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Aerobic rice system improves water productivity, nitrogen recovery and crop performance in Brazilian weathered lowland soil

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ABSTRACT

Worldwide, rice systems are faced with the challenge of producing higher yields with less water. Water savings practices such as aerobic system and alternate wetting and drying (AWD) are being evaluated in lowland rice systems. However, few studies have been conducted on this subject in tropical South America where soils are highly weathered. Thus, a three-year field experiment was conducted in Brazil on a lowland Plinthaquults to investigate crop performance, water input productivity (WP_{in}) and N recovery under five irrigation regimes: continuous flooding (CF); AWD with short cycle (AWDS); AWD with long cycle (AWDL); saturated soil without ponded water (SS); and aerobic (AR). The drying events in AWDS occurred more frequently than in AWDL. The experimental design was a split-plot with irrigation regimes in the main plot and N fertilizer rate, 0 or 150 kg N ha^{-1}, in the subplot. ^{15}N micro-plots were set up to examine the fate of N fertilizer. The highest grain yields for 150N and 0N treatments resulted from the AR irrigation regime and averaged 9.1 and 6.5 mg ha^{-1}, respectively. Yields among the others irrigations regimes varied from year to the next, but the average was 8.5 and 5.4 mg ha^{-1} in the 150N and 0N treatments, respectively. Higher yields are attributed to higher N uptake and greater N recovery in the AR treatment. Apparent N recovery averaged 58% in the AR treatment compared to 34% in the other treatments. Similarly, total recovery (plant and soil) of ^{15}N in the AR treatment was 82%, compared to 62, 61, 56, 56% in SS, AWDS, AWDL, CF respectively. Higher N recovery in the AR was likely the result of lower N losses. Irrigation inputs ranged from 15 mm in the AR to 1337 mm in the CF treatment. The WP_{in} (kg m^{-3}) averaged 0.8 in AR, and 0.5, 0.4, 0.5 and 0.4 in SS, CF, AWDS, AWDL and CF. Thus, in this environment, rice productivity, water productivity, and N use efficiency were all enhanced in aerobic systems relative to continuous flooding or any alternative irrigation regime.

1. Introduction

Rice (*Oryza sativa*) systems have an important role in providing affordable carbohydrates for a fast-growing world population in the coming decades (Maclean et al., 2013). By 2050, rice production must increase by 15% to meet world demand (Sharkey et al., 2016); requiring an increase in productivity on current cropland as well as possibly expanding to new areas suitable for rice. Despite the potential for rice growth in regions such as South America and West Africa, the lack of irrigation water is often the primary limitation (Balasubramanian et al., 2007; Coelho et al., 2006). Even in regions where irrigation water is readily available, there is increasing pressure to improve water productivity.

To meet the demand for increased yield as well as reduced water use, alternative irrigation strategies need to be tested that can achieve these dual goals (Bouman et al., 2007). Some irrigation strategies that have been tested in rice systems include: a) aerobic rice in which fields are not flooded and soil is kept unsaturated throughout most of the season, usually being rainfed or sprinkler-irrigated (Alberto et al., 2011; Belder et al., 2005a,b; Bouman et al., 2005; Kadiyala et al., 2015b; Kato and Katsura, 2014; Lampayan et al., 2010); b) alternate wetting and drying (AWD), in which the crop is subjected to intermittent periods of flooding and drying (Awio et al., 2015; Belder et al., 2005a,b; Carrijo et al., 2017; Dong et al., 2012; Linquist et al., 2015); and c) saturated soil systems where soil pores are kept saturated, but without ponding water (Bouman et al., 2007; Bouman and Tuong, 2001; Lu et al., 2000).

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All strategies result in reduced water use but yields were also reduced in some cases. Therefore, understanding what conditions lead to yield reductions is important for the adoption of these strategies.

One of the most promising regions in Brazil for rice expansion is the Araguaia river basin in Brazilian's Cerrado, which has alluvial soils with high hydraulic conductivity, very stable micro-structure, clay fraction rich in Fe-Al oxides and kaolinite, low CEC and pH, and highs contents of Al (Sanchez, 1976). The upper horizons of these soils have very stable micro-structure that does not disperse when subjected to tillage, and due to the lack of 2:1 clays, is relatively ineffective for puddling (Balasubramanian et al., 2007; Stone, 2005). These soils are not considered ideal for rice production as they lack the typical high-density layer below the root zone which restricts water percolation (Bouldin, 1986).

Nitrogen is the most essential nutrient in rice production, and irrigation management directly affects its availability for rice uptake and loss pathways (Fageria and Baligar, 2005). Under continuous flooding the soil remains in a reduced anaerobic state and nitrification is thought to be limited (Van Cleemput et al., 2007). However, water regimes or high percolation rates can result in nitrification, exposing N to potential losses via denitrification and leaching (Aulakh and Bijay-Singh, 1996). An evaluation of water management strategies must consider effects on potential N loss pathways.

Therefore, this research aimed to propose an irrigation regime which maintains crop performance while decreases water use in the tropical weathered plain region of Brazilian's Cerrado, and quantify its effect on yield, water productivity, and the fate and recovery of N.

2. Material and methods

2.1. Site description

Field experiments were established in the region of Lagoa da Confusão, State of Tocantins (10°46′39.80″S; 49°55′20.94″W and 190 m ASL) during the rainy summer seasons of 2014, 2015 and 2016 (Fig. 1). The local climate is classified as Awi – tropical wet and dry climate (Alvares et al., 2013). Average annual rainfall is 1800 mm with most of it occurring from September to May and the average annual temperature is 26.7 °C.

The soil is classified as a Plinthaquults (US Taxonomy) with a Plinthic horizon within 60 cm of the soil surface which slows down water percolation. The physiochemical properties are shown in Table 1.

2.2. Field experiment

The experiment was conducted on the same farm in each year of the study but at a different location. In 2014 and 2016 the sites were juxtaposed and presented the same soil characteristics, and 2015 it was slightly away with different characteristics. The experimental design was a split-plot randomized complete block with four replications. Main plot treatments consisted of five irrigation regimes: continuous flooding (CF); AWD with short cycles of flooding and drying (AWDS – 7 days flooded and 7 days non-flooded); AWD with long cycles of flooding and drying (AWDL – 21 days flooded and 7 days non-flooded); soil maintained in a saturated state without flooding (SS); and aerobic (AR). Subplots were two N treatments: 0 and 150 kg N ha^{-1}. All treatments received irrigation water, although in AR, irrigation was used only to incorporate top-dressed N fertilizer.

