA MGAP, 2018) (Fig. 1). There is one experimental unit per region: In the North (Lat:-30.50S, Long:-57.12 W) experiments were conducted during the seasons: 2011/12–2013/14 - 2014/15; in the Central region (Lat:-32.18S, -55.17 W), experiments were conducted during the seasons: 2011/12–2012/13 - 2013/14; in the East region (Lat:-33.27S, Long:-54.17 W), the experiments were conducted throughout seasons 2009/10, 2010/11, 2011/12 and 2012/13.

The 10 experiments were conducted in typical soil types of each region. Soils properties determined in a laboratory for the different field sites are presented in Table 1.

2.2. Field management

Typical rotation in the experimental sites consisted in one year of rice followed by two to three years of perennial pastures (mixes of grasses and legumes). Minimum tillage was done in the previous summer, 6–9 months before the planting date. Land preparation consisted in one- or two-discs plowings to control weeds and incorporate previous crop (pasture) residue Additionally, 1 landplane were done and contour levees of 20–30 cms height were constructed. Tillage operations, sowing, pre, post-emergence weed controls and first Nitrogen application was done on dry soils before permanent flooding.

The planting date was mainly in October in all sites (from late

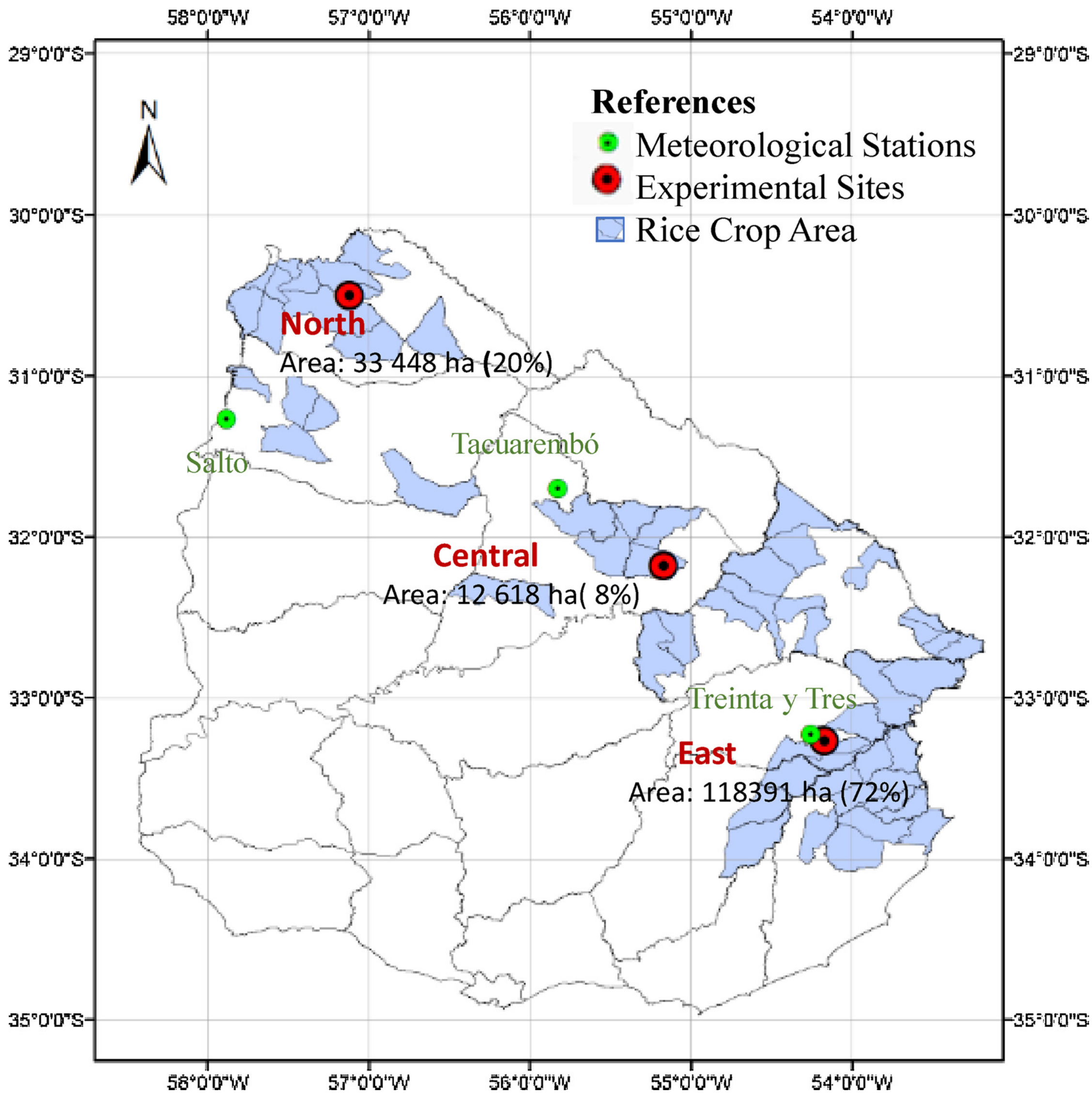

Fig. 1. Location of the National Institute of Agricultural Research(INIA) rice field experimental sites, reference weather stations (INIA) and rice areas of North, Central and East rice regions of Uruguay (DIEA MGAP, 2018).

Table 1
Soil property description for each experimental unit North, Central and East. Soil fertility and parameters information was determined in private and INIA soil laboratories. Soil texture information was registered for the first horizon.0–30 cms.

Soil Parameter	Region		
	North	Central	East
pH (water)	6.7	5.4	5.9
Organic Matter %	3.4	1.1	2.1
P - Bray 1	1.3	5.3	3.8
P Citric Acid (ppm)	12.3	.	6.9
K (meq/100 g)	0.29	0.13	0.18
Texture			
Sand %	6	17	30
Lime %	25	60	43
Clay %	69	23 *	28
Soil	Vertisol	Planosol	Brunosol

* Soil texture information. SIGRAS webpage.

September up to early November) as dictated by local weather conditions. In the Northern region the crop was planted on 3/11, 25/9, 25/9, in the Central region planting date was on 19/10, 16/10, 1/10 and in Eastern region crop was planted on 1/10, 8/10, 22/10 and 19/10 for the different consecutive seasons evaluated. All treatments were dry seeded with a commercial direct drill machine of 13 line (Semeato) at all sites. Soil moisture content ranged from 35 to 46 mm / 10 cm; normally the crop is planted with soil moisture content around field capacity.

Indica type cultivars were planted at all sites. In the North and Central region, the cultivar planted was INIA Olimar. Seeding rate of this variety was 160 kg seed ha^{-1}. In the East region INIA Olimar was planted in the first season (160 kg ha^{-1}) and El Paso144 in the following seasons at 143 kg ha^{-1}, as this variety was the main one planted in this region.

