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Research Paper

Impact of alternate wetting and drying on rice physiology, grain production, and grain quality

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ABSTRACT

As the world's population increases, demands on staple crops like rice (*Oryza sativa* L.) will also increase, requiring additional fresh water supplies for irrigation of rice fields. Safe alternate wetting and drying (AWD) is a water management technique that is being adopted across a number of countries to reduce the water input for rice cultivation. The impact of AWD on plant growth, yield and grain quality is not well understood. A field trial of AWD was conducted at Mymensingh, Bangladesh over two boro (dry) seasons using eight field plots, four under AWD and four continuously flooded (CF). This manuscript describes the results of check cultivar BRRI dhan28 which was replicated in 35–40 rows per plot giving a total of 140–160 replicates per treatment. A study on the soil solution concentration of many elements indicated that manganese, iron, zinc, and arsenic were different under AWD conditions compared to CF on a number of sampling time points, but did not show a pattern related to the AWD treatment. A survey of soil strength using a penetrometer detected a small, but statistically significant, hardening of the surface soil of the AWD plots. At harvest the shoot and grain mass was significantly greater for the plants grown under AWD (9.0-9.4% and 12.0-15.4%, respectively) with the plants grown under AWD having a greater number of productive tillers. Physiological examination in the first year showed that although AWD decreased (~21%) leaf elongation rate (LER) of recently transplanted seedlings during the first drying cycle, subsequent drying cycles did not affect LER, while tillering was slightly increased by AWD and there was evidence of higher leaf abscisic acid (ABA) in AWD plants. In the second year analysis of six phytohormones revealed that AWD increased plant foliar isopentenyladenine (iP) concentrations by 37% while leaf *trans*-zeatin concentrations decreased (36%) compared to CF plants. The elemental composition of the shoots and grains was also examined. In both years AWD decreased grain concentration of sulphur (by 4% and 15%), calcium (by 6% and 9%), iron (by 11% and 16%), and arsenic (by 14% and 26%), while it increased the grain concentration of manganese (by 19% and 28%), copper (by 81% and 37%), and cadmium (by 28% and 67%). These results indicate that plants grown under safe AWD conditions at this site have an increased grain mass compared to plants grown under CF, and this may be partly due to a high number of productive tillers. AWD decreases the concentration of arsenic in the grains in this site, but it elevates the concentration of cadmium.

1. Introduction

Rice is one of the most important food crops in the world. For 3 billion people, rice contributes between 35 and 60% of their dietary calorie intake (Fageria, 2007). Irrigated lowland rice systems produce ~75% of global rice (Fageria, 2007). Producing high yield under irrigated systems requires large quantities of water (Bouman, 2009). It is estimated that to produce 1 kg of rice grain, 2500 L of water is needed (Bouman, 2009). Globally this equates to one third of the world's available fresh water being used for rice irrigation (Bouman, 2009). Within Asia, the proportion of fresh water being used for rice irrigation is greater, with approximately 50% of fresh water being used for rice irrigation (Kukal et al., 2004). With global rice production needing to increase by

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70% by 2030 to feed an ever growing world population (Maclean et al., 2002), demands on fresh water for irrigation of rice will only increase unless water management techniques that reduce water use are developed and implemented. These water management techniques, while decreasing total water loss, should maintain or increase yield.

One technique that has been developed to reduce total water for irrigation in rice is alternate wetting and drying (AWD). In AWD the field is not continuously flooded (CF), instead the soil is allowed to dry out for one or more days after the disappearance of ponded water, and after this drying phase the field is re-flooded (Lampayan et al., 2015). While techniques that use this intermittently flooded system have been around for a number of decades, formalised guidelines on the implementation of AWD were outlined in 2002 by the International Rice Research Institute (IRRI) (Lampayan et al., 2015). Initially it is recommend that farmers use what is termed "safe AWD" to start with, where the water in the fields is left to drain to a depth of 15 cm during each cycle, but importantly, when the crop starts to flower, flooding is restored. Once farmers are confident in using safe AWD they can progress on to allowing the water to drain to depths of 20–30 cm (or deeper) and to allow the cycles to continue into flowering when the plants are more sensitive to water stress.

A growing body of evidence is being collected on the impacts of AWD on both water use and rice yield, compared to either CF conditions or standard farmer practices (FP). For example, in a *meta*-analysis across a number of different field trials, when AWD was compared to FP, Lampayan et al. (2015) indicated that there was no overall significant decrease in yield, and in 16 out of 24 farmer participatory demonstration sites (across multiple countries) there was a significant increase in yield. This increase in yield ranged from 0.2-1.0 t ha^{-1}. In the same analysis in the trials where water input was measured, all the AWD irrigated trials had lower water input compared to the FP trials. The percentage difference between the water management practices ranged from 17 to 38% less water used in the AWD trials (Lampayan et al., 2015). A number of other studies have also shown that AWD increases grain yield when compared to either CF or FP (Yang et al., 2009; Zhang et al., 2009; Wang et al., 2014). However, in some studies, AWD either does not alter (Yao et al., 2012; Linquist et al., 2015; Shaibu et al., 2015; Howell et al., 2015) or slightly lowers yield (Sudhir-Yadav et al., 2012; Linquist et al., 2015; Shaibu et al., 2015). AWD has now been implemented and is recommended practise in a number of countries including Bangladesh, the Philippines, Myanmar, and Vietnam (Lampayan et al., 2015).

