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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 $\leq 1\%$), 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 $\leq$ 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):

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

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)):

$$Weight = \frac{n_{rep}}{2 \times n_{obs}} \quad (2)$$

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 $\leq$ 3 studies) and a second bootstrap was performed following the original procedure but excluding the studies with potentially disproportionate leverage.

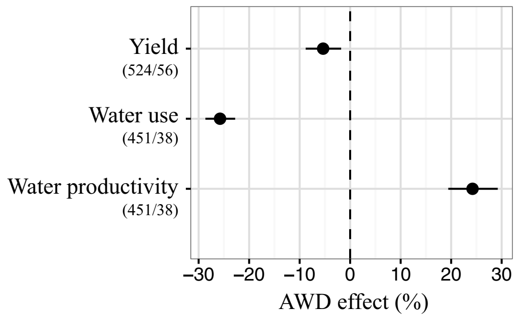

Fig. 1. Effect of AWD on yield, water use (irrigation + rainfall) and water productivity (grain yield/water use). Mean effect sizes (●) and bootstrapped confidence intervals (–) are represented. The number of observations/number of studies included in each dataset are indicated in parenthesis.

If the new effect size produced the same outcome (e.g. continued being significantly different from zero or significantly different from another category) as the initial analysis, the initial result was considered robust and all the studies were maintained; otherwise, the new outcome based on the smaller data set is presented (this occurred in only one category).

3. Results

The literature search returned a total of 674 articles, of which 57 met our criteria. Two articles (Sudhir-Yadav et al., 2011a,b) reported on the same experiment (yield data was extracted from the first and water use data was extracted from the latter) and thus a total of 56 unique studies were compiled, containing 528 side-by-side yield comparisons between AWD and CF yields (Table 1).

More than 80% of the studies were from Asia and 31% from China. The majority of the studies used transplanted seedlings, inbred varieties and conducted AWD throughout the season. Thirty-eight studies (451 observations) reported water use and water productivity. Outliers totaled 0.75% of the yield dataset, 0% of the water use dataset, and 0.44% of the water productivity dataset.

3.1. Overall effect of AWD on yield, water use and water productivity

Overall, AWD decreased yield by 5.4% (CI: −8.7% to −1.8%) and water use by 25.7% (CI: −28.6% to −22.7%) compared to CF (Fig. 1). As a result, AWD increased water productivity (grain yield per unit of water) by 24.2% (CI: 19.3% to 29.3%).

3.2. Soil properties and management practices influencing yield in AWD

With respect to the influence of soil properties on AWD performance, in all cases AWD yields were lower than CF (Fig. 2). However, when AWD was practiced in acidic soils (pH < 7), AWD relative yield was −5.3% (CI: −7.5% to −3.1%) compared to −18.7% (CI: −24.1% to −12.5%) when it was practiced on soils with pH ≥ 7. Also, AWD performed better on soils with high SOC (>1%) with relative yields being −4.3% (CI: −6.4% to −2.1%) compared to −11.6% (CI: −15.4% to −7.4%) on soils with lower SOC. Soil texture had no observed effect on AWD relative yields.

With regard to water management, we examined the phenological stage during which the drying cycles were imposed (AWD timing) and the degree of soil drying (AWD threshold). When AWD was conducted during the vegetative stage versus the reproductive stage there was no effect on AWD yields (data not shown) so these categories were combined into a single category. When AWD was conducted only during the vegetative or reproductive phase