Fertilization management of the crop consisted of basal application of Nitrogen (16–30 kg N ha^{-1}), Phosphorus (30–46 kg P_2O_5 ha^{-1}) and Potassium (18 – 99 kg K_2O ha^{-1}) plus two urea fertilization in coverage at tillering prior to the flood and panicle initiation (12.4–55 kg N ha^{-1} each) based on soils fertility analyses results. In the central region 30 kg ZnSO4 ha^{-1} was also applied in the last season. Herbicide applications to control weeds varied across seasons and regions according to their degree of incidence.

2.3. Field crop and water measurements

The main information collected at the experimental sites included the following variables:

-Rice yields (kg ha^{-1}) at 14% moisture. The area harvested in the middle of plot was 6.1 m^2 in the East. In the North and Central region three samples of 5.1 m^2 each (10 rows X 3metres) were harvested per plot and averaged. The rice samples were mechanically threshed. Grain yields were normalized to 14% moisture. Harvest was done manually when grain moisture was lower than 21% and average green percentage was lower than 8%, according to rice industry recommendations. Grain percentage was visually separated and weighted from a 50-gr sample and moisture contents was determined using an electronic moisture tester (Steinlite) from a 100 g sample in the laboratory.

-Industrial Grain Quality. Whole grain percentage was determined with the cylinder of "Trieurs" specific to each variety. This parameter is defined as the unbroken grains of rice and large broken grains whose length is equal or greater than ¾ of the average length of whole grains. Total white percentage is an estimate of the amount of whole and broken grains that are produced in the milling of cargo rice to a degree of whiteness that ranges from 37 to 40 degrees. It was determined with a grinder and a white grade meter. Chalking percentage is estimated visually and includes the whole and broken rice grains that present an opaque aspect like chalk, in 50% or more of the grain. All parameters were determined in INIA and ACA (Rice Growers Association) Laboratories.

-Water input (WI) volume (m^3 ha^{-1}) were measured in all regions with helicoidal flowmeters (ARAD, WMR in the East and DOROT / KAPA brand of 110 mm size in the North and Central). Flowmeters were installed at the entrance of each plot to allow independent management of each irrigation treatment. In the North and Central region irrigation was by gravity from a dam while in the east water input was pumped from the river.

Total water (WT) includes irrigation water input plus rainfall registered during the crop cycle.

-Water Productivity (WP) (kg m^{-3}) is defined as kilograms of rice grain produced per unit of input water (Bouman et al., 2007a).

- Irrigation Water Productivity (WPi) it was determined by the relationship between the rice yield at 14% of moisture (kg) and Irrigation Water Input (WI).
- Total Water Productivity (WPir) was calculated considering rainfall + Irrigation Water Input (WT).
- Evapotranspiration Water productivity (WP_{ET}), was estimated as rice yield (14%) registered by irrigation treatment in each region, over cumulative weight of crop evapotranspirated water (ETc). Crop Evapotranspiration (ETc) was calculated based on the equation: $ETc = ETo \times Kc$, using a crop coefficient average factor $Kc = 1.04$, weighed by crop period (Kc initial: 1.05 for 0–55 days after emergence - DAE, Kc mid: 1.20 (55–95 DAE) and Kc end: 0.75 for late season growth stage (from 95 DAE) (Allen, 1998). An average crop cycle from emergence to harvest of 141 days was considered. Average number of days from emergence to flowering (50%) was 96 and harvest was done 45 days after flowering (Table 6). Potential Evapotranspiration (ETo) was obtained from locally modified Penman equation - FAO (Allen, 1998) adjusted for the conditions of Uruguay, available at: http://www.inia.org.uy/disciplinas/agroclima/penman.htm (Tables 2 and 3).

-Moisture content in the soil was determined in the AWD treatment in the East region. The methods used were gravimetric, with weekly measurements at a depth of 0–15 and 15–30 cm, and by capacitance probes FDR (Decagon Devices, EC-5) with continuous measurements, installed at a depth of 0–10 cm. The available water storage capacity for the East region soil was determined by the difference between the volumetric moisture at field capacity and the volumetric moisture at permanent wilting point. Both parameters were obtained from the tension-humidity curve obtained using the Richards method (Richards, 1948).

-Flowering date percentage was determined by visually counting the emerged panicles every second day in a monitored area of 1-meter length with three replications per plot. When 50% of total panicles were flowering, this date was recorded as flowering and used to estimate the number of days from rice emergence.

-Weather parameters were retrieved from INIA (National Institute for Agricultural Research) meteorological stations in the North (Salto Grande), East (Treinta y Tres) and Central (Tacuarembó) (GRAS, 2019), available at: www.inia.uy/gras/Clima/Banco-datos-agroclimatico).

Daily weather parameters (average from 2009 to 2015) included: Solar Radiation (kJ m^{-2} d^{-1}), Minimum and Maximum Temperature (Tmin. °C, Tmax. °C), Vapour pressure (%), Rainfall (mm), Wind speed (ms^{-1}) (Table 2). Quality control and filling/correction of weather data were performed based on NASA-POWER (http://power.larc.nasa.gov/ as described in Grassini et al. (2015), Carracelas et al. (2017). Information is also available at: GYGA - www.yieldgap.org. A rainfall

Table 2
Description of the climate parameters across the regions registered in the nearest INIA meteorological stations from the experimental sites for the East Central and North region. Average of 6 seasons from Oct to March (2009–2015).

Parameters	Region		
	North	Central	East
Solar Radiation (kJ m^{-2} d^{-1})	21968	21583	20190
Minimum temperature (degrees Celsius)	17	16	15
Maximum temperature (degrees Celsius)	29	27	27
Vapour pressure (kPa)	2.2	2.1	2
Wind speed (m s^{-1})	1.9	2.1	2.4
Total, Precipitation (mm)	915	929	736
Effective Precipitation EP (mm)	661	706	540
Evaporation "Tank A" (mm)	939	817	889
ET_0 Penman (mm)	685	641	614
Etc (mm)	712	665	639
Weather station location	*INIA - Salto*	*INIA - Tacuarembó*	*INIA -Treinta y Tres*
Latitude (S)	*−31.3*	*−31.7*	*−33.2*
Longitude (W)	*−57.9*	*−55.8*	*−54.3*

Table 3
Weather parameters registered by season in each reference weather station in the East, Central and North region (GRAS, 2019). Effective precipitation (EP mm), Evaporation "Tank A", Potential (ET_0) and crop (ETc) evapotranspiration. Average number of days from emergence until harvest considered was 141.

