Field Crops Research 222 (2018) 101–110

Contents lists available at ScienceDirect

Field Crops Research

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

Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics

Daniela R. Carrijo[a,*], Nadeem Akbar[a,1], André F.B. Reis[a,2], Chongyang Li[b], Amélie C.M. Gaudin[a], Sanjai J. Parikh[b], Peter G. Green[c], Bruce A. Linquist[a]

[a] Department of Plant Sciences, University of California – Davis, 387 North Quad, Davis, CA, 95616, USA
[b] Department of Land, Air and Water Resources, University of California – Davis, 387 North Quad, Davis, CA, 95616, USA
[c] Department of Civil and Environmental Engineering, University of California – Davis, One Shields Avenue, Davis, CA, 95616, USA

ARTICLE INFO

Keywords:
Oryza sativa
Intermittent irrigation
Root
Heavy metal
Nitrogen
Plant water status

ABSTRACT

Continuously flooded rice systems are a major contributor to global rice production and food security. Allowing the soil to dry periodically during the growing season (such as with alternate wetting and drying irrigation - AWD) has been shown to decrease methane emissions, water usage, and heavy metal accumulation in rice grain. However, the effects of AWD on rice yields are variable and not well understood. A two-year study was established to quantify the impacts of a range of treatments differing in AWD severity (degree of soil drying between flooding events) on yield (as well as factors that may affect yields), soil hydrology in the soil profile, and grain arsenic (As) concentrations relative to a continuously flooded control (CF). Three AWD treatments of increasing severity were imposed between full canopy cover (around 45 days after sowing) and 50% heading: AWD-Safe (field was reflooded when the perched water table reached 15 cm below the soil surface) and AWD35 and AWD25 (field was reflooded when the soil volumetric water content at 0–15 cm depth reached 35% and 25%, respectively). During the drying periods, the 0–15 cm soil layer in the AWD-Safe remained saturated, whereas in AWD35 and AWD25 the soil dried to the desired volumetric water contents. In contrast, soil moisture at 25–35 cm below the soil surface was similar across all treatments. Yield was not reduced in any of the AWD treatments, compared to the CF control. There were no consistent differences in yield components, ^{13}C discrimination, and N dynamics. Results suggest that the availability of water and the presence of roots at the 25–35 cm soil depth during the drying periods ensured that the crop did not suffer drought stress and thus yields were maintained. Grain As concentration in the AWD-Safe treatment was similar to that in the CF control but decreased by 56–68% in AWD35 and AWD25. AWD-Safe is often promoted as a means of practicing AWD without reducing yields; however, in this study this practice did not reduce grain As concentration because the soil did not reach an unsaturated state. These findings demonstrate that knowledge of surface and subsurface hydrology, and the root system are important for understanding the potential of AWD.

1. Introduction

Rice is a staple crop for almost four billion people and the demand for rice is expected to grow through 2025 in response to increasing population (Bouman, 2007). About 75% of global rice production is grown in irrigated lowlands (IRRI, 2017), where the fields are usually continuously flooded throughout the growing season. While continuously flooded rice systems are highly productive, they are associated with a number of issues including high water use (Bouman et al., 2007b), high methane emissions (Linquist et al., 2012), and heavy metal accumulation in the grain [e.g. Zhang et al. (2010) for mercury; Zhao et al. (2010) for arsenic]. Therefore, the development of systems that maintain or increase yields while reducing these negative impacts are important for meeting sustainable intensification goals (Godfray and Garnett, 2014).

Alternate wetting and drying (AWD) has been proposed as an irrigation practice that has the potential to achieve these goals in rice systems. With AWD, fields are subjected to intermittent flooding, where

* Corresponding author.
E-mail addresses: drcarrijo@ucdavis.edu (D.R. Carrijo), nadeem.akbar@uaf.edu.pk (N. Akbar), andrefbr@usp.br (A.F.B. Reis), cyfli@ucdavis.edu (C. Li), agaudin@ucdavis.edu (A.C.M. Gaudin), sjparikh@ucdavis.edu (S.J. Parikh), pggreen@ucdavis.edu (P.G. Green), balinquist@ucdavis.edu (B.A. Linquist).
[1] Present address: Department of Agronomy, University of Agriculture – Faisalabad, 38040, Pakistan.
[2] Present address: Department of Agronomy, University of Sao Paulo – Luiz de Queiroz College of Agriculture, Av. Pádua Dias 11, 13418-900, Piracicaba, Brazil.

https://doi.org/10.1016/j.fcr.2018.02.026
Received 2 December 2017; Received in revised form 24 February 2018; Accepted 25 February 2018
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irrigation is interrupted and water is allowed to subside via evapotranspiration and percolation until the soil reaches an aerobic state, after which the field is reflooded. Compared to continuously flooded rice systems, AWD has been shown to reduce water use by 23–33% (Carrijo et al., 2017), reduce greenhouse gas emissions (methane plus nitrous oxide) by 45–90% (Linquist et al., 2015a), and reduce methylmercury and total arsenic concentration in rice grain by 38–60% (Rothenberg et al., 2016; Tanner et al., 2018) and 50% (Das et al., 2016), respectively.

While the negative impacts of continuously flooded rice systems can be addressed with the implementation of AWD, in many cases yields are reduced. Based on a meta-analysis, Carrijo et al. (2017) found that the degree of soil drying during the drying events (termed AWD severity) was critical to ensuring that yields were maintained. They reported that compared to continuous flooding, yields were not reduced with mild AWD (soil water potential at root depth > −20 kPa or perched water did not drop below 15 cm from the soil surface) but were reduced on average by 23% with severe AWD (soil water potential at root depth < −20 kPa).