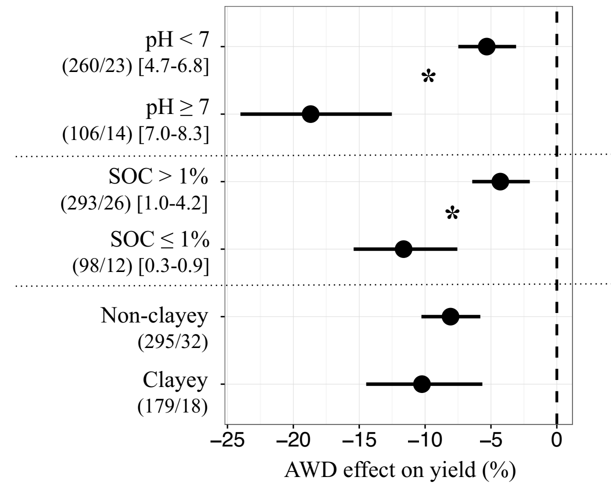

Fig. 2. AWD effect on yield depending on the soil properties pH, SOC (soil organic carbon) and texture. Mean effect sizes (●) and bootstrapped confidence intervals (–) are represented. For each category, the number of observations and number of studies are in parenthesis and the range is in brackets. Confidence intervals not overlapping between categories indicate that they cause different effects on AWD relative yields (indicated by "*").

there was no yield reduction (AWD relative yield: −0.5%, CI: −4.3% to 3.5%), compared to an 8.1% yield reduction (CI: −9.9% to −6.2%) when it was practiced throughout the whole season (Fig. 3a). With respect to AWD threshold, there was no yield penalty with AWD when FWL ≤ 15 cm (AWD relative yield: −1.9%, CI: −4.4% to 0.3%) or SWP ≥ −20 kPa (AWD relative yield: −3.4%, CI: −7.2% to 0.5%) were used as the threshold. However, when the threshold was drier (SWP < −20 kPa) yield was reduced by 22.6% (CI: −27.9% to −16.5%). Different establishment practices (transplanting or direct seeding), number of drains conducted (> or ≤5) and varietal type (hybrid or inbred) were also examined, but none influenced AWD relative yields (data not shown).

Given that rice yields may be reduced when exposed to unsaturated soil conditions (Bouman and Tuong, 2001) and that we found AWD threshold to have a large influence on AWD performance (Fig. 3b), we evaluated the interaction of soil properties and management practices with AWD threshold (Fig. 4). Because the categories FWL ≤ 15 cm and SWP ≥ −20 kPa did not reduce yield compared to CF (Fig. 3b) we combined them into a single category termed "Mild AWD" and we termed the category SWP < −20 kPa as "Severe AWD". Separating the data into this many categories resulted in some categories having a low number of observations and/or studies (e.g. SOC ≤ 1% under Severe AWD and "vegetative or reproductive" under Severe AWD). This may be the reason that in the case of SOC (Fig. 4b) the effect size of both Mild AWD categories is negative with CI not overlapping zero. Despite this, what is readily apparent by examining Fig. 4 is that soil properties and management practices had no effect on yields under Mild AWD. In contrast, under Severe AWD these factors were much more influential. Specifically, under Severe AWD, yields were lower in: 1) soils with high pH (≥7), with AWD relative yield = −46.5% (CI: −54.2% to −37.5%) compared to −17.1% (CI: −22.6% to −11.4% to) in soils with low pH; 2) soils with low SOC (≤1%), with AWD relative yield = −38.8% (CI: −46.1% to −30.4%) compared to −10.1% (CI: −14.9% to −5.0%) in soils with high SOC; and 3) when AWD was practiced throughout the entire season, with AWD relative yield = −27.1% (CI: −33.4% to −19.7%) compared to −3.0% (CI: −8.0% to 2.5%) when AWD was practiced only during the vegetative or reproductive stage. We also performed this analysis with the other factors previously considered (varietal type, number of drains and establishment method), but none showed a significant effect on

Table 1
Overview of the studies used for analysis[a].