Region	Season	Parameters (mm)			
Weather Station		EP	Evap. "Tank A"	ET_0 Penman	Etc
East - INIA Treinta y Tres (-33.2S, -54.3 W)	2009-10	819	747	562	585
	2010/11	371	1048	631	656
	2011/12	446	894	655	681
	2012/13	525	868	610	634
	Average	***540***	***889***	***614***	***639***
Central - INIA Tacuarembó (-31.7S, -55.8 W)	2011/12	553	928	657	683
	2012/13	679	774	639	664
	2013/14	887	748	626	651
	Average	***706***	***817***	***641***	***665***
North - INIA Salto (-31.3S, -57.9 W)	2011/12	580	1004	722	751
	2013/14	673	946	661	687
	2014/15	731	866	672	699
	Average	***661***	***939***	***685***	***712***

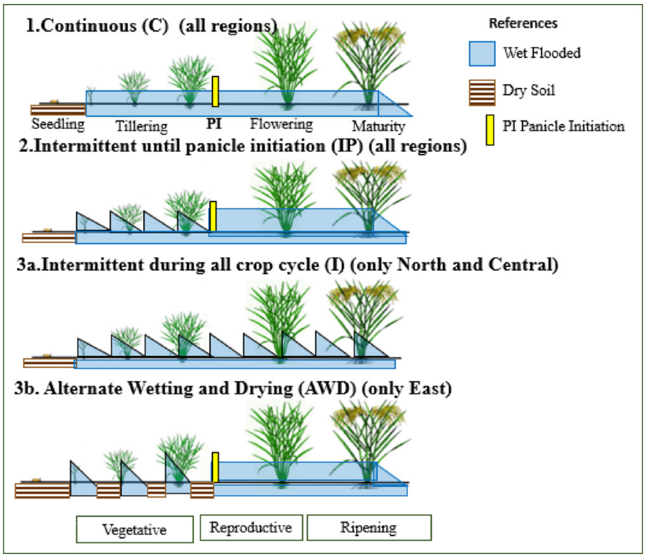

Fig. 2. Summary of Irrigation treatments tested in different regions of Uruguay. Traditional continuous flooded (C) and Intermittent until panicle initiation (IP) as common treatments across all regions, Intermittent during all crop cycle (I) in North and Central region and alternate wetting and drying (AWD) tested only in East region.

gauge to determine rainfall was additionally installed in each experimental site. Effective precipitation - EP (mm) was calculated considering surface runoff water according to the precipitation index method and is available at http://www.inia.uy/gras/Monitoreo-Ambiental/Balance-H%C3%ADdrico/Calculo-Precipitacion-Efectiva.

Parameters like Evap. "Tank A", EP, ET0 and ETc were calculated for the seasons where the experiments were conducted for each region. (East: 2009/10, 2010/11, 2011/12; Central: 2011/12, 2012/13, 2013/14 and North: 2011/12, 2012/13 and 2014/15) (Tables 2 and 3).

2.4. Treatments and experimental design

Three irrigation management practices were evaluated in each region (North Central and East). Continuous traditional flooding (C) that represents the most common rice flood management (control), Intermittent irrigation until panicle initiation (IP) and a third treatment that varied across the region to be able to impose higher water stress in plants: Intermittent during all cycle (I) in North/ Central regions and alternate wetting and drying (AWD) in the East (Fig. 2).

In treatment C, flooding started 15–20 days after emergence and a water layer of 10 cm above the soil surface was maintained after flooding throughout all the crop cycle. Irrigation water input filled out the bays within levees and replenish evapotranspirated water. In treatment IP and I the water layer alternated between 10 cm and 0 cm above the soil surface and was re-established when the soil was still saturated. The AWD treatment permitted the soil to dry periodically (allowing a water depletion of 50% of soil available water) until panicle initiation. The common treatments along the three regions were C and IP and the third treatment was I in North / Central and AWD in East region.

The experimental design in the East region was a complete randomized block design with four blocks. In the North and Central region, the experimental design was a split plot with 2 blocks. Main plots were the field layout (FL) while Irrigation treatment was the split plot.

2.5. Data analysis

A linear mixed effects model was used to fit each one of the response variables (Irrigation Water input, Total Water input, Rice Yield, Water Productivity (WPi, WPir, WP_{ET}), and Grain Quality parameters) for all the experiments, with Irrigation, Region, Block and Irrigation*Region interaction as fixed effects, and Year and Irrigation*Year interaction as random effects. An Analysis of variance was then performed followed by means separation using the Tukey test. The analyses were performed using the packages lme4 (Bates et al., 2015) and emmeans (Lenth, 2018) in R software (R Core Team, 2018). Following the significance of statistical analyses outputs, the irrigation information was not presented by Season. The tested interaction irrigation*season was non-significant for most parameters evaluated: Grain Yield, Irrigation water input, Total water input, Water Productivity (WPi, WPir, WP_{ET}) and Chalkiness. The same criteria were applied for the irrigation by region interaction.

3. Results

3.1. Irrigation water used and total water input

Traditional continuous flooding irrigation resulted in the highest water input in all regions. A significant interaction between region and irrigation treatments was detected ($P < 0.05$). In the North region, WI savings, relative to control treatment of 28% (4133 m^3 ha^{-1}) and 42% (6217 m^3 ha^{-1}) was determined for IP and I respectively. In the Central Region, Intermittent irrigation treatments allowed a significant WI saving in average of 34% (2798 m^3 ha^{-1}) in relation to C. In the East region, AWD determined a significant WI reduction, of 29% (2067 m^3 ha^{-1}) in relation to C. A non-significant water use reduction WI of 14% (1016 m^3 ha^{-1}) was registered in the IP treatment in relation to C for this region (Table 4, Fig. 3).

Total average water savings, WT (irrigation + rainfall) for IP and I treatments, relative to the control treatment of 24% (5176 m^3 ha^{-1}) and 17% (2798 m^3 ha^{-1}) were recorded for the North and Central region respectively. In the East region, WT savings of 14% (1754 m^3

Table 4
Average Irrigation Water Input (WI) and Total average Water Input (WT = Irrigation plus Rainfall) m^3 ha^{-1} for different irrigation systems and rice regions in Uruguay.

Treatments	Water Input m^3 ha^{-1}			
	Irrigation (WI)		Irrigation + Rainfall (WT)	
Irrigation *Region				
East				
1. Continuous (C)	7101	a	12594	a
2. Intermittent until panicle initiation (IP)	6085	ab	11870	ab
4. Alternate Wetting and Drying (AWD)	5034	b	10840	b
Central				
1.Continuous (C)	8187	a	16087	a
2. Intermittent until panicle initiation (IP)	5847	b	13747	b
3. Intermittent during all crop cycle (I)	4932	b	12832	b
North				
1.Continuous (C)	14711	a	21428	a
2. Intermittent until panicle initiation (IP)	10578	b	17295	b
3. Intermittent during all crop cycle (I)	8494	c	15210	c
Average	7886		14656	
CV%	13.42		4.96	
$P < 0.05$	***		***	
Irrigation * Season - $P < 0.05$	*NS*		*NS*	

Means followed by different letters are significantly different with a probability less than 5% ($P < 0.05$). Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05; NS: non-significant differences. CV: coefficient of variation.

