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Enhancing water and cropping productivity through Integrated System of Rice Intensification (ISRI) with aquaculture and horticulture under rainfed conditions

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ABSTRACT

The System of Rice Intensification (SRI), based on modifications in the management practices for rice cultivation, is being utilized in many countries, although not without some controversy. One reason cited for non-adoption or disadoption of SRI is difficulties with water management under rainfed conditions with unreliable or aberrant rainfall distribution, which causes either flooding or long dry spells, or both. These constraints could be dealt with by tapping groundwater resources or by capture and use of rainwater runoff and/or by diversification of the farming system.

A 2-year field experiment was conducted in Odisha, India to evaluate SRI under rainfed conditions and also to explore options for enhancing the economic productivity of land and water under such conditions. Four rice cropping systems were evaluated: (i) conventional rice cultivation under rainfed conditions, (ii) SRI methods as adapted to rainfed cultivation, (iii) rainfed SRI methods with drainage facilities and supplementary pump-irrigation, and (iv) integrated SRI (ISRI) where rainwater runoff was harvested and stored for aquaculture and horticulture crops while also providing supplementary irrigation for the rice crop.

The rice crop grown with adapted SRI practices under rainfed condition showed significant improvements in the plants' morphology and physiology. Phenotypic changes included: greater plant height and tillering, more number of leaves, and expanded root systems. These changes were accompanied by changes in plants' physiological functions like greater xylem exudation rate and more light interception by the canopy, increased chlorophyll content in the leaves, and higher light utilization and photosynthetic rates during flowering. These factors were responsible for improved yield-contributing characteristics and for higher grain yield (52%) as compared with crops grown by conventional production methods. Comparing yield from rainfed conventional vs. SRI methods between drought and normal-rainfall years indicated that the latter methods are more drought-tolerant and productive; greatly expanded and active root systems with SRI have been important contributing factors.

Introducing drainage and supplementary irrigation improved both the grain yield (by 29%) and water productivity for rainfed SRI. Further, integrating aquaculture and horticulture with SRI management and rainwater harvesting increased the rice yield further (by 8%) and the net water productivity. This integrated system was found to raise the net income per unit of water by more than 60-fold compared to conventional rainfed rice cultivation. This option looks promising for improving food security for smallholders under erratic or diminished rainfall conditions.

1. Introduction

Food security is threatened by continuing population growth, declining arable land per capita, and water scarcity (Fedoroff et al., 2010; Satterthwaite et al., 2010), with these effects being exacerbated by the phenomena of climate change (Wheeler and von Braun, 2013). In recent years farmers have been experiencing declining growth of productivity, which is associated with several widespread phenomena such as land degradation, soil

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fertility loss, salinization, erratic rainfall, and extreme weather events (IFPRI, 2009). In the near future, farmers and their agricultural systems need to be able to cope with more frequent incidences of extreme weather events due to climate change (Gornall et al., 2010; Lobell et al., 2009; Meinke et al., 2009; Naylor et al., 2007).

In rainfed areas, which amount to about 54 million ha worldwide, with a lack of irrigation facilities, rainfall is the only source of water for a rice crop that is grown just once a year, during the rainy season (Bouman et al., 2007). Due to uneven and unreliable rainfall distribution over the cropping season, either most of the rainwater from heavy downpours runs off and is lost from the rice fields, or long dry spells result in low productivity. Common features of rainfed rice production include low productivity (both crop and water), poor fertilizer use-efficiency, and environmental pollution.

To meet rising food demand we need to increase the sustainability of food production in socially acceptable ways and from diminishing land and water resources (Schneider et al., 2011; Swaminathan, 2007). Agriculture systems will need to evolve by intensifying production from available land, while practicing water-efficient techniques that will sustain also the associated ecosystems (Fedoroff et al., 2010; Giovannucci et al., 2012) under a changing climate (Gornall et al., 2010; Meinke et al., 2009; Naylor et al., 2007).

1.1. Water management alternatives in rice cultivation

A number of rice production systems that use various water-saving irrigation practices have been proposed to deal with such constraints, including alternate wetting and drying (Belder et al., 2004, 2007; Bouman and Tuong, 2001; Zhang et al., 2008); continuous soil saturation (Tuong et al., 2004); sprinkler irrigation (Muirhead et al., 1989); direct-dry seeding systems that use less water (Tabbal et al., 2002); and aerobic rice culture (Kato et al., 2009; Nie et al., 2012). However, they all too often involve some reduction in grain yield, increased costs of production, and a need for very precise control over irrigation water (Bouman et al., 2007).