Authors and date	Country	Soil			AWD		Water use
		pH	C (%)	Text	timing	threshold	
Abassi and Sepaskhah (2011)	Iran	7.8	–	C	T**	M/S	Yes
Awio et al. (2015)	Uganda	–	–	–	T**	–	–
Balasubramanian and Krishnarajan (2001)	India	7.6	–	N	T	–	*
Banerjee et al. (2002)	India	8.1	0.5	N	T	–	–
Belder et al. (2004)	China	6.5	1.0	N	T	M/S	Yes
	Philippines	5.4	1.8	C	V/T		
Belder et al. (2005a)	Philippines	6.7	2.0	C	T	S	Yes
Belder et al. (2005b)	China	–	–	N	T	S	Yes
	Philippines				V/T		
Biswas and Mahapatra (1979)	India	–	–	–	T	S	–
Bueno et al. (2010)	Philippines	6.5	1.9	C	T	S	Yes
Cabangon et al. (2001)	China	4.7	2.0	N	T	M	Yes
		6.5	1.0				
Cabangon et al. (2011)	Philippines	6.7	2.0	C	V/T	M/S	Yes
Chapagain and Yamaji (2010)	Japan	6.4	2.8	N	T	–	Yes
de Vries et al. (2010)	Senegal	5.1	1.0	C	V/R/T	M/S	Yes
		5.6	0.8				
Dong et al. (2012)	Vietnam	–	1.4	C	V	M	–
Dunn and Gaydon (2011)	Australia	6.0	1.4	N	V	–	Yes
Feng et al. (2007)	China	–	1.4	N	T	S	Yes
Geethalakshmi et al. (2011)	India	7.1	0.6	N	T	–	Yes
Ghosh et al. (2011)	India	5.8	0.8	C	T	M	Yes
Howell et al. (2015)	Nepal	–	–	–	V/T	M	Yes
Hu et al. (2015)	China	5.3	1.7	–	R/T	–	Yes
Jabran et al. (2015)	Pakistan	7.8	0.5	–	T	–	Yes
		7.9					
Jha (1981)	India	6.0	0.5	N	T	–	Yes
Khan et al. (2015)	Bangladesh	6.4	0.9	C	T	–	–
Khosa et al. (2011)	India	7.4	0.5	N	T	M/S	–
Lampayan et al. (2014)	Philippines	–	–	C	T	M/S	Yes
Li (2012)	China	7.4	3.0	N	T	–	*
Liang et al. (2013)	China	7.1	1.6	N	T	M	–
		6.4	1.9	C			
Linquist et al. (2014)	USA	5.6	0.7	N	V/T	–	Yes
Lu et al. (2000)	Japan	–	–	N	R	M	Yes
Marimuthu et al. (2010)	India	–	–	–	T	–	Yes
Matsuo and Mochizuki (2009)	Japan	–	–	N	T	M	Yes
Moterle et al. (2013)	Brazil	–	–	–	T	–	–
Oliver et al. (2008)	Bangladesh	–	–	N	T	M/S	Yes
Paul and Rashid (2013)	Bangladesh	–	–	N	T	M/S	Yes
Pirmoradian et al. (2004)	Iran	7.1	–	N	T	M/S	Yes
Rahman and Bulbul (2014a)	Bangladesh	6.8	–	C	V	M/S	–
Rahman et al. (2014b)	Bangladesh	–	–	N	T	M	Yes
Raju et al. (1992)	India	–	0.7	N	T	–	*
Roel et al. (1999)	USA	–	–	C	V	–	Yes
Shaibu et al. (2015)	Malawi	6.3	1.1	N	V/T	–	Yes
Singh et al. (1997)	India	8.0	–	N	T	M	–
Singh et al. (2009)	India	6.7	4.2	N	T	–	–
		8.3					
Sudhir-Yadav et al. (2011a, 2011b)	India	8.0	0.5	N	T	M/S	Yes
Sujono (2010)	Indonesia	–	–	–	T**	–	Yes
Tan et al. (2013)	China	6.8	1.6	C	T	–	Yes
Tan et al. (2014)	China	–	–	N	T	S	Yes
Towprayoon et al. (2005)	Thailand	6.1	1.2	C	T	–	–
Wiangsamut et al. (2013)	Philippines	6.6	0.3	N	V	S	Yes
		7.3	0.7				
		6.6	0.7				
		7.6	1.3				
		7.2	1.8	C			
Yagi et al. (1996)	Japan	6.1	1.6	N	T	–	–
Yang et al. (2004)	China	7.9	3.2	C	T	–	–
Yang et al. (2007)	China	–	2.5	N	V/R	M/S	Yes
Yao et al. (2012)	China	5.7	3.5	–	T	M	Yes
		5.5	2.8				
Zhang et al. (2008)	China	–	2.5	N	R	S	–
Zhang et al. (2009)	China	–	2.5	N	T	M/S	Yes
Zhang et al. (2010)	China	–	2.5	N	R	S	Yes
Zhang et al. (2012)	Philippines	6.2	2.0	C	T	M	Yes

