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Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis

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ABSTRACT

Rice systems provide a major source of calories for more than half of the world's population; however, they also use more water than other major crops. Alternate wetting and drying (AWD) is an irrigation practice (introduction of unsaturated soil conditions during the growing season) that can reduce water inputs in rice, yet it has not been widely adopted, in part, due to the potential for reduced yields. We conducted a meta-analysis to: 1) quantify the effect of AWD on rice yields and water use; and 2) to identify soil properties and management practices that favor AWD yields and promote low water use relative to continuous flooding (CF- control). We analyzed 56 studies with 528 side-by-side comparisons of AWD with CF. Overall, AWD decreased yields by 5.4%; however under Mild AWD (i.e. when soil water potential was ≥ −20 kPa or field water level did not drop below 15 cm from the soil surface), yields were not significantly reduced in most circumstances. In contrast, Severe AWD (when soils dried beyond −20 kPa) resulted in yield losses of 22.6% relative to CF. These yield losses were most pronounced in soils with pH ≥ 7 or carbon < 1% or when AWD was imposed throughout the season. While water use was lowest under Severe AWD, under Mild AWD water use was reduced by 23.4% relative to CF. Our findings both highlight the potential of AWD to reduce water inputs without jeopardizing yield as well as the conditions under which these results can be realized.

1. Introduction

Rice (*Oryza sativa* L.) is a major staple crop with more than 50 kg of rice being consumed per capita per year worldwide (FAOSTAT, 2016). Globally, over 478 million tons of milled rice was produced in 2014/15 of which over 90% was used directly for human consumption (USDA, 2016). While rice is essential for ensuring global food security, traditional rice cultivation, practiced in flooded paddy soils, demands higher water inputs than other cereal crops (Pimentel et al., 2004). With the increasing threat of water scarcity currently affecting 4 billion people around the globe (Mekonnen and Hoekstra, 2016), it is crucial to develop agronomic practices with the potential to reduce water use while maintaining or increasing yields to support a growing population.

One practice that has been shown to reduce water use in rice systems is an irrigation management practice referred to as Alternate Wetting and Drying (AWD) (Linquist et al., 2014; Lampayan et al., 2015). Under AWD, fields are subjected to intermittent flooding (alternate cycles of saturated and unsaturated conditions) where irrigation is interrupted and water is allowed to subside until the soil reaches a certain moisture level, after which the field is reflooded. AWD has been reported to reduce water inputs by 23% (Bouman and Tuong, 2001) compared to continuously flooded rice systems.

AWD also has the potential of reducing greenhouse gas (GHG) emissions, especially methane (Wassmann et al., 2010; Li et al., 2006). Linquist et al. [2014] reported that AWD reduced global warming potential (GWP – $CH_4 + N_2O$) by 45–90% compared to continuously flooded systems. With the anthropogenic emissions of GHG now on the order of 48 Gt CO_2 eq. year^{-1} (Montzka et al., 2011), there have been worldwide efforts to promote AWD in rice in an attempt to reduce GHG emissions. For example, in the USA, the American Carbon Registry recently approved a methodology called "Voluntary Emission Reductions in Rice Management Systems" which allows farmers to receive carbon credits for various practices they adopt in their rice systems, including AWD (http://www.arb.ca.gov/cc/capandtrade/protocols/riceprotocol.htm). Other benefits of AWD are the reduction of arsenic accumulation in the grain (Das et al., 2016; Linquist et al., 2014), reduction of methylmercury concentration in soil (Rothenberg et al., 2016), and reduction of energy/fuel consumption in cases where irrigation is supplied by pumping (Nalley et al., 2015; Kürschner et al., 2010).

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Given these benefits, many efforts have been made to disseminate AWD particularly in Asia. In China there are reports of wide spread adoption of what they refer to as a "mid-season" drain (Li and Barker, 2004) which is similar to AWD. However, with the exception of China's mid-season drain, adoption of AWD is limited (Cabangon et al., 2016; Lampayan et al., 2015; Kürschner et al., 2010) and can be attributed, among other factors, to the varying success in maintaining yields. Given this uncertainty, we conducted a meta-analysis with the following objectives: 1) quantify the effect of AWD on rice yields and water use relative to a continuously flooded (CF) control and 2) identify soil properties and management practices that are most favorable for implementing AWD.

2. Materials and methods

2.1. Data collection

A literature search was conducted on Web of Science and Google Scholar for articles published from January 1898 to June 2015 comparing rice yields under AWD versus CF in side-by-side field experiments. In Web of Science, we conducted five searches with the following keywords in the topic: 1) 'rice' and 'alternate wetting and drying'; 2) 'rice' and 'intermittent wetting and drying'; 3) 'rice' and 'alternate waterlogging'; 4) 'rice' and 'intermittent waterlogging'; 5) 'rice', 'flood', 'yield', and 'field' occurring in the title and 'irrigation'; 'flood'; 'yield' and 'field'. In Google Scholar, we searched for items containing both the terms 'rice' and 'alternate wetting and drying' in the title of the article.occurring in the title and 'irrigation'; 'flood'; 'yield' and 'field'

Only publications comprising field experiments with side-by-side comparisons of AWD and CF were selected. Here, we refer to AWD as an irrigation practice where, at least once during the growing season, the soil is allowed to dry to a certain extent below saturation and is then reflooded. Accordingly, studies that referred to AWD as rice subjected to flush or sprinkle irrigation were excluded (these fields were never flooded), as were experiments where the field was reflooded as soon as the field water level reached the soil surface (these soils never fell below saturation). In all cases, AWD was compared to a CF control treatment where the field was kept submerged from the initial flood (i.e. transplanting in transplanted systems, sowing in water seeded systems, or 3–4 leaf stage in drill seeded systems) until the pre-harvest drainage.