The main plots consisted of a 105 m^2 hydrologically independent plots created by a 50 cm high levee and 60 cm deep drain around plot perimeter. Plots were sown with long-grain rice variety (IRGA 424) developed for grown in lowland subtropical region of Brazil. The sowing technique was the dry direct seeded rice in all treatments in a row width of 17 cm. Plant density after emergence was approximately 150 plants m^{-2}. Planting dates were 7 December 2013, 18 November 2014 and 9 December 2015. In the 150 kg N ha^{-1} sub-plots, N was applied as pearled urea (46% N) and applied in four splits of equal rates at the following stages: sowing, tillering (V5–V6), panicle initiation (R0), and collar formation of flag leaf (R2) (Counce et al., 2000). All nitrogen applications were made by hand. At the time of topdressing, if the treatment was flooded the water level was lowered above soil surface and urea applied over the soil and plots re-flooded shortly after. If the treatment was not flooded, 5 mm of water was applied to promote incorporation into the soil. Phosphorus fertilizer was applied at the rate

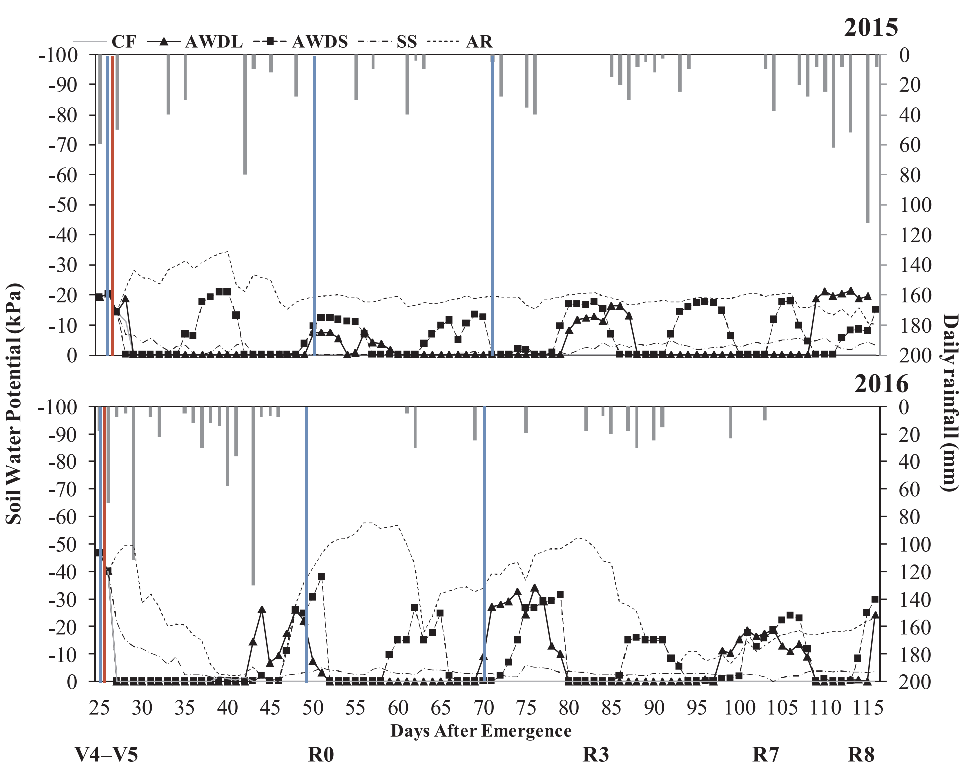

Fig. 1. Soil water potential in root zone (0–0.1 m) in 2015 and 2016 in left axis (values are shown as lines), and daily rainfall (mm) in right axis (values are shown on inverse scale as bars) throughout crop season. The treatments are: continuous flooding (CF), AWD long (AWDL), AWD short (AWDS), saturated soil (SS), and aerobic (AR). The acronyms bellow X-axis indicates phenological stage: Active tillering (V4–V5); Panicle initiation (R0); Panicle exertion (R3); End of grain filling (R7); one grain with brown hull (R8). The red bar indicates when irrigation initiated and blue bars the nitrogen topdressing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Chemical and physical properties of field experiment soil (0–15 cm).

	pH	Organic Matter	P	S	K	Ca	Mg	Al	H	CEC[a]	Clay	Silt	Sand	Ki[b]	Bulk Density
Year		$g\,dm^{-3}$	$mg\,dm^{-3}$		$mmolc\,dm^{-3}$						(%)				$g\,cm^{-3}$
2015	5.5	55	27	12	5.3	47	9	0	34	95	34	28	39	1.67	0.88
2014 & 2016	5.7	50	16	7	3.0	27	15	0	34	79	42	23	35	1.8	0.89

[a] CEC = Cation exchange capacity.
[b] Ki = Weathering coefficient. It is related to weathering degree of clay fraction: $SiO_2\ Al_2O_3^{-1}$.

of 60 kg ha^{-1} P_2O_5 as superphosphate and potassium as KCl at 140 kg ha^{-1} K_2O to all plots at sowing.

Irrigation water was applied through a pressurized system with an independent inlet in each main plot. Initial irrigation began roughly 25 days after seedling emergence as is common in drill seeded systems and the water level was maintained at 5–7 cm high in CF and in the flooding periods of AWDL and AWDS.

Weed management consisted of two sequential glyphosate burndown applications (total of 3.1 kg ha^{-1}), pre-emergence application of clomazone (250 g of ha^{-1}), oxyfluorfen (120 g ha^{-1}). Weed populations varied according to irrigation regime, and post-emergence herbicide management was carry out in all plots as appropriate to the treatment with the worst infestation. It consisted of metsulfuron-methyl (1.8 g ha^{-1}), bentazon (290 g ha^{-1}); cyhalofop-butyl (360 g ha^{-1}) applied about 20 days after crop emergence in all treatments.

The cropping system on the fields used in this study was a rice-soybean rotation. Following soybean harvest, the plots were plowed twice with 56 cm disk plow and rolled before and after rice drill seeding rice.