[a] Text = texture (C = clayey, N = non-clayey), AWD timing (T = throughout the season, V = vegetative, R = reproductive), AWD threshold (M = mild, S = severe), Water use (Yes = data available), –indicates no data available. *data were reported in units which could not be converted to the units of water use or water productivity considered in our analysis and thus were not included. **studies were not included in the category "throughout season" (Fig. 3a) due to potential publication bias.

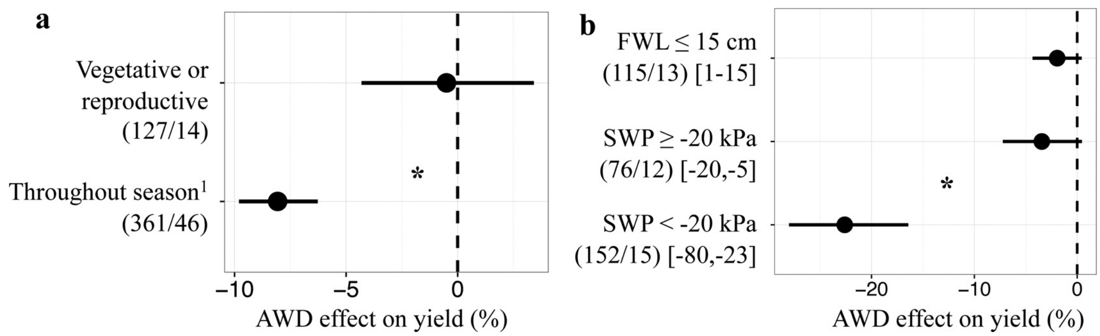

Fig. 3. AWD effect on yield depending on (a) AWD timing and (b) AWD threshold. Mean effect sizes (●) and bootstrapped confidence intervals (–) are represented. For each category, the number of observations and number of studies are in parenthesis and the range is in brackets. Confidence intervals not overlapping between categories indicate that they cause different effects on AWD relative yields (indicated by "*"). FWL = field water level; SWP = soil water potential.[1] This data set excludes 3 studies due to potential publication bias.