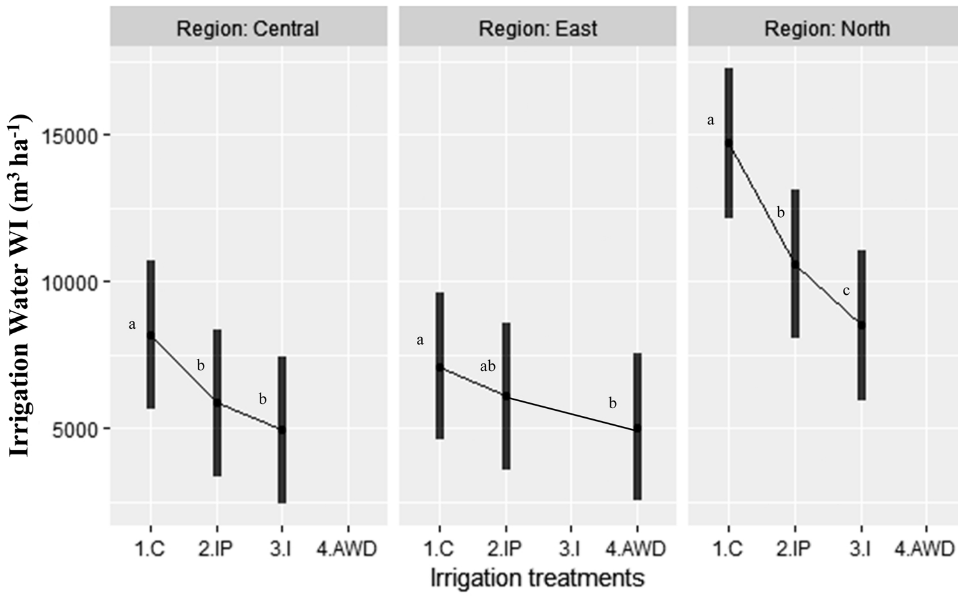

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Fig. 3. Irrigation water input $m^3\ ha^{-1}$ (WI) for different treatments and rice regions in Uruguay. Black dot represents marginal means (least square means), grey bars are indicating standard errors. Different letters are significantly different with a probability less than 5%.

ha^{-1})were registered in AWD in relation to C. A non-significant interaction was registered between Irrigation and Season for water input ($P < 0.05$) (Table 4),

3.2. Rice yield and water productivity

There was no significant interaction between irrigation and region for yield and WP ($P < 0.05$). Rice Yield in the East was 21% higher (1716 kg ha^{-1}) than the average yield recorded for the North and Central Region (Table 5).

There were no significant differences in rice grain yield between continuous flooded and Intermittent (I, IP) irrigation treatments. The AWD treatment resulted in a significant yield reduction of 1339 kg rice ha^{-1} (14.6% reduction) in relation to C (Table 5, Figs. 4 and 5).

Average water productivity (WPi) levels ranged from 1.09 recorded in the traditional control C to 1.77 kg m^{-3} in the intermittent irrigation treatment I. Total water productivity (WPir) was on average 0.64 kg m^{-3} (rainfall + irrigation) with no differences within IP, AWD and C treatments. The I treatments resulted in a significantly higher WPi and WPir in relation to the traditional control C treatment (Table 5, Fig. 6).

The highest WPi (kg m^{-3}) was obtained with intermittent irrigation during all the crop cycle (I) in all regions 1.77 kg m^{-3} (Figs. 6 and 7). Intermittent irrigation determined a significant increase in WPi in relation to the control continuous flooded treatment of 62% and 23% for I and IP respectively. AWD determined a non-significant increase of 25% in WPi in relation to C.

Average water productivity WPi and WPir registered in the East region was 1.81 and 0.89 kg m^{-3} respectively. The lowest values of those parameters were observed in the North 0.88 and 0.48 kg m^{-3} for WPi and WPir in that order. The Central region registered values of WPi

Table 5
Rice grain yield (kg ha^{-1}, 14% moisture) and Water Productivity, kg rice grain per m^3 of water (kg m^{-3}) considering only irrigation water input (WPi) and total water (WPir) irrigation + rainfall) during the crop cycle, by irrigation treatments and regions.

Treatments	Rice Yield (kg ha^{-1})		Water Productivity (WP) kg m^{-3}			
			WPi- Irrigation		WPir- Irrigation + Rainfall	
Irrigation						
1.Continuous (C)	9194	a	1.09	c	0.59	b
2. Intermittent until panicle initiation (IP)	8755	a	1.34	b	0.64	ab
3. Intermittent during all crop cycle (I)	8710	ab	1.77	a	0.71	a
4. Alternate Wetting and Drying (AWD)	7855	b	1.37	abc	0.62	ab
Average	8628		1.39		0.64	
CV%	3.75		14.49		5.75	
$P < 0.05$	***		***		***	
Region						
I. Central - Ce	7628	b	1.49	a	0.55	b
II. North - N	8485	b	0.88	b	0.48	b
III.East - E	9772	a	1.81	a	0.89	a
Average	8628		1.35		0.62	
CV%	4.30		15.71		6.34	
$P < 0.05$	***		***		***	
Irrigation*Region $P < 0.05$	*NS*		*NS*		*NS*	
Irrigation*Season - $P < 0.05$	*NS*		*NS*		*NS*	

Means followed by different letters are significantly different with a probability less than 5% ($P < 0.05$). Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05; NS: non-significant differences. CV: coefficient of variation.

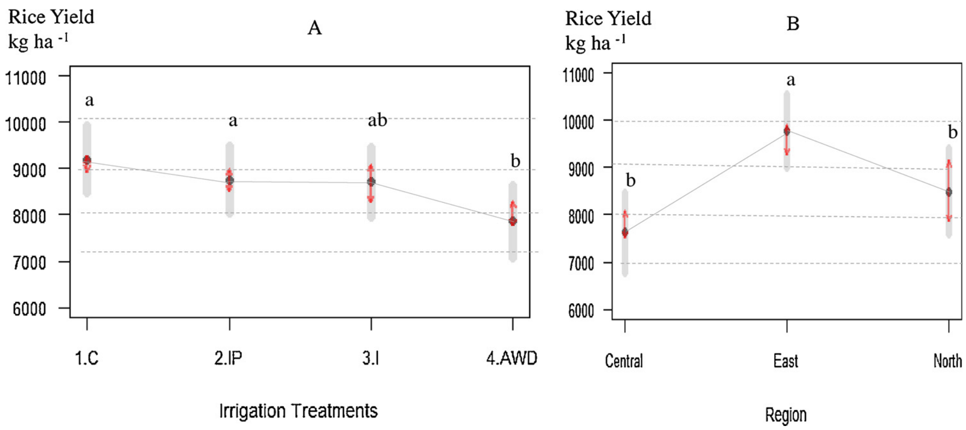

Fig. 4. Rice Yield at 14% moisture, (kg grain ha^{-1}) registered by irrigation treatments (A) and for each region (B). Black dot represents marginal means (least square means), bars are indicating standard errors, arrow lines indicates confidence interval by Tukey. Different letters are indicating significant differences within treatments for each region with a probability less than 5%.