2.3. Crop performance

Panicle density, above ground crop biomass and N content were determined at maturity by sampling all rice plants within a 0.5 m^2 quadrat allocated at the soil level. Although the sampling dates varied according treatments cycle length, they were always made at brown hull grians (R8) (Counce et al., 2000). Panicles were counted, and a representative subsample was dried at 65 °C in an oven to constant weight and water content was extrapolated to the entire sample. Nitrogen concentration was determined by Kjeldahl digestion (Bremner and Mulvaney, 1982) and total N uptake was calculated as the product of N content (g kg^{-1}) and plant biomass (g m^{-2}). At this time, five plants per plot were randomly sampled to determine spikelet number (m^{-2}) and grain number (m^{-2}). Grains were manually detached from the rachis, filled and unfilled grains were separated by air blowing, counted and weighed. Grain weight (mg) was determined from three subsamples containing a hundred grains. Ratio of filled grain was determined by dividing filled grain by total spikelet number (%), and grain number was calculated as the product of filled grain by panicles number (m^{-2}). Grain yield was determined from a 3 m^2 area harvesting. Impurities were separated in a sample cleaner (Mediza, Panambi, RS) and moisture corrected to 13% in unhusked grains. Finally, the harvest Index (HI) were determined in a 20% representative subsample from the 3 m^2 area, as the ratio of grain yield (dry basis) to above ground biomass at crop maturity.

2.4. Isotopic nitrogen recovery and apparent nitrogen recovery

In 2015 and 2016 years labeled ^{15}N-fertilizer was applied to microplots inside the 150 kg ha^{-1} N subplot following this same rate and timing as the N applied in the main plot. Microplots were 0.245 m^2 and comprised of 4 sowing rows. Microplots were isolated by a metal frame with bottom and top open, 12 cm above and 18 cm deep into the soil. Nitrogen was manually applied as urea (abundance of 3.04% ^{15}N) by diluting in 2.5 L of water and immediately applying to the microplots using a sprinkling can. The water regime inside microplots was the same as the main plot treatment and had an independent water inlet to avoid $^{14}N/^{15}N$ contamination. Top-dress N was applied on dry soil and flooded shortly thereafter, thus allowing urea incorporation into the soil and reducing the potential for volatilization losses.

Biomass was sampled above ground from the two middle rows of each microplot at maturity. Each plant was cut at ground level and separated into vegetative (leaves and stems) and reproductive (panicle) parts. Roots were sampled from a cube of soil measuring 0.34 × 0.2 × 0.2 m, and roots were separated from soil by water sieving. All plant biomass was dried at 65 °C oven to constant weight.

Soil samples to depth of 1 m were taken after harvest using a 0.05 m diameter Dutch auger. The soil was partitioned into 20 cm sections, oven dried at 40 °C to constant weight, and analyzed for N as described below.

Total N and ^{15}N abundance (% ^{15}N atoms) were determined using an automated mass spectrometer coupled to an ANCA-GSL N analyzer (Sercon Co., UK). The total N concentrations and $^{15}N/^{14}N$ isotope ratio were calculated according to Barrie and Prosser (1996) and dilution calculation adapted from Cabrera and Kissel (1989).

$$NDFF = \frac{(15\mathrm{Np} - 15\mathrm{Nn})}{(15\mathrm{Nf} - 15\mathrm{Nn})} \times Nt \tag{1}$$

where NDFF is the amount of N in the plant or soil derived from fertilizer (kg ha^{-1}), ^{15}Np is the amount of ^{15}N in plants (% atoms), ^{15}Nn is the natural ^{15}N abundance (% atoms), ^{15}Nf is the quantity of ^{15}N in the fertilizer (3.04% atoms) and Nt is the plant N uptake or total soil N (kg ha^{-1}). The isotopic nitrogen recovery was calculated using Eq. (2):

$$INR = \frac{NDFF}{Nrate} \times 100 \tag{2}$$

where INR is the ratio of NDFF in plant or soil, and N rate is nitrogen applied as urea to the crop (150 kg ha^{-1}). The difference between total N uptake and NDFF in microplot samples was called N uptake derived from soil by isotopic method (NDSiso).

The apparent N fertilizer recovery (ANR, kg of fertilizer N uptake kg N applied^{-1}), is defined as the difference of N uptake in plant biomass among fertilized and unfertilized N plots divided by N rate.

$$ANR = \frac{(Nuptakefert - Nuptakeunfert)}{Nrate} \tag{3}$$

2.5. Evapotranspiration and water measurements

Rainfall, radiation, air humidity and temperature data were measured hourly using a weather station (Davis Vantage Pro2, Davis, Inc., USA) located on site. The amount of irrigation water was quantified using a flow hydrometer installed in all water inlets. Surface water from plots was not drained, but dry downs for various treatments was accomplished through evapotranspiration and percolation water loss. The soil volumetric water content was measured by dialetric conductivity probe (GS1 – Decagon, WA, USA) in a 3–15 cm depth and recorded every 30 min in 150N subplots of two replicate blocks.

To express soil water content as water tension, a soil water retention curve was developed from undisturbed samples collected at 0.1 m depth from 2015 and 2016/2014 experimental sites. Samples were subjected to pressures of −2, −4, −6, −8, −10, −30, −50, −70, −100 and −1500 kPa using the Richards pressure plate extractors. A soil water retention curve was established by fitting the pressure and theta values to van Genuchten model and parameters were estimated using RETC software (Van Genuchten et al., 1991). The RETC also estimated K_{sat} of top (0–10) and in the less impermeable layer (60–80) being 1.35 and 0.16 m d^{-1}, respectively. The macro, meso and micro porous size distribution for A horizon are 45%, 15%, 39% and in B plinthic are: 31.9%, 4.5%, 63.6%, respectively, determined according Libardi (2012).

The leaf area index (LAI) and the light extinction coefficient was indirectly determined with an optical hemisphere sensor (LI-Cor 2200, Li-Cor, Inc., USA) as described by Jonckheere et al. (2004). Measurements began 15 days after emergence and were repeated every 15 days. All data collection occurred at approximately 09:00 am hours or on cloudy days. One reading was taken over the canopy and 5 readings at soil (or water) surface. Crop height was measured at time of LAI sampling as distance from soil surface to last opened leaf.

Evapotranspiration (ET_C) was estimated by the Penman–Monteith equation, using the measured crop parameters. Zero plane displacement (d) and roughness length for momentum (Z_{om}) and vapor (Z_{oh}) were estimated based on crop height (Allen, 1998). Crop surface resistance (r_s) was assumed as 80 sm^{-1}of (r_l) (Dingkuhn et al., 1999).

Water productivity (WP_{in}) was calculated in relation to water input as the ratio of dry grain mass per unit of water delivered by irrigation (I) + nrainfall (R) (kg m^{-3}), and water loss through percolation (mm) was calculated as water delivered (mm) – Evapotranspiration (mm).