Some of the above reports have shown alternate wetting and drying (AWD) by itself reducing rather than increasing grain yield due to nitrogen loss, shoot biomass reductions, and a shortened grain-filling period (Belder et al., 2004; Tabbal et al., 2002). Conversely, some other reports have shown AWD able to maintain or even increase grain yield because of enhanced growth of roots (Yang et al., 2007), a higher grain-filling rate, and remobilization of carbon reserves from the vegetative tissues into grains (Zhang et al., 2008, 2009). Overall, changing from continuously flooded to a more-aerobic rice culture also has implications for other aspects of the rice production system, including nutrient dynamics and weed control. Excessive water use in rice cultivation not only lowers water productivity, but also increases NO_3-N leaching, causing environmental pollution by contaminating ground and surface water resources.

1.2. System of Rice Intensification: general background and major principles

The System of Rice Intensification (SRI), initially developed in Madagascar (Laulanié, 1993), has been extended to more than 50 countries by governmental and non-governmental organizations (http://sri.ciifad.cornell.edu/). SRI has been characterized as a natural resource management technology for enhancing crop yield using less water and other inputs, making it particularly relevant for smallholding farmers (Noltze et al., 2012; Stoop et al., 2002; Uphoff, 2003).

SRI principles focus on neglected biological and natural resource potentials and processes to raise yields through adjustments in farmers' agronomic practices resulting in large efficiency and production gains (Uphoff, 2007). SRI practices diverge from conventional agronomic management for irrigated rice and include: (a) transplanting young seedlings, preferably 8–12 days old (at 2–3 leaf stage), quickly, carefully, and at shallow depth (1–2 cm deep), (b) transplanting single, widely-spaced seedlings in a square pattern, thereby greatly reducing plant populations, (c) maintaining mostly aerobic soil conditions rather than continuous flooding of fields during the vegetative growth period, (d) preferably using organic manures like compost or mulch, and (e) controlling weeds with a mechanical hand weeder that actively aerates the soil surface (Stoop et al., 2002). These practices enhance root system development and root growth and hence the plants' interactions with the soil biota.

1.3. The dilemmas of rainfed rice cultivation and relevance of SRI principles

Conventional water management for rice has kept paddy fields continuously submerged. However, SRI practice reduced water requirements, keeping paddy soils moist but not continuously flooded, either by making minimum daily applications of water or by alternately wetting and drying the field (Stoop et al., 2002).

Unreliable rainfall distribution over the cropping season, a condition that is very common for much of rice cultivation in India and other rice-growing countries, has a significant impact on rainfed rice cultivation and results. Due to the uncertainty of rainfall, many rice farmers go for direct dry-seeding instead of transplanting method. Very high seed rates in direct seeding (>100 kg ha^{-1}) increase the competition among plants for growth resources, resulting in poor root growth and anchorage, lodging, and low grain yield. On the other hand for transplanting, farmers often use over-aged seedlings when the onset of the rains is delayed. When seedlings have to stay in the nursery for weeks, less time remains for their development and to complete their growth cycle in the main field, which automatically translates into yield losses.

Another frequent problem in rainfed rice cultivation is to control and to avoid crop damage by excess water from heavy downpours. Conversely, when there is insufficient rain, however, crops suffer drought stress. Both situations will hamper root growth and tillering, which ultimately result in reduced grain yields.

During the rainy season, it is quite difficult to practice any water-saving irrigation methods. This applies certainly to the SRI methodology; farmers frequently report that intermittent irrigation or AWD water management is difficult to implement in many locations. Often this is given as a reason for limited adoption and/or for discontinuing SRI as in Indonesia (Takahashi, 2013), Cambodia (Ly et al., 2012) and Timor Leste (Noltze et al., 2012).

To a certain extent these problems can be solved by combining water-saving measures with engineering solutions, as well as by agronomic and soil management practices (Ali and Talukder, 2008). Water harvesting is one of the options which can improve agricultural productivity by collecting and conserving rainwater for supplemental irrigation and other beneficial uses. An Indian NGO, PRADAN, has demonstrated a low-cost, water-harvesting technology that it calls 'the 5% model' which encourages farmers to convert 5% of their rainfed paddy fields into catchment ponds to trap and store rainwater during the monsoon. This enables them to provide supplementary irrigation to their crop, which generally raises their income and food security (UNEP, 2012).

Similarly, a Multi-Purpose Farming (MPF) system developed with farmers in Cambodia that builds upon SRI productivity gains enables them to increase and sustain much greater productivity from their limited land resources by converting some of it from rice monoculture to diversified agriculture with pond culture as