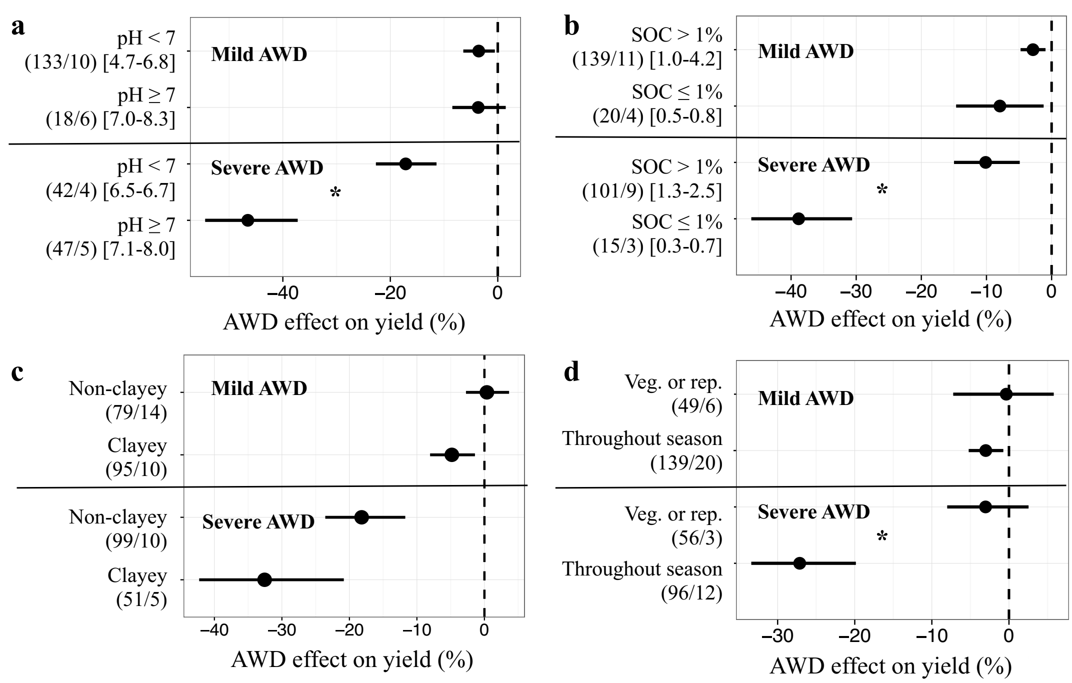

Fig. 4. Effect of AWD under two AWD thresholds (Mild AWD and Severe AWD) according to the moderating variables: a) soil pH, b) soil organic carbon (SOC), c) soil texture and d) AWD timing (Veg. or rep. = vegetative or reproductive). Mean effect sizes (●) and bootstrapped confidence intervals (–) are represented. For each category, the number of observations and number of studies are in parenthesis and the range is in brackets. Confidence intervals not overlapping between categories indicate that they cause different effects on AWD relative yields (indicated by "*").

AWD yields, in addition to some categories having relatively small datasets (data not shown).

3.3. *Soil properties and management practices influencing water use in AWD*

AWD relative water use was not affected by soil texture or number of drains (data not shown) but it was affected by AWD threshold. Under Mild AWD water use decreased by 23.4% (CI: −29.5% to −17.0%) compared to 33.4% (CI: −36.5% to −30.1%) under Severe AWD (Fig. 5).

4. Discussion

4.1. *Water management affecting yield*

Rice is known to be sensitive to non-saturated soil conditions (Bouman and Tuong, 2001); therefore, it is not surprising that overall yields were reduced in AWD and that the degree of soil drying (AWD threshold) had a large effect on yield. We included two methods to quantify AWD threshold in our analysis: field water level (FWL) and soil water potential (SWP). The FWL methodology was designed to be easily used by researchers and farmers and it measures the height of water relative to the soil surface in perforated tubes placed inside rice fields. Bouman et al. [2007] found that if the field is reflooded when the FWL reaches 15 cm below the soil surface (termed Safe AWD) rice yields were not reduced. Our results are in agreement with theirs, and furthermore, we found no significant yield penalty when AWD was conducted with a threshold of SWP ≥ −20 kPa (Fig. 3b). However, in some cases the threshold of SWP ≥ −20 kPa may be too dry as discussed below.

