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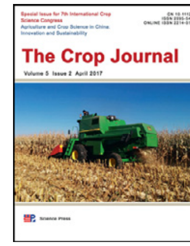

Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission

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ABSTRACT

To meet the major challenge of increasing rice production to feed a growing population under increasing water scarcity, many water-saving regimes have been introduced in irrigated rice, such as an aerobic rice system, non-flooded mulching cultivation, and alternate wetting and drying (AWD). These regimes could substantially enhance water use efficiency (WUE) by reducing irrigation water. However, such enhancements greatly compromise grain yield. Recent work has shown that moderate AWD, in which photosynthesis is not severely inhibited and plants can rehydrate overnight during the soil drying period, or plants are rewatered at a soil water potential of −10 to −15 kPa, or midday leaf potential is approximately −0.60 to −0.80 MPa, or the water table is maintained at 10 to 15 cm below the soil surface, could increase not only WUE but also grain yield. Increases in grain yield WUE under moderate AWD are due mainly to reduced redundant vegetative growth; improved canopy structure and root growth; elevated hormonal levels, in particular increases in abscisic acid levels during soil drying and cytokinin levels during rewatering; and enhanced carbon remobilization from vegetative tissues to grain. Moderate AWD could also improve rice quality, including reductions in grain arsenic accumulation, and reduce methane emissions from paddies. Adoption of moderate AWD with an appropriate nitrogen application rate may exert a synergistic effect on grain yield and result in higher WUE and nitrogen use efficiency. Further research is needed to understand root–soil interaction and evaluate the long-term effects of moderate AWD on sustainable agriculture.

Abbreviations: AGP, ADP glucose pyrophosphorylase; AWD, alternate wetting and drying; CI, conventional irrigation; GHG, greenhouse gases; GWP, global warming potential; HNI, nitrogen harvest index; LWP, leaf water potential; IE_N, internal N use efficiency; NUE, nitrogen use efficiency; ROA, root oxidation activity; SBE, starch branching enzyme; SPS, sucrose-phosphate synthase; StS, starch synthase; SuS, sucrose synthase; SWP, soil water potential; WUE, water use efficiency; Z, zeatin; ZR, zeatin riboside.

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1. Introduction

Global agriculture in the 21st century faces the tremendous challenge of providing sufficient and healthy food for a growing population under increasing water scarcity, while minimizing environmental consequences [1–3]. Rice (*Oryza sativa* L.) is one of the most important food crops in the world and is consumed by more than 3 billion people [4]. It is estimated that, by the year 2025, it will be necessary to produce about 60% more rice than currently produced to meet food needs [4,5]. About 75% of total rice production comes from irrigated lowlands [5,6]. Irrigated rice accounts for about 80% of the total fresh water resources used for irrigation in Asia [7]. Fresh water for irrigation, however, is becoming increasingly scarce because of population growth, increasing urban and industrial development, and decreasing availability resulting from pollution and resource depletion [1,8]. Rice fields have been identified as an important source of atmospheric methane (CH_4), one of the major potent greenhouse gases (GHG), and contribute approximately 15–20% of global anthropogenic CH_4 emissions [9,10]. Nitrous oxide (N_2O), another potent GHG, may be emitted from rice fields as a combined effect of nitrogen (N) fertilization and water management [11–13]. Furthermore, there have been recent health concerns associated with arsenic (As) concentrations in rice grain [3,14–16]. In certain parts of the world, As concentrations in rice grain are high and exert adverse health effects [3,14–17].

These concerns posed by rice may be addressed by changes in water management, in particular from continuously flooded anaerobic systems to those in which aerobic cycles are introduced periodically during the growing season. This regime is often referred to as alternate wetting and drying (AWD) [3,18,19]. It is proposed [20,21] that adoption of moderate AWD such that soil drying in the AWD regime is controlled properly, plant water status is not adversely affected during the drying period, and an appropriate nitrogen application rate is used can result in a synergistic effect on rice yield and in high WUE and nitrogen use efficiency (NUE). It would advance the development of sustainable agriculture to disseminate the effectiveness of moderate AWD, identify the mechanism by which moderate AWD increases both grain yield and WUE, and elucidate the effects of interaction between moderate AWD and N application rates on yield, WUE, and NUE. This review addresses these topics.

2. Effectiveness of water-saving techniques and the irrigation index for moderate AWD

To counter water shortage and increase WUE, many water-saving regimes have been introduced, including an aerobic rice system [22–24], a system of rice intensification [25–27], non-flooded mulching cultivation [28–30], and AWD irrigation [31–33]. These regimes could substantially enhance WUE by reducing irrigation water. However, such enhancement greatly compromises grain yield [20,22,28,31]. Among these technologies, AWD has been applied mostly in China in an area of more than 12 million ha each year [18,32–37] and is being adopted in Asian countries such as Bangladesh, India, The Philippines, and Vietnam [1,8,22,31]. It also remains debatable whether the technology can achieve the dual goals of increasing grain yield and saving water [31–38]. The discrepancies between studies are attributed to variation in soil hydrological conditions and timing of the irrigation methods applied [31–33]. The work of Yang et al. [15,18], Chu et al. [19], and Zhang et al. [33–36] has shown that the drying condition in AWD is the most important factor affecting yield. If moderate AWD is adopted, such that soil drying in the AWD regime is controlled properly, photosynthesis is not severely inhibited and plants can rehydrate overnight, such a regime could not only save water but also increase grain yield (Table 1). Furthermore, moderate AWD improves rice quality, including a reduction in As accumulation in grain. It reduces CH_4 emissions from the paddy field, thereby decreasing global warming potential (GWP) and greenhouse gas intensity (GWP/grain yield) (Table 1). In contrast, a severe AWD regime in which photosynthesis is severely inhibited and plants cannot rehydrate overnight during the soil drying period could markedly decrease grain yield and quality, although it also increases WUE and reduces grain As and CH_4 emission from paddy fields compared to a continuous flooding regime (Table 1).

The question raised is how to control soil drying properly and to develop moderate AWD. There are several ways to control soil drying in AWD, such as by fixing the number of

Table 1 – Increase (+) or decrease (–) in grain yield, water use efficiency (WUE), grain quality, grain arsenic (As) content, and emission of greenhouse gases (GHG) from paddy field under alternate wetting and drying (AWD) irrigation relative to those under conventional irrigation in rice (unit: %).

Item	Moderate AWD	Severe AWD	Data adapted from references
Grain yield	5.6 to 12.8	−18.5 to −35.3	[3], [18–21], [33–36]
Irrigation water	−22.4 to −34.6	−38.4 to −49.5	
WUE (grain yield/irrigation water)	27.3 to 55.7	21.6 to 36.7	
Head rice	5.6 to 12.8	−18.5 to −35.3	[34]
Chalkiness	−1.2 to −3.4	3.2 to 5.3	
Amylose content	−0.4 to 0.7	−0.9 to 1.2	
As in grain	−50.3 to −66.5	−54.5 to −70.6	[3,63]
CH_4	−51.4 to −72.5	−90.7 to −112.8	[3,19]
N_2O	15.5 to 98.6	125 to 167	
Global warming potential (GWP)	−48.6 to −67.2	−73.1 to −99.5	
GHG index (GWP/grain yield)	−48.3 to −78.9	−67.5 to −92.7	