1.49 kg m^{-3}, 69% higher compared to the North region, and WPir 0.55 kg m^{-3}.

Evapotranspiration water productivity (WP_{ET}) was 1.37 kg m^{-3} for C and 1.31 kg $m^{-3}$for IP and I with no significant differences within treatments but it was significantly reduced to 1.15 kg m^{-3} when AWD technique was implemented. Significant differences were also registered of WP_{ET} by region. The highest WP_{ET} was estimated for the East region (1.55 kg m^{-3}) and no differences were registered between the North and Central regions with an average value of 1.16 kg m^{-3}(Fig. 8). The analyzed interactions (irrigation*region and irrigation*season) were no significantly different also for $WP_{ET,}$ like the results obtained for WPi and WPir ($P < 0.05$).

3.3. Grain quality

Implementing alternative water-saving irrigation techniques did not influence grain quality parameters such as white grain and chalkiness percentages, for all regions. In addition, whole grain percentage was not affected negatively in the East and Central regions (Table 6). There was no significant effect on number of days to flowering after emergence by implementing alternative irrigation techniques in the North and Central regions. However, IP and AWD treatments delayed flowering (50%) date by 8 days in average, in relation to C in the East region (Table 6).

Intermittent irrigation I, led to a significant reduction in whole grain percentage of 5.7% in relation to C only in the North region (Fig. 9).

4. Discussion

4.1. Irrigation management effects on water input

Traditional continuous flooding has been the main irrigation technique for rice implemented by farmers in Uruguay. Irrigation water input measured under continuous flooded conditions averaged 10,000 m^3 ha^{-1} ranging (from 7000 to 15,000 m^3 ha^{-1}). Total water input averaged 16,700 m^3 ha^{-1} when rainfall was included, ranging from 12,600 to 21,400 $m^3$$ha^{-1}$. The big differences measured between regions are associated with the soil characteristics (texture, organic matter) (Table 1) and land gradients. Rice in the East and Central region is cultivated on lower percolation and lower infiltration rate soils (planosols) compared to the North areas (vertisols). Slopes in the North region are also higher and field layout techniques in this region are different, with lower height and closer contour levees in comparison to the Central and East region. In this region higher runoff water losses normally occur to maintain the crop being continuously flooded. This information is aligned with the irrigation water reported in continuous traditional irrigation by other authors not only in Uruguay but also around the world: net water input (irrigation water plus rainfall minus surface drainage) of 15000–15600 m^3 ha^{-1} in Australia (Dunn and Gaydon, 2011), irrigation water applied from 13,140 to 24,050 m^3 ha^{-1} (Linquist et al., 2015), field measured applied irrigation averaged 8720 ranging from 2440 to 18,800 m^3 ha^{-1} in USA (Massey et al., 2018), total water input (rain plus irrigation) in field

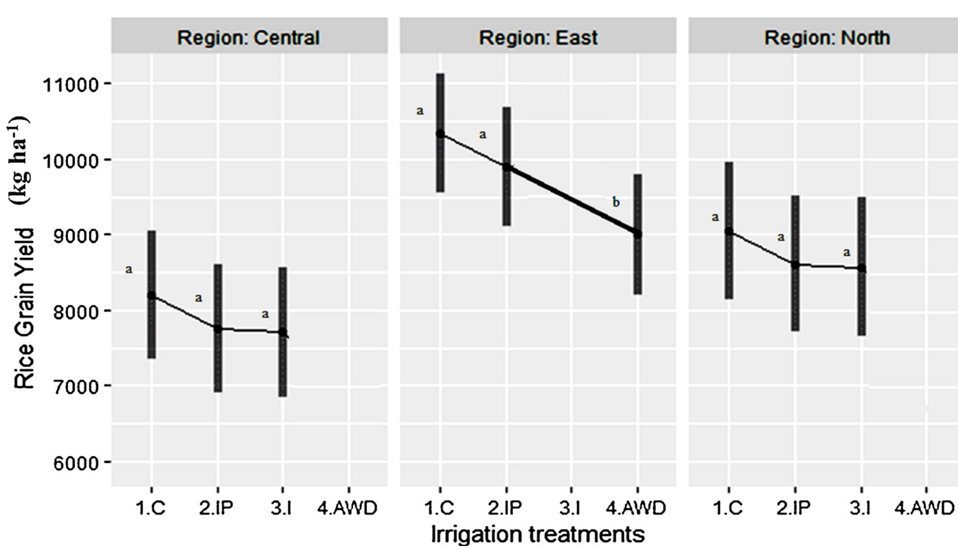

Fig. 5. Rice Yield at 14% moisture, (kg grain ha^{-1}) registered by irrigation treatments for each region: Central, East and North. Black dot represents marginal means (least square means), grey bars are indicating standard errors. Different letters are significantly different with a probability less than 5%.

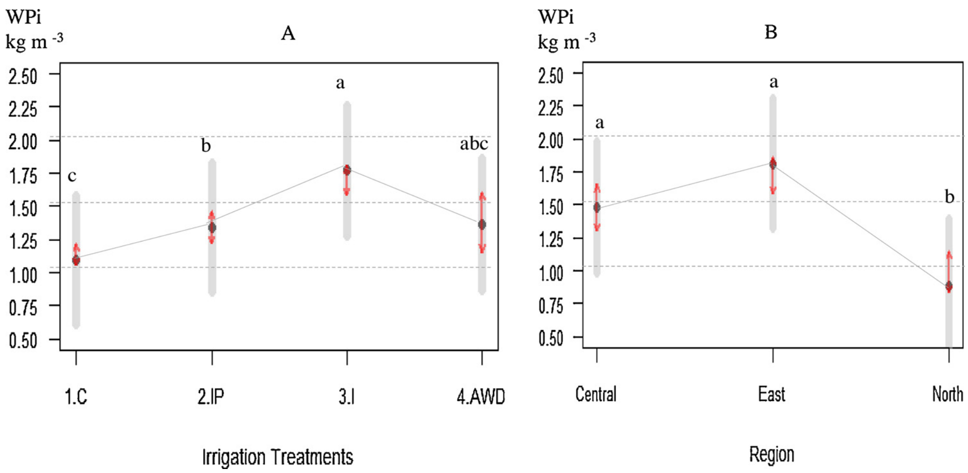

Fig. 6. Water productivity ((WPi = kg m^{-3}) considering only irrigation water used by irrigation treatments (A) and by region (B). Black dot represents marginal means (least square means), bars are indicating standard errors, arrow lines indicates confidence intervals by Tukey. Different letters are indicating significant differences within treatments for each region with a probability less than 5%.