The relationship between FWL and SWP was recently investigated in loam and clay loam soils where Lampayan et al. [2015] reported that when FWL ≤ 15 cm the SWP was between 0 and −10 kPa. However, when soil texture is considered, our analysis suggests that even under Mild AWD, yields can be reduced in clayey

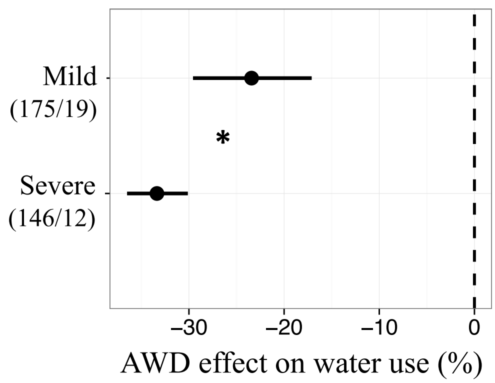

Fig. 5. Effect of AWD on water use (irrigation + rainfall) according to AWD threshold. Mean effect sizes (●) and bootstrapped confidence intervals (–) are represented. Numbers of observations/studies included in each category are in parenthesis. Confidence intervals not overlapping between categories indicate that they cause different effects on AWD relative water use (indicated by "*").

soils (Fig. 4c). Dividing up the clayey category by FWL ≤ 15 cm and SWP > −20 kPa indicated that the yield reduction was in the SWP category, not the FLW category (data not shown) suggesting that, at least in some cases, an SWP threshold of −20 kPa may be too dry. This conclusion, however, was based on only four studies and thus more research is required to develop AWD thresholds according to soil type.

The timing of AWD, either during the vegetative or reproductive stage, did not have an effect on yields (data not shown). Similarly, Bouman and Tuong (2001) summarized results from six studies investigating the effect of drought timing in rice and concluded that there was no developmental stage where rice was more sensitive to water stress. We also found that when AWD was practiced throughout the season, yields were reduced compared to when it was only practiced in either the vegetative or reproductive stage (Fig. 3a). Furthermore, AWD timing did not have a large effect on yields under Mild AWD but yields were much lower under Severe AWD practiced throughout the season than in only one phase of the season (Fig. 4d). These findings suggest a possible cumulative negative effect of multiple drying events on yield. While it would have been desirable to explore these issues of timing further it was not possible because first, there was a limited number of observations and studies (i.e. Severe AWD Veg or Rep – Fig. 4d), and second, in many studies where AWD was practiced throughout the season the higher number of drain events were on average less severe, thus confounding our analysis.

Importantly, identifying AWD practices or conditions that increase yields would be an important finding. In this study, while there were treatments in various studies that resulted in significant yield increases, in none of the categories we defined was there a significant increase in yields that was attributable to AWD. Yang and Zhang (2006) and Li et al. (2016) reported that soil drying during the grain filling phase can increase yield by promoting faster remobilization of carbon and root enlargement for maximum nutrient uptake. If this is a mechanism of increased yields under AWD then it may be possible to observe greater yields under AWD when nutrients are limiting.

4.2. Soil properties affecting yield

AWD yields in acidic soils were higher than in soils with a pH of ≥ 7 (Fig. 2), possibly for a number of reasons. First, alkaline soils often have high percentage of exchangeable sodium (Na) which causes soil particles to disperse and form impermeable layers (Abrol et al., 1985). This may not be a limitation to plant development in flooded conditions, where rice has a shallow root system, but may affect plants in an AWD system, where roots may grow deeper into the soil (Yang et al., 2004). Second, high levels of Na in alkaline soils can lead to Na toxicity effects in plants, which is less of a problem in flooded rice since ions can be leached out of the root zone and not be taken up by the plant. However, in unflooded and drier soils, higher Na concentration can lead to higher uptake (Abrol et al., 1985) and thus rice may be less tolerant to Na under AWD. This point is supported by the fact that under Severe AWD yield is reduced more in high pH soils than in low pH soils (Fig. 4a). Finally, alkaline soils may have higher nitrogen losses due to ammonia volatilization (Moormann and Van Breemen, 1978). Volatilization is more prevalent under non-flooded conditions, thus lower yields may be due to reduced N uptake under AWD conducted in alkaline soils.