Yield reductions observed using severe AWD may be due to a number of factors. First, it may be water stress. The sensitivity of rice to unsaturated soil conditions can be attributed at least in part to its shallow root system (Parent et al., 2010). Second, AWD may result in increased N losses due to nitrification and denitrification (Pandey et al., 2014), which can lead to reduced plant N uptake. Third, allowing the soil to dry early in the season can promote weed growth (de Vries et al., 2010), leading to increased competition and lower yields. Finally, drying events can increase blast (*Magnaporthe oryzae*) pressure, a major disease of rice which reduces yields (Bidzinski et al., 2016).

There is a high degree of variation across AWD studies with respect to how yields respond to AWD (Carrijo et al., 2017). Lacking in most studies is an understanding of soil hydrology and rooting patterns throughout the rooting depth. Deep roots may be critical for water extraction during the drying periods in AWD (Ludlow and Muchow, 1990) provided that sufficient water is available at depth. Also, at issue is the question of how do AWD benefits (i.e. reductions in methane and heavy metal accumulation) vary with changes in AWD severity. Few studies have evaluated these effects despite the wide range of AWD severities reported in the literature. Therefore, the objective of this study was to establish a range of treatments differing in AWD severity to quantify impacts on yield (as well as factors that may affect yields such as yield components, N uptake, root traits, carbon isotope discrimination), soil hydrology throughout the rooting depth, and grain As concentrations.

2. Material and methods

2.1. Study site characteristics

A two-year field experiment was conducted at the Rice Experiment Station (39°27′47″N, 121°43′35″W) in Biggs, CA during the summers of 2015 and 2016. The soil at the site was a Vertisol, comprised of fine, smectitic, thermic, Xeric Epiaquerts and Duraquerts, with a soil texture of 29% sand, 26% silt and 45% clay, a pH of 5.3, 1.06% organic C and 0.08% total N (Pittelkow et al., 2012). The concentrations of total As and Cd in the soil were 3.85 mg kg^{-1} and 0.2 mg kg^{-1} respectively. Total As in the soil was measured through digestion with nitric, sulfuric and perchloric acids up to 310 °C on a programmed heating block. The digested solution was reduced so that all arsenic species were transformed to arsenite and quantified by inductively coupled plasma (ICP) atomic emission at 194 nm using hydride vapor generation (Tracy et al., 1990). Total Cd in soil was obtained through digestion with nitric acid and hydrogen peroxide in a closed vessel microwave system (Sah and Miller, 1992), followed by quantification using ICP-mass spectrometry. The climate at the site is Mediterranean with a mean annual precipitation of 472 mm and average daily temperatures of 15.5 °C (CIMIS, 2017). The total precipitation and average daily temperature during each growing season was 5.2 mm and 22.6 °C in 2015 and 10.1 mm and 21.7 °C in 2016 (CIMIS, 2017), respectively.

Table 1
Summary of management practices in 2015 and 2016.

Crop development and general management practices	2015		2016	
	Date	DAS	Date	DAS
Fertilization[a]	May 18th	−2	May 23rd	−1
Sowing	May 20th	0	May 24th	0
Initial flood	May 22nd	2	May 26th	2
Canopy cover ≥60%	Jul 1st	42	Jul 11th	48
50% heading	Aug 11th	83	Aug 12th	87
Pre-harvest drain	Sep 7th	110	Sep 19th	118
Harvest	Sep 30th	133	Oct 20th	149

Water management in AWD treatments	2015			2016		
	Date	DAS	Duration[c]	Date	DAS	Duration
Start of 1st drying period[b]	Jul 7th	48		Jul 12th	49	
AWD-Safe reflooded				Jul 15th	52	3
AWD35 reflooded	Jul 16th	57	9	Jul 19th	56	7
AWD25 reflooded	Jul 19th	60	12	Jul 22nd	59	10
Start of 2nd drying period	Jul 27th	68		Jul 26th	63	
AWD-Safe reflooded				Jul 29th	66	3
AWD35 reflooded	Aug 3rd	75	7	Aug 2nd	70	7
AWD25 reflooded	Aug 9th	81	13	Aug 5th	73	10

[a] Except for N fertilization in the microplots in 2016, which was done immediately prior to the initial flooding of the field.
[b] The start day of a drying period was considered the day when the perched water table was at the soil surface.
[c] Duration refers to the number of days from the start of a drying period to reflooding. DAS = days after sowing.

2.2. Treatments and experimental design

In 2015, two AWD treatments (AWD35 and AWD25) were compared to a continuously flooded (CF) control irrigation treatment, and an additional AWD treatment (AWD-Safe) was added in 2016. The plots were comprised of 0.3 ha basins, which were precision leveled and had no slope. The basins were separated by levees and drain ditches below the field soil level were constructed between basin levees to prevent lateral seepage between basins. Treatment position within the experimental field was re-randomized in each year. In both years, treatments were arranged in a randomized complete block design with three replications. More detailed information about the treatments and other management practices are reported in Table 1.

In the CF treatment, the field was flooded from sowing to about 3 weeks before harvest. In the AWD treatments two drying periods were imposed where the irrigation was interrupted and the floodwater (i.e. perched water table) was allowed to subside until a certain point before being reflooded. In AWD35 and AWD25 the field was reflooded when the soil moisture at 0–15 cm soil depth reached 35% and 25% volumetric water content, respectively. In AWD-Safe the field was reflooded when the perched water table reached 15 cm below the soil surface (Lampayan et al., 2015). Except for the two drying periods, irrigation, nutrient and pest management in the AWD treatments was similar to the CF control. The first drying period began in all AWD treatments when canopy cover across all plots reached a minimum of 60% (on average 45 days after planting). This was done to suppress weeds that may germinate in unsaturated soil (Rao et al., 2007) and ensure that

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