In addition to recording yield data from each study, we also collected data on water use and water productivity. Water use was defined as the total water input (irrigation plus rainfall) from sowing to harvest. Water productivity – the amount of yield per unit of water used (kg ha^{-1} m^{-3}) – was either calculated or extracted directly from the study.

Apart from recording the response variables of interest (yield, water use and water productivity), we also recorded and categorized the following moderating variables when reported: soil texture (clayey or non-clayey based on USDA soil texture classes (USDA, 1993)), soil pH (< or ≥ 7), soil organic carbon content – SOC (> or ≤ 1%), varietal type (hybrid or inbred), establishment method (direct seeded or transplanted), number of drains conducted during AWD (≤ 5 or >5), AWD timing (when in the growing season the drying cycles were imposed) and AWD threshold (the driest level to which the soil was subjected before being flooded again).

AWD timing was categorized as: 1) vegetative or reproductive, if all drying cycles occurred only during the vegetative or reproductive stage; 2) throughout season, if the drain events spanned across both vegetative and reproductive stages, independent of the duration or frequency of the drying period(s). Of note, studies having AWDs categorized as reproductive usually involved drain events through to maturity. When there was no report on the phenological stage, we assumed that plants switched from vegetative to reproductive stage at 60 days after sowing (in transplanted systems, sowing date was calculated from the seedling age at transplanting), based on a typical crop cycle of 120 days (Yoshida, 1981).

AWD threshold was measured in many different ways, including volumetric water content, gravimetric water content, days after ponded water disappeared, qualitative measurements such as "hair cracking", soil water potential in the rooting zone (SWP) and field water level (FWL). Since SWP and FWL were the most common and are quantifiable, we grouped them into two categories for AWD threshold: 1) Severe AWD, when the SWP in the rooting zone was allowed to drop below −20 kPa (SWP < −20 kPa); and 2) Mild AWD, when SWP in the rooting zone was not allowed to drop below −20 kPa (SWP ≥ −20 kPa) or, if the FWL was measured, it was not allowed to drop more than 15 cm below the soil surface (FWL ≤ 15 cm), also known as Safe AWD (Bouman et al., 2007).

2.2. Data analysis

Meta-analysis procedures using the package "metafor" of R software (R Core Team, 2015) were used to compare yields, water use and water productivity under AWD versus CF. First, the effect size of AWD was calculated for each observation (side-by-side comparison between AWD and CF) as the natural log of the response ratio (Eq. (1)) (Hedges et al., 1999):

$$Effect\ size = ln\left(\frac{x_{AWD}}{x_{CF}}\right) \tag{1}$$

where x = response variable (yield, water use, water productivity). Secondly, effect sizes were weighted. The majority of studies did not report any measurement of variance of the means; therefore, each effect size was weighted based on the number of replicates and the number of observations in each study (Eq. (2)):

$$Weight = \frac{n_{rep}}{2 \times n_{obs}} \tag{2}$$

where n_{rep} is the number of experimental replications and n_{obs} is the total number of observations from an individual study. For each response variable (yield, water use and water productivity) outliers were identified as ±5 standard deviations from the mean of the weighted effect sizes and removed. Finally, the mean effect size of AWD was calculated as the mean of the weighted effect sizes of the observations and bootstrapped 95% confidence intervals (CI) were generated using the "boot" package in R with 4999 iterations. The mean effect size of AWD was considered significantly different than CF if its CI did not overlap zero. When comparing categories, mean effect sizes were considered significantly different when their CI did not overlap with each other. For ease of interpretation, all the graphs herein show the back-transformed effect sizes as the percentage change caused by AWD in relation to CF (which we also refer in the text as "AWD relative yield" or "AWD relative water use").

For all mean effect sizes calculated, publication bias was assessed visually using funnel plots and with the regression test for detecting funnel asymmetry by Egger et al. (1997) ("metafor" package). The inverse of the weights (Eq. (2)) were used as estimators of variance in the publication bias assessment (Borenstein et al., 2009). If there was indication of publication bias, a study-bias assessment was performed as follows: 1) mean AWD and CF yields/water use/water productivity were obtained for each study; 2) an AWD/CF ratio was calculated from those means resulting in each study having one AWD/CF ratio; 3) studies with a ratio falling outside the range of ±2 standard deviations from the mean ratio of all studies were removed (always ≤ 3 studies) and a second bootstrap was performed following the original procedure but excluding the studies with potentially disproportionate leverage.