2.6. Statistical analysis

The data was analyzed using Statistical Analysis System, version 9.2 (SAS Institute Inc., 2009). The assumptions of homogeneity of variance and error normality were tested by PROC TRANSREG Boxcox statement. If assumptions were violated, the variable was transformed by convenient lambda. Crop performance ANOVA was performed by PROC GLM split-plot design based on irrigation, N level, and year as well as its interactions as fixed effect model. Replicates were considered random effects to main plot and (replicate × main plot) as the random effect for subplot. ANOVA of water and nitrogen indices was performed by PROC GLM based on irrigation and year. When F probability was < 0.05 the means were separated by Least Significance Difference (LSD).

3. Results

3.1. Weather data

Rainfall patterns varied across growing seasons and total growing season precipitation ranged from 886 to 1262 mm (Table 2). Mean temperatures averaged 25.8 °C and only varied 1.3 °C between seasons with 2016 being the warmest year.

3.2. Soil water potential in root zone

Differences in root zone soil water potential were observed due to differences in irrigation treatments and rainfall (Fig. 1). In 2015, higher precipitation before sowing led to more water in the soil profile at sowing than in 2016. After the initiation of the irrigation treatments, soil water potential in CF remained at 0 kPa and in SS between at 0 and −5 kPa. Soil water potential in the AWDS and AWDL ranged from 0 kPa during the flooding cycles to −21 kPa and −34 kPa in the drying cycles of 2015 and 2016, respectively. The AR treatment experienced the lowest soil water potential. In 2015 shortly after panicle initiation the water potential reached −35 kPa and in 2016 when irrigation started AR was −60 kPa and increased until −8 kPa around panicle initiation due heavy rainfall. After that, the soil water potential ranged from −58 kPa to −10 kPa. In the AR treatment, the soil water potential averaged −20 kPa and −33 kPa from 26 DAE to maturity in 2015 and 2016, respectively.

3.3. Crop performance

Irrigation regimes and N fertilizer significantly affected spikelet number, panicle density and number of grain (Table 3), while grain weight was only affected by year, being 25 mg in 2015 and 27 mg in 2016. In the 0N plots, the AR treatment had the most spiklets per panicle, although in 2015 CF and AWDL were equivalent to AR. In the 150N plots spikelet number increased 16% across irrigation and year and irrigation effect was minimized, although AR tended to remain higher. The panicle density without N fertilizer was higher in AR (307, 361 and 266 panicles m^{-2} in 2014, 2015 and 2016, respectively) than all other irrigation regimes which were similar and averaged 183 panicles m^{-2} across years. With N fertilizer, AR and CF were similar and higher than AWDL, AWDS, and SS in 2014, however, in 2015 and 2016 panicle density in the AR treatment were higher than other irrigations regimes. The number of grains per square meter in 0N plots was higher in AR (28551, 38627, 26026 grains m^{-2} in 2014, 2015 and 2016 respectively) than CF, AWDL, AWDS and SS which were similar and averaged 14045, 18224 and 14042 grains m^{-2} in 2014, 2015 and 2016, respectively. For the 150N plots, the number of grain in AR was similar to CF across years (34608 and 25300 grains m^{-2} for AR and CF respectively in 2014, 43927 and 38720 grains m^{-2} for AR and CF respectively in 2015, grain m^{-2} for AR and CF respectively in 2016), and AWDL, AWDS and SS averaged 18963, 26948, 20557 grains m^{-2} in 2014, 2015 and 2016, respectively. Filled grain percentage had no significant effect for any effect and averaged 90% of filled grain per spikelet across irrigation regime, N level and years.

Above ground crop biomass ranged from 8.3 to 21.8 mg ha^{-1} across years, N Level and irrigation treatments (Table 4). In 2014 for 0N plots, AR and AWDS presented the highest biomass (16. and 14.9 mg ha^{-1}, respectively) while CF and SS averaged the lowest (9.2 and 8.3 mg ha^{-1}, respectively). In the 150N plots, AWDL, AWDS, SS and AR presented similar biomass averaging 16.9 mg ha^{-1}. In the 0N plot of 2015, AR, AWDS and AWDL were equivalent and averaged 14.4 mg ha^{-1}, while for 150 N plots of 2015 all irrigations regimes presented similar biomass averaging 17.6 mg ha^{-1}. Finally, in 2016, in

Table 2
Growing season rainfall and temperature during different stages of rice development in 2014, 2015 and 2016.

	Rainfall (mm)				Average Temperature (°C)			
Year	Vegetative	R0–R4[a]	R5–R8[b]	Total	Vegetative	R0–R4	R5–R8	Total
2014	354	358	174	886	24.8	25.1	25.9	25.3
2015	513	230	519	1262	25.8	25.3	25.4	25.5
2016	823	75	166	1064	25.8	27.2	26.8	26.6

[a] R0–R4 = from panicle initiation to beginning of anthesis.
[b] R5–R8 = from caryopsis elongation to brown hull.

Table 3
Grain weight (mg), spikelet number ($panicle^{-1}$), panicle density ($panicle\ m^{-2}$), filled grain (%), number of grain ($grain\ m^{-2}$) and grain yield ($Mg\ ha^{-1}$). The irrigation treatments are: continuous flooding (CF), AWD long (AWDL), AWD short (AWDS), saturated soil (SS), and aerobic (AR).

	Grain weight (mg)		Spikelet ($panicle^{-1}$)		Panicle Density (m^2)		Filled Grain (%)		Number of Grain ($grain\ m^{-2}$)	
N level	0	150	0	150	0	150	0	150	0	150
2014										
CF	–	–	72b	92ab	193b	275ab	90	93	13896b	25300ab
AWDL	–	–	75b	86b	189b	219b	93	94	14175b	18834b
AWDS	–	–	79b	94ab	186b	205b	89	92	14694b	19270b
SS	–	–	78b	101ab	172b	186b	89	94	13416b	18786b
AR	–	–	93a	112a	307a	309a	85	86	28551a	34608a
2015										
CF	25	25	103a	110a	232b	352b	88	90	23896b	38720a
AWDL	25	25	100a	110a	169b	263b	92	86	16900b	28930b
AWDS	25	25	92b	107a	172b	258b	89	92	15824b	27606b
SS	25	26	93b	103a	175b	236b	87	93	16275b	24308b
AR	26	26	107a	109a	361a	403a	92	96	38627a	43927a
2016										
CF	27	27	88b	103a	196b	251b	88	86	17248b	25853ab
AWDL	28	27	79b	106a	167b	193c	92	89	13193b	20458b
AWDS	27	27	75b	104a	157b	205bc	95	89	11775b	21320b
SS	27	27	75b	98a	186b	203bc	93	87	13950b	19894b
AR	28	27	98a	112a	266a	318a	92	91	26068a	35616a
ANOVA										
Irrigation (I)	*ns*		*		**		*ns*		*	
N level (N)	*ns*		**		**		*ns*		**	
Year (Y)	**		**		**		*ns*		**	
I*N	*ns*		*ns*		*ns*		*ns*		*ns*	
I *Y	*ns*		*ns*		*ns*		*ns*		*ns*	
N*Y	*ns*		**		*		*ns*		**	
I*N*Y	*ns*		*ns*		*ns*		*ns*		*ns*	
CV (%)	*2.1*		*11.1*		*16.6*		*6.9*		*17.1*	

