Field Crops Research 218 (2018) 59–68

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

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

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ARTICLE INFO

Keywords:
Water saving
AWD
Isotopic recovery
Nitrogen use efficiency
Ultisol

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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https://doi.org/10.1016/j.fcr.2018.01.002
Received 26 July 2017; Received in revised form 2 January 2018; Accepted 4 January 2018

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

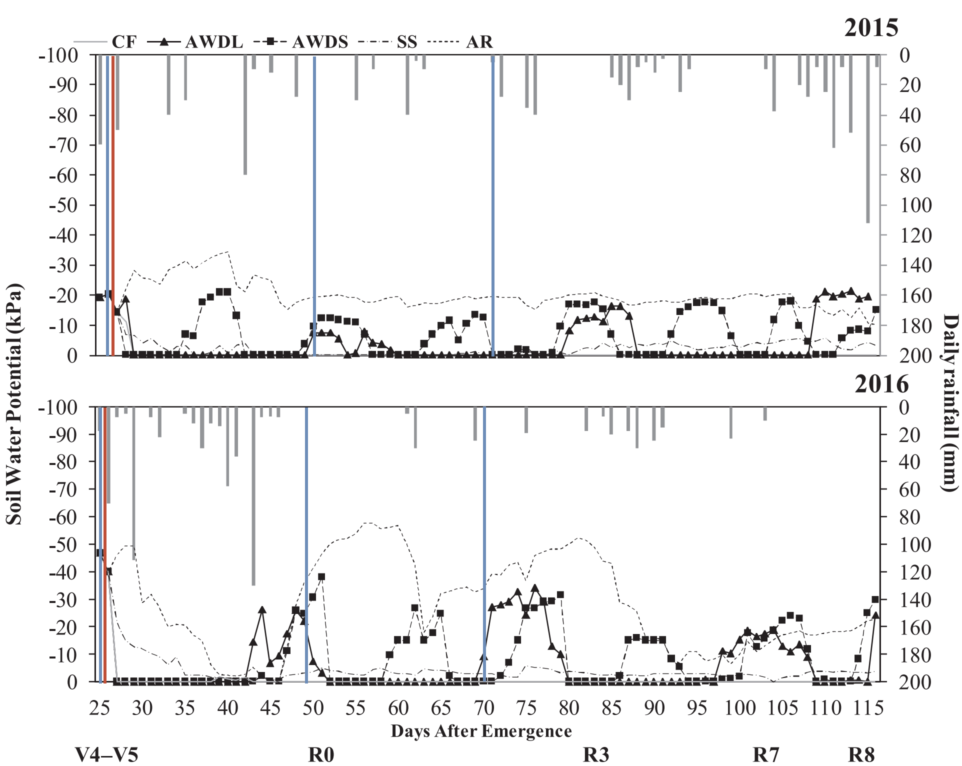

Fig. 1. Soil water potential in root zone (0–0.1 m) in 2015 and 2016 in left axis (values are shown as lines), and daily rainfall (mm) in right axis (values are shown on inverse scale as bars) throughout crop season. The treatments are: continuous flooding (CF), AWD long (AWDL), AWD short (AWDS), saturated 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.)