experiments and farmer fields ranged from 6500 to 15,250 m^3 ha^{-1} in China and from 5770 to 35,004 m^3 ha^{-1} in Philippines (Bouman et al., 2007a), total water input including rainfall measured in experiments ranged from 11,710 – 14,300 m^3 ha^{-1} in Brazil (de Avila et al., 2015). Rice receives more irrigation water than is needed according to crop evapotranspiration requirements using traditional irrigation methods. The estimated average crop evapotranspiration from emergence until crop harvest (ETc) in this study was 6720 m^3 ha^{-1} with some differences within regions. The highest value was registered in the North (7120 m^3 ha^{-1}) followed by the Central (6650 m^3 ha^{-1}) and East region (6390 m^3 ha^{-1}) (Table 2). It was found in validation experiments adapting alternative irrigation techniques on commercial farms on clay soils that 6000 m^3 ha^{-1} of irrigation water input for rice is an achievable target with no yield or quality penalties (Massey et al., 2014).

Alternative irrigation techniques tested in this paper determined water use savings, in all regions evaluated. In the North and Central, the intermittent irrigation IP and I determined a significant input water saving of 28% (3237 m^3 ha^{-1}) and 41% (4736 m^3 ha^{-1}) on average in relation to the control continuous flooded respectively. There is a chance to optimize rainfall capture and reduce irrigation inputs by implementing alternative irrigation management practices. In the East water input saved was lower in relation to the other regions by implementing intermittent irrigation IP (14%, 1016 m^3 ha^{-1}) and even under the more stressed AWD treatment (29%, 2067 m^3 ha^{-1}). The lower rainfall received during the crop cycle in the East in relation to the other regions (Table 2), determined a lower opportunity to optimize rainfall capture by the implementation of alternative irrigation techniques. Average rainfall registered in our studies from Oct to March was 574 mm, 670 mm and 795 mm for East, North and Central regions respectively. Average rainfall of the three regions (680 mm) was 9% higher than the registered historical average over a 17-year period (624 mm) (Database GYGA web page, Carracelas et al. (2017)). It has been reported by many authors in several studies an increase in rainfall capture by implementing intermittent irrigation techniques and a reduction in irrigation water inputs (Massey et al., 2014; de Avila et al., 2015; Massey et al., 2018). The main reasons of reduced water inputs identified by other authors were also associated with a reduction in percolation (Sudhir-Yadav et al., 2012) and lower floodwater runoff losses (Bouman et al., 2007b). Reported average water savings of 12% and 18% during two consecutive years, were recorded by Dunn and Gaydon (2011). Results from this paper agree with international work and show that intermittent irrigation management has a significant potential to increase WPi across Uruguay.

4.2. Irrigation management effects on grain yield, quality and water productivity

The implementation of intermittent irrigation until panicle

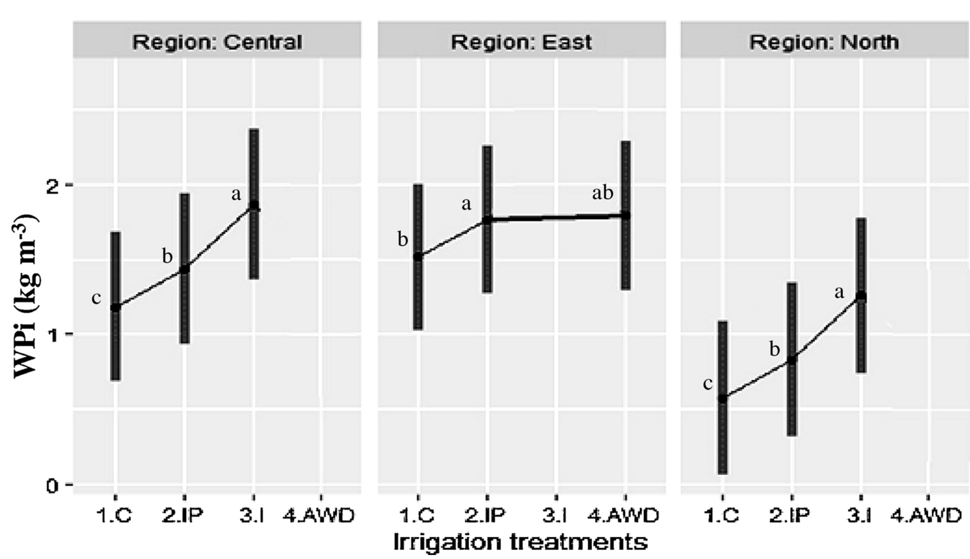

Fig. 7. Water productivity (kg m^{-3}) considering only irrigation water input (WPi) by irrigation treatments for each region: Central, East and North. Black dot represents marginal means (least square means), grey bars are indicating standard errors. Different letters are significantly different with a probability less than 5%.

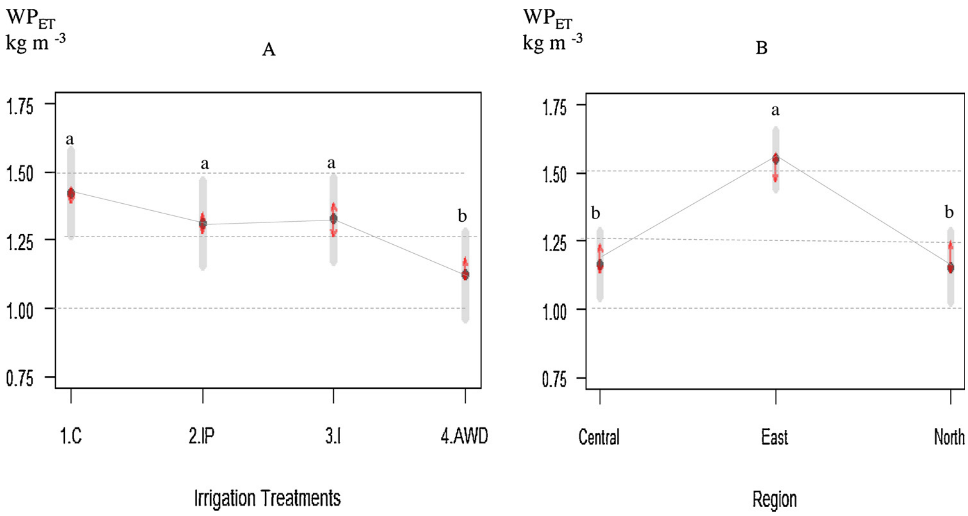

Fig. 8. Water productivity (kg m^{-3}) as a function of evapotranspirated water (WP_{ET}) by irrigation (A) and by region (B). Black dot represents marginal means (least square means), bars are indicating standard errors, arrow lines indicates confidence intervals by Tukey. Different letters are indicating significant differences within treatments for each region with a probability less than 5%.