ns: not significant, * significant at 5%, ** significant at less than 1% of probability of error by F test. Values followed by the same letter are not significantly different by LSD test at $p < 0.05$.

the 0 N plots AR, AWDL and CF were equivalent presenting a biomass of 14.1 $mg\ ha^{-1}$ and in the 150N plots, as also happened in 2015, all irrigation regimes had equivalent biomass, averaging 16.0 $mg\ ha^{-1}$.

The N uptake in the 0N plot of AR treatment was 120 and 116 $kg\ ha^{-1}$, respectively in 2014 and 2015. In contrast, in the CF, AWDL, AWDS, and SS treatments N uptake averaged 81 and 84 $kg\ ha^{-1}$. In 2016, N uptake in AR and CF were similar and averaged 112 $kg\ ha^{-1}$ – being 39% more than AWDL, AWDS, and SS. In the 150N treatments, N uptake ranged from 195 to 210 $kg\ ha^{-1}$ in AR and was higher than all the other treatments, which were similar with annual averages ranging from 116 to 150 $kg\ ha^{-1}$.

The leaf area index in the 2015 0N plots showed 5.1 $m^2\ m^{-2}$ in AR irrigation regime, while CF and AWDL were 3.8 and 4.0 respectively. In the 2015 150N, AR was 8.3 $m^2\ m^{-2}$ and CF and AWDL were 7.4 and 6.1 $m^2\ m^{-2}$ respectively. In the 2016 0N, AR was 4.3 $m^2\ m^{-2}$ while the other irrigation ranged from 3.4 to 3.6 $m^2\ m^{-2}$, and in the 150 N, AR reached 6.1 $m^2\ m^{-2}$ and the others irrigation averaged 5.3 $m^2\ m^{-2}$.

Harvest index ranged from 0.32 to 0.58 across years, N Level and irrigation treatments (Table 4). In 2014 for 0N plots, SS presented the highest HI (0.52) while CF, AWDL, AWDS and AR were lower (0.39, 0.39, 0.38 and 0.32, respectively). In the 150N plots, all irrigations presented no significant difference, averaging 0.43. In the 0N plot of 2015, SS had the highest HI of 0.57, while all others irrigations averaged 0.41. For 150 N plots of 2015 all irrigations regimes also did not present differences in HI, averaging 0.51. Finally, in 2016, in the 0N and 150N plots had no differences among irrigation treatment, averaging HI of 0.41 in 0N and 0.45 in 150N.

The cycle length was affected by N level and irrigation regimes across years. In the average, AR 150N reached maturity with 117 days of cycle, although in 2014 the cycle extended for additional 3 days. AR 0N, and CF, AWDL, AWDS at both N levels were, in average, 7 days shorter than AR150, and climatic conditions across years slightly varied one or two days. SS 0N and SS 150N reached maturity with 107 days, being those with the shortest cycle to maturity. Grain yields ranged from 4.1 to 10.6 $mg\ ha^{-1}$ and were affected by irrigation regime, N level, and year (Table 4). AR had the highest grain yield across 0N plots in 2015 (7.1 $mg\ ha^{-1}$) and 2016 (6.4 $mg\ ha^{-1}$), while in 2014, grain yield in AR was only different relative to CF. In the 150N plots, the differences across irrigation regimes were less pronounced. In all years, AR had the highest grain yields although this was not always significant. Importantly, in 2016, yields in the 150N plots were similar among treatments, averaging 8.2 $mg\ ha^{-1}$. The addition of N increased yields by 3 $mg\ ha^{-1}$ regardless of irrigation regime and year. An interaction between year and N level was observed because in 2015, the yield increase in response to N input was on average 34% higher than in 2014 and 2016.

The N content of straw in 150N plots ranged from 4.7 to 10.4 $g\ kg^{-1}$ across years and irrigation treatments (Table 5). In all years the straw and grain N content was higher in the AR treatment than in the other treatments. Apparent N recovery (ANR) was affected by irrigation regime and year, and ranged from 0.12 to 0.63 $kg\ kg^{-1}$ of N. In 2014 and 2016, AR had the highest ANR (0.50 and 0.61 $kg\ kg^{-1}$, respectively) whereas all other irrigation regimes averaged 0.24 and 0.35 $kg\ kg^{-1}$, respectively. In 2015, the ANR of AR and SS were equivalent (averaged 0.58 $kg\ kg^{-1}$), and averaged 28% higher than CF, AWDL and AWDS.

3.4. Isotopic nitrogen recovery

The isotopic recovery in plant ranged from 38 to 65% across irrigation regimes and year (Table 6). AR had the highest N-fertilizer uptake (65%), followed by that in CF, AWDL, AWDS and SS, which averaged 47%. Irrigation regime did not affect the amount of ^{15}N recovered in the grain (37% and 26% in 2015 and 2016, respectively) and root (0.3% and 0.9% in 2015 and 2016, respectively); however,

Table 4
Above ground crop biomass (Mg ha^{-1}), total N uptake at crop maturity (kg ha^{-1}), leaf area index (LAI) at 95 days after emergence (m^2 m^{-2}), harvest index (adimensional) and grain yield (Mg ha^{-1}). The irrigation treatments are: continuous flooding (CF), AWD long (AWDL), AWD short (AWDS), saturated soil (SS), and aerobic (AR).