AWD performed better in soils with SOC > 1% (Fig. 2). High SOC is beneficial in that it is associated with low bulk density, aggregate stability, high porosity and improved structure; all of which lead to increased water holding capacity and plant available water (Murphy, 2014). The lower yields observed under Severe AWD in low SOC soils relative to high SOC soils (Fig. 4b) suggest these factors may be important. SOC was also found to be positively correlated with N mineralization in aerobic rice soil but not anaerobic (Kader et al., 2013), suggesting that N availability may be increased under AWD systems conducted in high SOC soils.

4.3. Water use and water productivity

AWD reduced water use on average by 25.7% compared to CF (Fig. 1). Although under Severe AWD water use was reduced by 33.4% (Fig. 5), this was also accompanied by reduced yields (Fig. 3b). If the goal is to maintain yields, Mild AWD is necessary which reduced water use by 23.4%.

Accounting for the water savings (-27.5% relative to CF) being greater than the reduction in yield (-5.4% relative to CF), water productivity was 24.2% higher in AWD than in CF. Considering only Mild AWD, water productivity was 25.9% higher than CF (data not shown). With water resources becoming increasingly limited (Postel, 1999), this is an important benefit of AWD. However, depending on the cost of water and rice, higher water productivity does not necessarily indicate that a practice is more economical for a farmer. For example, Nalley et al. (2015) investigated the economic viability of different AWD treatments and found the lowest profit in the treatment with highest water productivity. Thus, other factors besides water productivity need to be considered.

Reduced water use in AWD systems can be attributed, at least in part, to reduced percolation and seepage. Percolation and seepage are significantly reduced in the absence of flood water; however, such losses are highly dependent on the hydrological properties of a given soil (Sanchez, 1973). For example, in a sandy loam soil in India, Sharma et al. (2002) measured 51% of the total water input in the rice field being lost by percolation, while in clayey California rice soils, Linquist et al. (2015) reported about 15% of applied water being lost to percolation and seepage.

Furthermore, in cases where AWD is practiced during the wet season (the case of approximately half of the studies in this analysis), a 25.7% reduction in total water use might translate into an even greater reduction in irrigation water use. For example, during a period where the soils are not flooded, a rain event during that time is less likely to result in surface runoff and can delay the time required until irrigation may be needed to reflood the field (Massey et al., 2014). On the other hand, it is important to recognize that AWD may be difficult to implement during the wet season because rice systems are often in low-lying valleys and it may not be possible to dry the field, especially in high rainfall years (Adhya et al., 2014).

5. Conclusions and future directions

Numerous studies have shown that AWD irrigation management can reduce both GHG emissions and water use which are both valuable benefits in terms of achieving sustainable intensification goals. However, it is also known that AWD can reduce rice yields if not implemented correctly. One of our objectives in this analysis was to identify management and soil conditions under which AWD can be practiced without sacrificing yields. We found that the AWD threshold had a major effect on yields and that yields could be maintained in most soils under Mild AWD. Using Mild AWD also provided a 23% reduction in water use. Importantly, we also found that soil properties can affect AWD performance; highlighting the need for regional research to fine-tune recommendations for farmers.

This work provides a quantitative analysis of the current literature available; however, in developing the database for this study, it became clear that more effort is needed in reporting experimental details if data are to be used to extrapolate findings to other locations and further develop management guidelines. Importantly for AWD studies, water management was highly variable between studies and was often not well described. Details on the timing, duration and severity of drains are essential for understanding results. Tensiometers, or the more affordable perforated field tubes that measure the water level below the soil, are both useful tools that can and should be used. Second, the total number of studies and observations in this analysis was too limited to analyze interactions that may be important in developing AWD practices. For example, the number of drying events during a season and severity of the drying event (AWD threshold) are both important factors; however in our database these two factors were confounded as experiments with many drying events also tended to have less severe drying events. Finally, these outcomes demonstrate that AWD is a promising management practice, but increased efforts need to be made to scale out results to the field and irrigation district scales where additional constraints may be encountered.

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