It has been shown that AWD can affect the concentration of arsenic in rice grains. Arsenic in rice grains is a major concern in some parts of the world, especially South Asia and South-East Asia, where large quantities of rice are consumed (Zhao et al., 2010). Inorganic arsenic is a class I human carcinogen (NRC, 2001). Under anaerobic conditions inorganic arsenic is present as arsenite (Xu et al., 2008). Arsenite is more mobile in the soil than arsenate, the species of arsenic predominantly present under aerobic conditions (Xu et al., 2008). In a study exploring grain arsenic accumulation under AWD, CF, and aerobic conditions it was found that the concentrations of arsenic in the grains of plants grown under AWD were comparable to those grown under aerobic irrigation and significantly less than those grown under CF conditions (Chou et al., 2016). Linquist et al. (2015) observed that under AWD conditions where the plants were re-flooded at the reproductive stage (like safe AWD) the concentration of arsenic in the grain was either not significantly different or increased in comparison to the plants grown under CF. However, under an AWD treatment where the AWD is continued during the reproductive stage, grain arsenic was reduced by up to 64% compared to the plants grown under CF. Similar results have been seen under intermittently flooded conditions, where a 41% decrease in grain arsenic was observed in comparison to CF (Somenahally et al., 2011). Elements other than arsenic have been shown to be affected by AWD. For example, in a pot experiment the concentration of zinc was significantly greater in brown rice when the plants were grown under AWD compared to CF (Wang et al., 2014). The accumulation of elements by plants is affected by the availability of these elements within the soil. Changing from anaerobic to aerobic conditions and *vice versa*, will alter the redox within the soil and therefore the phytoavailability of elements. For example, dissolved arsenic, iron, and manganese concentrations increase under reducing conditions when compared to oxidising conditions, whereas the release of cadmium, copper, and strontium to soil solution increases under oxidising conditions when compared to reducing conditions (Rinklebe et al., 2016).

One of the impacts of soil drying is to make soils harder (Bengough et al., 2011). Hard soils impact on root growth (Bengough et al., 2011), and it has been established that soil hardening due to soil drying is likely to limit new root growth in droughted rice plants as much as reduced water availability (Cairns et al., 2004). It is important, therefore, to establish if AWD is likely to alter soil strength in a way that might impact new root growth. Drier, harder soil is also likely to alter vegetative growth such as leaf elongation rate and tillering. Despite expectations that soil drying (Bouman and Tuong, 2001) would decrease tiller initiation and cause more frequent tiller death under AWD (Yang and Zhang, 2010), tiller number was significantly higher under AWD than CF throughout development (Howell et al., 2015), and AWD plants had a greater number of productive tillers independent of whether tiller number during development was higher or lower (Chu et al., 2015). Increased tillering likely accelerated canopy development of AWD plants, unlike leaf elongation rate on the main tiller, which did not differ between AWD and CF plants (Howell et al., 2015). Vegetative growth processes such as leaf elongation and tillering have been correlated with differences in phytohormone concentrations (Liu et al., 2011; Yeh et al., 2015).

To date, while a large number of studies have explored the impact of AWD on yield, the reason why studies have shown a diversity of effects that AWD has on yield compared to other practices is unknown. Additionally the reason as to why AWD has been shown to increase yield is yet unknown. It could be down to a wide range of factors, a number of which are explored in this manuscript. Furthermore, for a few grain elements the impact AWD has been assessed, however this is for a limited number of elements and the known impacts that AWD has on soil chemistry is limited.

The aim of this study was to evaluate the impact of safe AWD practise on grain production and grain quality and to explore if this is related to plant physiological responses or changes in soil (pore water) chemistry and hardness. To explore this, a field experiment was conducted at the Bangladesh Agricultural University, Mymensingh, Bangladesh over two years (2013 and 2014), during the dry season, under AWD and CF. This paper reports the findings of the improved cultivar, BRRI dhan28, under AWD conditions. The effect AWD had on elemental concentrations in the soil pore water and the physical effects that AWD had on the soil properties compared to CF was determined, as well as the impact on vegetative growth, leaf phytohormone concentrations, grain production, and grain elemental composition.

2. Methods

A field trial was conducted at the Bangladesh Agricultural University, Mymensingh over two years (2013 and 2014). Two different irrigation treatment were tested; for each treatment four replicate plots were used with cultivar randomly distributed in each plot. The water irrigation treatment used were continuously flooded (CF) and