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Rice root growth, photosynthesis, yield and water productivity improvements through modifying cultivation practices and water management

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ABSTRACT

Achieving higher productivity in irrigated rice production is becoming ever-more important. A modified rice-cultivation method, the System of Rice Intensification (SRI), recommends keeping rice fields moist but unflooded during the crop's vegetative stage, usually with alternate-wetting-and-drying (AWD), then maintaining shallow flooding during the post-vegetative stage of crop growth. However, no evidence is available on how flooding paddy fields continuously vs. alternately during the post-vegetative stage under SRI might influence the crops' physiology, root growth, grain yield, and water productivity.

Field experiments were conducted to investigate the impacts of two alternative crop management systems, namely, SRI and conventional management practice (CMP) under different water management treatments during the vegetative stage [continuous flooding (CF) vs. AWD] and then during post-vegetative stage: CF vs. AWD @ 1-DAD (days after disappearance of ponded water), 3-DAD or 5-DAD.

SRI practices, compared to CMP methods, significantly improved plants' root growth and xylem exudation rate, leaf area index and light interception by the crop canopy, plus photosynthesis rate at the grain-filling stage, resulting in higher grain yield. Overall, this modified method of rice crop management produced 58% higher grain yield with 16% less water. Across all water management treatments, significantly more grain was produced per unit of water applied with SRI management (6.3 kg ha-mm^{-1}) compared to CMP (3.3 kg grain ha-mm^{-1}). The highest grain yield with SRI (6.2 t ha^{-1}), and the greatest water productivity (6.7 kg ha-mm^{-1}) were obtained with SRI and 3-DAD post-vegetative irrigation. With CMP, highest grain yield (4.1 t ha^{-1}) and water productivity (3.5 kg ha-mm^{-1}) were with 1-DAD irrigation.

Differences measured in plants' response to modified management practices and alternative irrigation schedules indicated how phenotypic and physiological performances can be improved for a given genotype. Combining changes in crop and water management can improve water productivity as well as grain yield.

1. Introduction

Feeding the world's growing population is a major challenge (Godfray et al., 2010). Present standard methods for growing rice (*Oryza sativa* L.), a staple food for billions, requires large amounts of water. By 2035, the world will need to produce 116 million additional tons of rice for its greater population (GRiSP, Global Rice Science Partnership, 2013), and this must be achieved under conditions of greater water scarcity and climate change (FAO, 2012; Godfray, 2011). The currently prevailing system for growing irrigated rice is to flood paddy fields, maintaining standing water throughout the crop's growth cycle, and then to drain water from the fields 1–2 weeks before harvesting (Bouman et al., 2007). In flooded rice paddies, a large amount of the water supplied is non-productive due to large losses through runoff, evaporation, seepage, and percolation (GRiSP, 2013). In the future there simply will not be enough water in many areas to sustain this kind of irrigated rice production. Producing more grain with reduced amounts of water must be done in a sustainable way and without environmental harm (Yang and Zhang, 2010).

Researchers have been developing a number of water-saving technologies such as alternate wetting and drying (Belder et al., 2004; Bouman and Tuong, 2001), saturated soil culture (Tuong et al., 2004), direct dry-seeding (Tabbal et al., 2002), aerobic rice culture (Kato et al., 2009), and drip/sprinkler systems (Sharda et al., 2017). These methods have been found to reduce water use and improve water productivity, but their effects on grain yield have remained uncertain (Bouman et al.,

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2007), and the extent to which these techniques are economically remunerative remains unclear.

The System of Rice Intensification (SRI), a modified rice cultivation methodology developed in Madagascar, has been introduced in many rice-producing countries (Uphoff, 2012). SRI practices include transplanting younger seedlings with wider spacing than in conventional methods, leading to much reduced plant densities (by 4/5th to 9/10th less); active soil aeration; and keeping paddy fields unflooded, just moist, during the vegetative stage of crop growth (Stoop et al., 2002). This combination of practices has been reported to increase the yields of irrigated rice by 20–50% or more, while reducing water requirements by 20–35% (Jagannath et al., 2013; Kassam et al., 2011; Thakur et al., 2011; Wu and Uphoff, 2015).

Originally, SRI as developed empirically in Madagascar recommended applying small amounts of water each day to well-leveled fields, just enough water to keep the soil moist and meet the plants' (and soil organisms') basic needs – *le minimum de l'eau* (Laulanié, 1993). While such careful daily water management contributed to increased grain yields, it required considerable additional efforts by farmers. Therefore, many developed their own labor-reducing schedules of alternative wetting and drying (AWD). A study of SRI water management in Madagascar found that farmers who used SRI methods varied the length of their alternating wet and dry periods between 1–10 days (McHugh et al., 2002). Moreover, these schedules were developed more for farmers' convenience than for calculated productivity. As initially developed, SRI recommended maintaining just a thin layer of water (2–3 cm) on fields after the crop's panicle initiation (Stoop et al., 2002). However, this specification has never been tested systematically, while previous research (Stoop et al., 2009) would question its effectiveness. Under conditions of limited water supplies and hence a need to maximize water productivity (as in major parts of India), any possible savings in water use become increasingly important.