	Crop Biomass (Mg ha^{-1})		N Uptake (kg ha^{-1})		LAI (m^2 m^{-2})		Harvest Index		Grain Yield (Mg ha^{-1})	
N level	0	150	0	150	0	150	0	150	0	150
2014										
CF	9.2bc	13.9b	75b	122b	na	na	0.39b	0.45a	4.1b	7.1b
AWDL	13.4ab	15.4ab	89b	113b	na	na	0.39b	0.44a	5.5a	7.7ab
AWDS	14.9a	15.4ab	91b	111b	na	na	0.38b	0.48a	5.1ab	7.8ab
SS	8.3c	15.2ab	69b	119b	na	na	0.52a	0.45a	5.0ab	7.3ab
AR	16.1a	21.8a	120a	195a	na	na	0.32b	0.35a	6.0a	8.3a
2015										
CF	12.1ab	16.0a	83b	153b	3.8	7.4	0.43b	0.58a	6.0b	10.5a
AWDL	14.1a	15.1a	96b	139b	4	6.1	0.41b	0.53a	6.2b	8.9b
AWDS	14.9a	18.7a	88b	162b	3.3	7	0.35b	0.50a	5.9b	10.5a
SS	8.9b	19.1a	69c	149b	3.5	6	0.57a	0.46a	5.8b	9.7ab
AR	14.2a	18.6a	116a	210a	5.1	8.3	0.44b	0.49a	7.1a	10.6a
2016										
CF	14.8a	15.3a	105ab	140b	3.6	5.4	0.38a	0.43a	5.4b	8.4a
AWDL	13.8ab	16.2a	63b	128b	3.5	5.2	0.35a	0.47a	5.4b	8.3a
AWDS	10.6b	15.6a	75b	127b	3.4	5.3	0.44a	0.47a	5.0b	7.9a
SS	11.2b	15.6a	67b	133b	3.4	5.3	0.46a	0.45a	5.6b	7.7a
AR	13.8ab	17.1a	118a	195a	4.3	6.1	0.41a	0.42a	6.4a	8.5a
ANOVA										
Irrigation (I)	*		*		-		*		**	
N level (N)	**		**		-		*		**	
Year (Y)	*ns*		*		-		*		**	
I*N	**		*ns*		-		*		*ns*	
I *Y	*		*ns*		-		*ns*		*	
N*Y	*ns*		*ns*		-		*ns*		**	
I*N*Y	*ns*		*ns*		-		*ns*		*ns*	
CV (%)	*22*		*26*		-		*19*		*9*	

na: data not available, ns: not significant, * significant at 5%, ** significant at less than 1% of probability of error by F test. Values followed by the same letter are not significantly different by LSD test at $p < 0.05$.

Table 5
Straw and grain nitrogen content in 150N plots (g kg^{-1}) and apparent nitrogen recovery (ANR kg kg^{-1}). The irrigation treatments are: continuous flooding (CF), AWD long (AWDL), AWD short (AWDS), saturated soil (SS), and aerobic (AR).

	Straw N Content (g kg^{-1})	Grain N Content (g kg^{-1})	Apparent Nitrogen Recovery(kg kg^{-1})
2014			
CF	5.5b	11.3ab	0.31b
AWDL	5.3b	10.8b	0.12b
AWDS	4.8b	9.9b	0.19b
SS	5.5b	10.9ab	0.34b
AR	6.9a	12.4a	0.50a
2015			
CF	5.1b	12.2ab	0.47b
AWDL	4.8b	11.5b	0.31b
AWDS	4.7b	11.7b	0.49b
SS	3.2c	11.1b	0.53ab
AR	8.0a	13.8a	0.63a
2016			
CF	9.2a	12.8ab	0.25b
AWDL	6.7b	12.6b	0.33b
AWDS	7.9bc	12.6b	0.35b
SS	6.3c	12.6b	0.44b
AR	10.4a	13.9a	0.61a
Irrigation (I)	*	*	*
Year (Y)	*	*	*
I *Y	*	*ns*	*ns*
CV (%)	*10.6*	*8.8*	*33.9*

ns: not significant, * significant at 5%, ** significant at less than 1% of probability of error by F test. Values followed by the same letter are not significantly different by LSD test at $p < 0.05$. – not applicable.

recovery of ^{15}N in the straw was 20% higher in AR during 2015 and 34% higher in AR during 2016 than the other irrigation regimes. The NDSiso was affected by irrigation and year. In 2015, AR regime provided the highest amount of native nitrogen (105.8 kg ha^{-1}), while all other irrigation regimes averaged 55.5 kg ha^{-1}. In 2016, AR and CF regimes were equivalent (110.4 and 98.3 kg ha^{-1}, respectively), whereas AWDL, AWDS and SS averaged 67.6 kg ha^{-1}.

The ^{15}N recovery from the 0–20 cm soil layer averaged 15.9% in AR and 13.7% in SS across years and was generally higher than in the other treatments (recovery in the AR treatment was always significantly higher than in the CF treatment). The average ^{15}N recovery across years from the 20–40 and 40–60 cm soil layers was only 1.09% and 0.48%, respectively, and was not affected by irrigation. Because the ^{15}N content in the 40–60 cm layer was close to the detection threshold of the method used, deeper layers were not analyzed.

The total recovery (soil + plant) in the AR treatment was highest and averaged 82% across years (Table 6). All of the other irrigation regimes were similar and averaged 59%. Based on these results, 18% of the N-fertilizer is unaccounted for (and potentially lost) in the AR regime compared to 41% in the other irrigation regimes.

3.5. Evapotranspiration and water

The water delivered through irrigation ranged from 15 mm in AR (a small amount of irrigation water was applied to incorporate top-dress N fertilizer) to 1197 and 1337 mm in CF during 2015 and 2016 years, respectively. Regarding total water input, CF had the highest water consumption (2459 and 2401 mm in 2015 and 2016 respectively), and AR had the lowest (1277 and 1079 mm in 2015 and 2016, respectively). Estimated ET among irrigation regimes was similar and ranged from 527 to 566 mm in 2015, and from 524 to 549 mm in 2016 (Table 7).

The calculated water loss through percolation ranged from 540 to

Table 6
Isotopic N recovery in plant, soil, and N uptake derived from soil through isotopic method (NDS iso). The irrigation treatments are: continuous flooding (CF), AWD long (AWDL), AWD short (AWDS), saturated soil (SS), and aerobic (AR) in 2015 and 2016. The N rate was 150 kg ha^{-1}.