initiation = IP technique (common experimental treatment along the three regions) confirmed that it is possible to reduce water use during the vegetative non-critical period without reducing significantly the rice grain yield and not affecting grain quality, therefore, increasing WPi. An average irrigation water saving of 25% (approximately 2500 m^3 ha^{-1}) and a WPi increase of 23% from 1.09 to 1.34 kg m^{-3} (0.25 kg of grain increase per m^3 of water) were achieved by implementing the IP irrigation technique in comparison to the traditional continuous flooded practice. A non-significant yield loss of 4.8% were registered in the IP in comparison with C. This result is aligned with information obtained around the world where it was found in several experiments a water saving of 23% on average (5–50 % range), without significantly reducing grain yield by comparing intermittent saturated soil conditions treatments with continuously flooded (C) (Heenan and Thompson, 1984; Borrell et al., 1997; Bouman and Tuong, 2001; Tabbal et al., 2002).

Results reported in our experiments with the AWD treatment tested (allowed a 50% depletion of available water) indicated a yield loss of 15% in relation to C as soil was allowed to dry down. In this paper we confirmed that rice yield can be reduced when soil moisture was below saturation as it was found and reported by other authors (Bouman and Tuong, 2001; Tuong et al., 2005; Parent et al., 2010; Sudhir-Yadav et al., 2012). Carrijo et al. (2017) also found that yield was reduced by 23% in AWD treatments compared to C when soil water potential was lower than -20kpa. However, there is a high degree of variation in rice yield response to AWD depending on timing, duration and severity during the drying event of this technique. Some studies reported a reduction in water input by 15–30% without a significant impact on yield (Tabbal et al., 2002; Belder et al., 2004; Lampayan et al., 2005), which were associated with a lower level of stress imposed to rice plants and local climatic conditions, soil and slope types (PH, organic matter, texture). In some situations of shallow ground water depths (0.10-0.40 m) roots can still have access to water even during drying periods in AWD, like what happens in intermittent irrigation where the soil is always kept saturated. In safe AWD recommendations, soil water depth reaches no more than 0.15 m below the surface and the field is reflooded with the aim to minimize yield penalties to a standing 0.05 m water depth (Lampayan et al., 2009, 2015). Sudhir-Yadav et al. (2011a, 2011b), reported an optimum irrigation soil tension of −20 kPa at 0.20 m for AWD to reduce irrigation water input without affecting grain yields and therefore improving WPi and WPir. Other authors also found no yield penalty when soil water potential was higher than −20 kPa (Carrijo et al., 2017; Yang et al., 2017) or roots were able to provide total transpiration water demand from deeper soil layers (Carrijo et al.,

Table 6
Industrial quality parameters percentage and number of days from emergence to flowering (50%) for different irrigation techniques and rice regions in Uruguay.

Treatments	Industrial Quality %						Flowering from emergence (days)	
	White Grain		Whole Grain		Chalkiness			
Irrigation *Region								
East								
1. Continuous (C)	70.4	a	58.3	a	4.2	a	87.0	a
2. Intermittent until panicle initiation (IP)	70.7	a	62.1	a	4.5	a	94.0	b
4. Alternate Wetting and Drying (AWD)	70.8	a	59.6	a	3.9	a	96.0	b
Central								
1.Continuous (C)	69.1	a	67.9	a	5.9	a	97.0	a
2. Intermittent until panicle initiation (IP)	68.8	a	66.0	a	5.1	a	97.0	a
3. Intermittent during all crop cycle (I)	68.8	a	66.3	a	6.0	a	97.0	a
North								
1.Continuous (C)	68.3	a	62.2	a	1.2	a	98.0	a
2. Intermittent until panicle initiation (IP)	68.2	a	59.5	ab	1.1	a	100.0	a
3. Intermittent during all crop cycle (I)	68.0	a	56.5	b	2.7	a	100.0	a
Average	69.0		62.0		3.9		96.0	
CV%	1		4		45		3	
P < 0.05	*NS*		***		*NS*		***	
Irrigation*Season -P < 0 .05	**		*		*NS*		***	

Means followed by different letters are significantly different with a probability less than 5% (P < 0.05). Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05; NS: non-significant differences. CV: coefficient of variation.

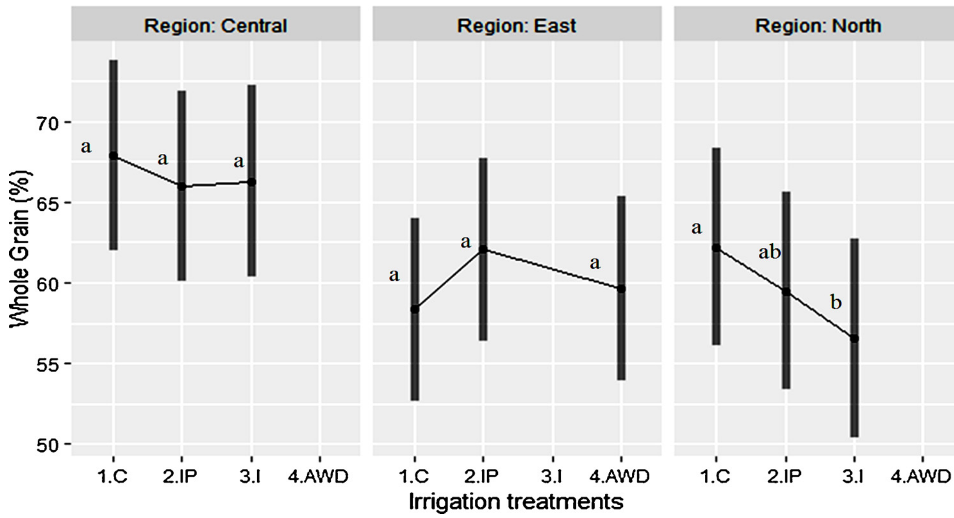

Fig. 9. Whole grain percentage for different treatments and rice regions in Uruguay. Black dot represents marginal means (least square means), grey bars are indicating standard errors. Different letters are significantly different with a probability less than 5%.