Most evaluations on the effects of different water management regimes for SRI have tested AWD irrigation practices or maintaining saturated soil just during the vegetative stage, comparing it with conventional flooding, the conventional management practices (CMP) approach (Chapagain and Yamaji, 2010; Krupnik et al., 2012; Lin et al., 2009; Singh, 2013; Thakur et al., 2014; Zhao et al., 2009). In some cases, significant savings in irrigation water have been reported while yield differences remained negligible (Chapagain and Yamaji, 2010; Krupnik et al., 2012; Singh, 2013). Other studies have reported both significant yield increase and water savings under SRI management (Lin et al., 2009; Thakur et al., 2014; Zhao et al., 2009). Stoop et al. (2009) have suggested that the responses have often been misinterpreted because of *confounding* between experimental (and non-experimental) factors, for instance, between the irrigation regime being evaluated and certain non-experimental factors, like plant density and/or the age of transplanted seedlings.

There could be considerable savings of irrigation water in the post-vegetative stage with some optimization of AWD as compared with continuous flooding. For SRI, an irrigation regime providing water at 3-DAD (days after disappearance of ponded water) has been recommended for the vegetative phase, followed then by shallow flooding of the field with 2–3 cm water during the post-vegetative stage (Thakur et al., 2014). In view of the attractive yields reported for SRI in general, there is reason to consider whether water use could be further optimized by keeping SRI fields just moist or AWD instead of being flooded, also during the post-vegetative stage.

Post-vegetative stage of water management deserves systematic investigation because in many countries, it is during the latter stages of rice plant growth that the crop encounters greater water scarcity and stress. In India, this can be due either to lesser rainfall during the rainy season (July-October) or higher temperatures during the winter season (October-March). These stresses have crucial impacts on eventual yield. As water scarcity is becoming a major concern in so many countries, the question arises whether any further reductions can be made in the amount of water applied during the post-vegetative stage under SRI management without incurring some grain yield loss. Making modifications in the water management regime during the post-vegetative phase could greatly increase water-use efficiency.

Research done thus far on water optimization under SRI crop management has not focused on how to reduce water applications after panicle initiation without suffering yield loss, and possibly making some gains in yield. This investigation was designed to assess the impacts of two alternative crop management systems, namely, SRI and conventional management practice (CMP) under different water management during, first, the vegetative stage – continuous flooding (CF) with CMP and 3-DAD with SRI – and then during the post-vegetative stage, either CF or irrigation at 1-DAD, 3-DAD or 5-DAD.

2. Materials and methods

2.1. Experimental site

A field experiment was conducted for two *rabi* dry seasons (January-May) during the years 2014 and 2015 at the Research Farm of the ICAR-Indian Institute of Water Management, Mendhasal in Khurda district of Odisha state, India (20° 30′ N/87° 48′ 10^2 E). The soils at the experimental site have been classified as *Aeric Haplaquepts*, sandy clay-loam (61% sand, 17% silt, and 22% clay), with a pH of 5.9.

2.2. Experimental design and treatments

The design was constructed to evaluate the physiological and morphological effects of different crop and water management practices in irrigated rice production. The split-plot design had three replications with sub-plot sizes of 20 × 10 m. All sub-plots were surrounded by bunds 30-cm wide followed by irrigation channels 50-cm wide, then again by bunds 30-cm wide to prevent lateral water seepage and nutrient diffusion between plots.

The two crop production systems were assessed in the main plots: the System of Rice Intensification (SRI), and conventional management practice (CMP). In the sub-plots within each block, four different water management treatments were implemented during the post-vegetative growth stage: CF (continuous flooding) and water applications either 1, 3, or 5 days after disappearance (DAD) of ponded or standing water in the field. During the preceding vegetative stage, the CMP plots were kept continuously flooded, while the SRI plots received irrigation water following 3 DAD schedule. Treatment details are described in Table 1.

2.3. Crop management with different cultivation practices

The experiment used a medium-duration rice *cv.* Surendra, 130–135 days duration, a popular photo-insensitive variety grown by farmers in the eastern part of India. Seeds were germinated in the shade and then broadcasted on nursery beds on January 10, 2014 in the first year and January 12, 2015 in the second year. In the SRI plots, 12-day-old single seedlings at a spacing of 20 × 20 cm were transplanted within 30 min after removal from the nursery on January 22, 2014 and January 24, 2015. In the CMP plots, 25-day-old seedlings, three per hill, were transplanted at a spacing of 20 × 10 cm on February 4, 2014 and February 6, 2015. Plant densities for the two crop production systems were thus, respectively, 25 and 150 plants m^{-2} for the SRI and CMP plots, giving the CMP plots six times more plants than SRI on an area basis. It should be noted that the SRI spacing used in this experiment was 20% closer than usually recommended for SRI because earlier studies in this location had shown 20 × 20 cm spacing to be optimum with this particular medium-duration variety under the local soil and climatic conditions (Thakur et al., 2010a). On the SRI plots, weeds were removed by using a mechanical weeder at 10, 20 and 30 days after transplanting (DAT), while in CMP plots, three hand weedings were done at the same DAT intervals.