	Plant recovery				Soil Recovery				Total	NDS
	Grain	Straw	Root	Total Plant	0–20 cm	20–40 cm	40–60 cm	Total soil	Recovery	iso
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	kg ha^{-1}
2015										
CF	37	14b	0.3	51b	7b	0.7	na	8b	58b	52.0b
AWDL	42	14b	0.3	56b	3c	0.2	na	3c	58b	61.2b
AWDS	36	14b	0.4	50b	9ab	1.7	na	10ab	60b	60.1b
SS	39	10b	0.3	49b	13a	0.4	na	13a	61b	48.6b
AR	39	25a	0.4	64a	12a	1.1	na	13a	77a	105.8a
2016										
CF	21	21b	0.9	43b	10b	1.2	0.5	12b	55b	98.3a
AWDL	21	16b	0.9	38b	15ab	0.7	0.2	15b	53b	66.8b
AWDS	29	17b	0.9	47b	15ab	1.6	0.5	17b	61b	70.2b
SS	28	16b	0.9	45b	15ab	2.3	0.6	18ab	62b	65.8b
AR	33	31a	1.2	65a	20a	1.0	0.6	22a	87a	110.4a
ANOVA										
Irrigation (I)	*ns*	**	*ns*	**	*	*ns*	*ns*	*	**	**
Year (Y)	**	**	**	*	**	*ns*	–	*	*ns*	*
I *Y	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	–	*ns*	*ns*	*
CV (%)	*17.4*	*18.9*	*42.3*	*15.9*	*29.3*	*80*	*58.2*	*26*	*15.6*	*19.4*

ns: not significant, * significant at 5%, ** significant at less than 1% of probability of error by F test. Values followed by the same letter are not significantly different by LSD test at $p < 0.05$. na: data not available.

1901 mm. The lowest percolation rates (715 and 540 mm, respectively in 2015 and 2016) were in the AR treatment, which received limited irrigation. Percolation rates in all treatments receiving irrigation, exceeded the amount of irrigation water applied. Total water input productivity (WP_{in}) showed the highest in AR regime (0.84 and 0.78 kg m^{-3} water in 2015 and 2016, respectively), followed by SS and AWDS. The CF and AWDL had the lowest productivity ranging from 0.36 to 0.46 kg m^{-3} in 2015 and 2016.

4. Discussion

In this three-year study in Brazilian's Cerrado, climatic conditions were relatively typical and rainfall was sufficient to avoid drought stress in rice as suggested by AR treatment having the highest yields. Importantly for this study, and in contrast to typical rice soils, these plinthaquults soils have high percolation rates (Table 7). Our primary objective was to evaluate water management practices that maintained or increased rice yields with reduced water inputs. This objective was achieved, as rice yields were as high or higher in the aerobic system relative to other irrigation regimes that maintained the soil in much moisture conditions. In addition, irrigation management had a significant effect on nitrogen recovery. Below we discuss the causes of these findings.

4.1. Higher yields related to greater N uptake

There are few reports showing increased rice yields under aerobic conditions. Kato et al. (2009) reported a similar conclusion for

Table 7
Irrigation water input, crop evapotranspiration in 150N plots, percolation loss, and water input productivity (WP_{in}) during growing season of 2015 and 2016. The irrigation treatments are: continuous flooding (CF), AWD long (AWDL), AWD short (AWDS), saturated soil (SS), and aerobic (AR).

	Irrigation (mm)	Total water input (mm)	Evapotranspiration (mm)	Percolation loss (mm)	WP_{in} (kg m^{-3})
2015					
CF	1197	2459	558	1901	0.43c
AWDL	966	2228	527	1701	0.46c
AWDS	633	1895	555	1340	0.56b
SS	363	1625	566	1059	0.60b
AR	15	1277	547	715	0.84a
2016					
CF	1337	2401	545	1856	0.36d
AWDL	1018	2082	538	1544	0.40d
AWDS	684	1748	528	1220	0.46c
SS	396	1460	549	911	0.53b
AR	15	1079	524	540	0.78a
ANOVA					
Irrigation (I)	–	–	–	–	**
Year (Y)	–	–	–	–	**
I *Y	–	–	–	–	*ns*
CV (%)	–	–	–	–	*9.4*

ns: not significant, * significant at 5%, ** significant at less than 1% of probability of error by F test. Values followed by the same letter are not significantly different by LSD test at $p < 0.05$.
Total water input = Rainfall + irrigation.
Percolation loss = Total water input – ET.

temperate rice in Japan. In our case it appears that higher yields were due to increased N uptake as the primary difference among irrigation treatments in both 150N and 0N plots, once SS also experienced the absence of ponding water and did not have crop performance similar to AR. Rice yield components have a strong relationship to N uptake (Lampayan et al., 2010), and the differences observed among irrigations regimes within 150N or 0N plots are an indirect consequence of N uptake. The AR treatment had the highest N uptake, resulting in higher sink capacity demonstrated by spikelet number, panicle density, grain per area and grain yield (Table 3). This effect was seen in all years in the N limited 0N plots; while in the 150N plots, the irrigation effect was not always significant. The reduced effect in the 150N plots is likely the result of the crop nearing point of maximum N uptake.

Interestingly, blast (*Pyricularia oryzae* Cav.) which is a disease in Brazilian tropical lowlands, and is often associated with high N levels (Osuna-Canizalez et al., 1991), was observed in all irrigation treatments but was most severe in the AR (data not shown). Therefore, the management of AR under on-farm conditions may require an adjustment in N rate to achieve a more optimum rate.

4.2. Causes of higher N uptake and N recovery

Higher N uptake in the AR treatment (Table 3) may be due to increased N from soil or reduction in N losses. Higher N uptake in 0N treatment (Table 3) suggests greater indigenous N supply in the AR treatment. This is also confirmed by the AR treatment having 34% more N uptake from indigenous supply than the average of others regimes (Table 6). Aerobic soil conditions are associated with higher N mineralization rates than anaerobic soil conditions (Aulakh et al., 2000; Dong et al., 2012; Kader et al., 2013) resulting in potentially higher N uptake (Dong et al., 2012). In 2015, the weather conditions were more favorable for crop development than 2016. The fewer rainfall in the beginning of crop cycle and higher temperatures from middle season onwards negatively impacted rice development in 2016 as described in crop parameters (Table 3 and Table 4). In 2015 higher amount of ^{15}N was taken up compared to 2016. However, in 2016 a higher quantity of labeled N remained in the soil as crop development decreased. The balance among soil and plant compensates each other and the total recovery (soil + plant) was equivalent in both years (Table 6). Higher N availability may be also a consequence of soil moisture regimes whereby less N is lost via denitrification and or leaching in the AR treatment.