2018).

Industrial grain quality parameters like whole grain, total white, chalkiness and green (%) are important in Uruguay as poorer grain quality results in reduced paddy price. When irrigating intermittently during all the irrigation cycle (I), whole grain was affected negatively in the North region only. Land surface gradients and infiltration rate in these soils are higher, which makes the successful implementation of this alternative irrigation technique more difficult to maintain soil moisture levels always under saturated conditions uniformly. Additionally, temperature and solar radiation are higher in the North compared to the Central and East region (Table 2), which could increase the stress level and the risk of negatively affecting whole grain percentage. This could be attributed to a higher sensitivity of this parameter to higher levels of water stress imposed to plants during the grain filling period. This parameter fell below the limit of 58% threshold set by the milling industry and would induce a payment penalty.

Input irrigation water productivity (WPi) registered in the experiments was on average 1.39 kg m^{-3} and total WPir was 0.64 kg m^{-3} averaged across all regions. Intermittent irrigation implemented during the entire crop cycle (I) resulted in the highest values of those parameters 1.77 kg m^{-3} and 0.71 kg $m^{-3}$for WPi and WPir respectively compared to 1.09 and 0.59 kg m^{-3} in the control. Water productivity values reported in this study are very good compared with ranges reported internationally: 0.2 -0.4 kg m^{-3} in India with continuous flooded, 0.3-1.1 kg m^{-3} in Philippines, (Bouman and Tuong, 2001; Sudhir-Yadav et al., 2012). WP considering total water input equals 0.4 kg m^{-3} (ranging from 0.2 to 1.2) (Bouman et al., 2007a). There are several definitions of WP as it was pointed out by Bouman et al. (2007a), which denotes the amount kg rice grain (yield) over volume of water used. Water productivity can be defined as the values reported in this paper that consider the rice yield over volume of water inputs by irrigation (WPi) and rice yield over volume of water inputs by irrigation and rainfall (WPir). This information is valuable for irrigation engineers, managers and farmers that are interested in optimizing the productivity of irrigation water and total water resources - rainfall and irrigation water, and also for regional water resource planners that could be interested in the amount of grain/food that can be produced with total water resources (Bouman et al., 2007a). On the other hand, rice breeders are interested in the productivity of the amount of transpired water (WPt) or evapotranspiration (WP_{ET}), for selecting more water efficient cultivars. Bouman et al. (2007b), and Sudhir-Yadav et al. (2012) reported WP_{ET} average values that ranged from 1.0 to 1.5 kg m^{-3} using the simulation crop model Oryza with no significant differences within several irrigation water tension threshold. This information is aligned with estimated average WP_{ET} values determined in this work, 1.15, 1.16 and 1.55 kg m^{-3} for the North Central and East region respectively. Additionally, no significant differences were registered for C IP and I irrigation treatments with an average WP_{ET} of 1.33 kg m^{-3}. However, AWD determined a significant WP_{ET} reduction of 13% which was mainly explained by the significant reduction of grain yield when this irrigation technique was implemented.

This study helped to identify irrigation techniques that use significantly less water while maintaining rice grain yield and therefore increasing WP, across a range of typical irrigated rice growing regions in Uruguay.

More research is needed in AWD and validation studies before promoting wide scale adoption of this alternative technique. Further research is also required to evaluate ranges of “safer” alternate wetting and drying management strategies that maintain soil water depletion in a range that does not reduce rice grain yields. Intermittent irrigation until panicle initiation is the most promising irrigation technique to save water without penalizing grain yields and quality across Uruguay. If the 25% water saved by implementing the IP technique is used to promote the expansion of rice crops in Uruguay, an additional 32,000 ha of rice could be annually cultivated, equivalent to 0.26 Mt of total rice production over the already 1.4 Mt available for trade would be possible. Widespread adoption of intermittent irrigation techniques could have the potential to expand rice crop area and significantly increase total rice production in Uruguay. However, results were obtained on experimental plots where irrigation is easy to manage. Under commercial conditions the implementation of Intermittent irrigation would be more challenging associated with scalability and agronomic concerns such as weeds and nutrients. There is a risk of losing yield, quality and total income by implementing alternative irrigation techniques on larger scales. Therefore, the implementation of this technology will be limited unless an economic incentive is applied for farmers to use water more efficiently as has been reported in other studies worldwide (Bouman et al., 2007a; Linquist et al., 2015). In the current scenario of increasing production costs, low grain prices and lacking economic incentives to adopt water saving techniques, continuous flooding from 15 to 20 days after emergence is likely to remain the standard adopted and recommended practice in Uruguay, unless policy incentives are put in place. IP is a potential successful viable irrigation alternative to be validated across Uruguay while AWD would need more research before wide scale adoption.

5. Conclusions

Alternative irrigation techniques like intermittent irrigation in North, Central and alternate wetting and drying (AWD) in the East region allowed a significant irrigation water saving of 5175 (35%), 2798 (34%), and 2067 m^3 ha^{-1} (29%) respectively compared to the early continuous flooded systems. Average irrigation water input was 7900 m^3 ha^{-1} and total irrigation water input plus rainfall was 14,700 m^3 ha^{-1} in the continuous flooded treatment.

Rice yield was not negatively affected when intermittent irrigation techniques were implemented, and soils were maintained above saturation. Alternating wetting and drying conditions with 50% of soil available water depletion determined a yield loss of 1339 kgs (15%) in relation to the traditional continuous flooded treatment.

Average water productivity for all treatments considering only irrigation water (WPi) and total with rainfall (WPir) was 1.39 kg m^{-3} and 0.64 kg m^{-3}, respectively. Water productivity was significantly increased with the implementation of intermittent irrigation techniques by 0.25 kg m^{-3} (from 1.09 to 1.34) with IP until panicle initiation and by 0.68 kg m^{-3} (from 1.09 to 1.77) with I during all irrigation period in relation to the continuous flooded treatment. Evapotranspiration WP_{ET} was not affected by the implementation of Intermittent irrigation (IP, I), in relation to the continuous flooded control C (average WP_{ET} = 1.33 kg m^{-3}). AWD determined a significant reduction of 0.20 kg m^{-3} in WP_{ET} in relation to C.

Industrial quality (white grain % and chalkiness %), was not affected negatively by implementing alternative irrigation technics in all regions. However, intermittent irrigation during the entire crop cycle, reduced significantly whole grain percentage in the North.

Intermittent irrigation until panicle initiation (IP) shown in this study to be a technology that allowed a significant increase in water productivity without negatively affecting rice grain yield, with no effect on grain industrial quality and a significant reduction in irrigation water input in experimental conditions across all regions.

Further research should look to validate and adapt these technologies on larger scales commercial fields.

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