The various fates N losses were not all measured in this study, but some of them are unlikely to have occurred due to methodology or site characteristics. Seepage was prevented due the metal frame of microplots. Ammonium volatilization directly from urea is negligible since fertilizer was incorporated into the soil right after application (Li et al., 2008). The ammonia volatilization from soil, which is a different process from ammonium volatilization directly from urea, is a pH dependent process which turns insignificant when pH is lower than 7.5 (Reddy et al., 1984). The soil in the study had an initial pH of 5.5–5.7 (Table 1), and thus, ammonia volatilization unlikely was the fate N loss.

While we were not able to identify the cause of N loss directly, losses were likely due to leaching and denitrification. Under CF, N-NH_4^+ rather than N-NO_3^- is the mineral predominant form in the soil and it is less susceptible to leaching (Devkota et al., 2013; Patrick and Reddy, 1978). Alternatively, under aerobic conditions (i.e. in AR treatment), nitrification is enhanced, and N-NO_3^-, which is highly susceptible to leaching, becomes the dominate form. However, there is no strong evidence of leaching because labeled N below 40 cm was less than 0.6 kg ha $^{-1}$ for all treatments, which is below method detection limit (Table 6).

Alternatively, nitrification-denitrification may be a loss pathway. In previous studies on the fate of ^{15}N applied to lowland rice, CF was largely reported as the irrigation regime which provided superior isotopic nitrogen recovery in relation to alternative methods (Dong et al., 2012; Kadiyala et al., 2015b; Rose et al., 2016; Zhou et al., 2012). The common factor between these studies was they took place on Alfisols and/or puddled soils, where water percolation rate is usually limited (Belder et al., 2007; Singh et al., 2001), and its submergence results in oxidizing zones just restricted to water/air interface and rhizosphere (Atulba et al., 2015). The major part of bulk soil remains anoxic, and nitrification processes are retarded. Conversely, soils with high percolation rates, like the one described in this study (K_{sat} 1.35 m d^{-1}), have a constant downwards flux of water as seen in percolation rates (to be discussed later in the subsection of “Water Use”). As a result, the N-NO_3^- formed in oxidizing zones move downward in the soil profile (Aulakh and Bijay-Singh, 1996; Bouldin, 1986) and either leach below the root zone (as mentioned above) or moves into anaerobic zones which promotes denitrification (Van Cleemput et al., 2007; Zhou et al., 2011). Denitrification can result in the loss of up to 75 kg of N ha^{-1} during a year time in rice environments (Van Cleemput et al., 2007) or nearly 40% of total N applied in a high percolation soil (Zhou et al., 2012). Further studies are required to explain the magnitude of these two processes in this particular environment.

Based on N recovery indices (isotopic and ANR), AR was found to be the most suitable irrigation regime in tropical Plinthaquults (Tables 5 and 6). The rate of 150 kg ha^{-1} was likely excessive as indicated by the lack of response to N in some of crop parameters and increased blast severity. Therefore, further work needs to focus on developing appropriate N management strategies for these soils under aerobic conditions.

4.3. Water use

The main difficulty with alternative irrigation strategies is fulfilling the crop's water requirement so as not to incur a yield reduction. Following the onset of irrigation, the AR regime resulted in a soil water tension of at most −35 kPa and −60 kPa, respectively in 2015 and 2016 (Fig. 1). We were not able to determine if these water tensions in soil resulted in drought stress. The effects of drought stress (which can begin at −10 kPa to −30 kPa) in rice are related to genotype, crop age and duration of drought stress (Bouman and Tuong, 2001; Pinheiro et al., 2006). However, according to Wopereis et al. (1996) rice transpiration rates remain nearly unchanged as soil water potential dropped from 0 to −100 kPa, with leaf curling occurring below −200 kPa. In a broad meta-analyses of alternate wet and dry irrigation, Carrijo et al. (2017) concluded there is no significant effect on rice yield when the soil water tension dropped to −20 kPa during the drying cycle. Kato et al. (2009) observed aerobic conditions did not decrease rice yield even with soil tension frequently reached −60 kPa (Fig. 1). Thus, based on the average soil tension of 0 to −33 kPa across all irrigation regimes after the onset of irrigation, if a negative effect occurred in the plants, it was not severe enough to overshadow the benefits of nitrogen availability on crop performance.

The differences observed in WP_{in} were linked to water input, which varied 93% among irrigation regimes while, in contrast, grain yield only varied by 12%. The higher water input needed CF and AWDL was due to the high amount water necessary to maintain flooded conditions in high percolation soils (Table 7). In 150N plots, CF and AWDL had a WP_{in}, of 0.4 and 0.5 kg grain kg water^{-1}, respectively; considerably lower than the 0.5–1.1 kg grain kg water^{-1} reported elsewhere (Belder et al., 2005a,b; Borin et al., 2016; Kadiyala et al., 2015a; Sánchez-Llerena et al., 2016; Wang et al., 2016; Yao et al., 2012). In contrast, AR had 0.8 WP_{in}, similar to (Kato et al., 2009) who also observed nearly equivalent yields relative to aerobic conditions. Previous studies reported saturated conductivity (Ks) ranging from 0.8 to 0.0003 m d^{-1} in traditional rice areas (Devkota et al., 2013; Liang et al., 2014; Singh et al., 2001; Tan et al., 2015; Wopereis et al., 1994), which is lower than this site-study (1.35 and 0.16 m d^{-1} in A and B plinthic horizons, respectively). Soils with micro-aggregate structure have low bulk density and high macroporosity (Buol and Eswaran, 1999) which is the physical attribute closest correlated to hydraulic conductivity (Ankeny et al., 1990). This soil has a macroporosity of 46% which is much higher than the average of 24% reported in a wide characterization of soil macroporosity in Asia (Aimrun et al., 2004). Taking into account the WP_{in}, soil physical properties and water consumption in the tested irrigation regimes we conclude that AR is the most suitable for a rational water management.

5. Conclusion

In this study, we found that aerobic rice systems had equivalent or better crop performance, N recovery and water productivity than continuously flooded or any other alternative rice systems. This is one of few studies reporting aerobic rice systems to be at least as high yielding as flooded systems. Higher yields reported here were largely due to increased N uptake because of less N going to unaccounted fates. Adoption of such a system will allow for an increase the rice acreage in Brazilian's Cerrado with lower demand for water resources and nitrogen inputs. However, more studies are required on these systems in order to better quantify N fertilizer requirements as well as address potential weed and pest issues which are likely to be unique to this system.

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