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Short communication

Modifying rice crop management to ease water constraints with increased productivity, environmental benefits, and climate-resilience

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ABSTRACT

Water scarcity increasingly constrains agricultural production, particularly for rice, one of our most important food crops. Conventional paddy production is the world's largest single consumer of water. Making certain changes in current cultivation practices, as discussed here, can raise rice crop yields while reducing water and other inputs. Diminished greenhouse gas (GHG) emissions, less runoff water pollution, and more climate-resilience are additional benefits. Spreading such changes in crop and water management within the rice sector can be a cost-effective response to agricultural water shortages, offering improvement in food security, adaptability to climate change, and environmental sustainability.

1. Introduction

Climate change, increasing limitations and variability of water supply, rising input costs, sub-optimal factor productivities, and increasing environmental degradation place constraints on contemporary agricultural production at the same time that changing weather patterns and unreliability are bringing greater frequencies of droughts, floods, and other extreme events (Nelson et al., 2009). Rice (*Oryza sativa* L.), a staple food for billions of people, is a 'thirsty' crop and the largest consumer of water within the agricultural sector. Increasing water shortages and unreliability threaten its sustainable production.

Growth in yield for many food crops, including rice, has stagnated since the end of the 20th century (Sheehy et al., 2007; Ray et al., 2012). This trend can be countered by introducing more-productive, well-adapted rice cultivars or by capitalizing on existing agro-ecological potentials including genetic resources suited to varying climate regimes, or both (Xiong et al., 2014). Here we consider the latter strategy.

For millennia, most rice has been grown in flooded fields even though rice is not really an aquatic plant. Although it can tolerate flooding, its roots gradually suffocate and eventually degrade under hypoxic soil conditions. Flooded soils also constrain rice plants' productivity by suppressing various beneficial soil organisms, mostly aerobic ones such as mycorrhizal fungi and Trichoderma, which facilitate roots' access to nutrients and protect against pathogens. Current production practices rely heavily on high seed rates, mineral fertilizers, and chemical biocides. The latter not only have negative impacts on soil health and water quality, but with increasing production costs are encountering diminishing returns (Peng et al., 2010).

2. System of rice intensification —a multi-faceted strategy

Many researchers have observed that water limitations and other environmental challenges can be coped with effectively and economically by making changes in current rice-cultivation practices. The System of Rice Intensification (SRI), an integrated soil-crop-nutrient-water management methodology developed in Madagascar, increases grain yield with less water consumption and has also other benefits (Stoop et al., 2002). The efficacy of SRI modifications in rice production methods has been demonstrated in China and >50 other countries (http://sri.cals.cornell.edu/countries/).

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Under SRI management, rice fields are not kept continuously flooded. Very young seedlings are transplanted singly, one per hill in a square grid pattern. Such wider spacing reduces plant population per m^2 by 80–90%, thereby reducing seed and planting costs. Having ample space for expanding its roots and canopy, each plant can express its growth potential more fully. Mechanical weeding keeps weed competition in check while actively aerating the soil around plants. Applying compost, mulch or manure, as much as possible, enhances soil organic matter which, under aerobic soil conditions, stimulates beneficial soil organisms to become more numerous and diverse, while simultaneously enhancing the growth and effectiveness of root systems (Anas et al., 2011; Watanarojanaporn et al., 2013).

Altering rice plants' growing conditions in this way evokes more productive and robust plant phenotypes from available genotypes (Thakur et al., 2010; Uphoff et al., 2015). Larger root systems, higher levels of chlorophyll and rates of photosynthesis, increased water-use efficiency, and delayed foliar and root senescence all contribute to prolonging the grain-filling process, leading to increased grain yield (Thakur et al., 2010, 2016),

Similar phenotypic effects as those evoked by SRI practices have been documented under experimental conditions with soil inoculation by certain bacteria or fungi (Chi et al., 2005, 2010; Redman et al., 2011; Doni et al., 2016). Further, rhizobacteria have been shown to increase rice roots' growth, volume and surface area (Yanni et al., 2001), and it is well-documented that soil organisms benefit from roots' exudation (Pinton et al., 2001). Studies on the positive-feedback connections between roots and the soil biota are not as extensive as desirable, however, and research on mechanisms whereby microorganisms affect plant gene expression in response to modifications in crop management is just getting started. Additional research may help to explain at least in part the favorable growth responses to SRI practices that have been reported over the past 15 years.

That SRI methods can give higher yields with reduced water use on a large scale has been demonstrated in China's Sichuan Province where once extension activities began in 2004, SRI use rose within 8 years from 1133 ha to 400,000 ha. The already-high yields in Sichuan were boosted by 22% while irrigation was reduced by 25%. Moreover, SRI's yield advantage in the two drought years was 12% greater than in the more normal seasons (Zheng et al., 2013).

Evaluations at China's National Rice Research Institute (CNRRI) have shown rice yields with hybrid varieties to be as much as 2.5 t ha^{-1} higher when planting fewer plants (less seed), switching from flooding to alternate wetting and drying (less water), and providing half of the N soil amendments in organic form rather than 100% as chemical fertilizer (Lin et al., 2009). Researchers at CNRRI and the China National Hybrid Rice Research and Development Center had already documented before these trials that SRI methods produced more productive phenotypes from given (hybrid) varieties (Tao et al., 2002; Yuan, 2002; Zhu et al., 2002). The researchers compared CNRRI's recommended practices with a less labor-demanding version of SRI (20-day seedlings instead of $<$15 days; and no mechanical, soil-aerating weeding). Even with incomplete use of SRI recommendations, more rice was produced with less seed, less water, and less fertilizer. SRI is constituted of agronomic principles more than of specific practices, the latter being adapted to local conditions, so there can be and are many variations or versions of SRI, referred to as 'modified SRI'. The innovation's provenance comes from an understanding of how to create better growth-promoting conditions above and below-ground.

A meta-analysis of findings published by Chinese researchers evaluating SRI compared with currently-favored best practices across 8 provinces found that 'average' use of SRI methods gave 10.4% more yield, while 'good' use of them (>75%) produced a 20% yield advantage (Wu and Uphoff, 2015). Within China, use of SRI methods has spread most rapidly in Sichuan and Zhejiang provinces where researchers evaluated the methods and then provided leadership with provincial departments of agriculture (e.g., Zheng et al., 2013). Elsewhere, according to a CNRRI scientists, SRI has been spreading and is becoming the main rice cultivation system in most of southern China with partial if not yet full adoption of its practices (IRIN, 2012).

A meta-analysis of published evaluations from 8 countries calculated that SRI methods raised total water productivity (including rainfall) by 52%, while the productivity of irrigation water was 78% greater. SRI management gave higher crop yield with, on average, 35% less irrigation water (Jagannath et al., 2013). Physiologically, SRI phenotypes have been found to synthesize twice as much carbohydrate in their leaves per unit of water taken up by the roots (Thakur et al., 2010). With water constraints for agriculture becoming more severe, water-efficient phenotypes with greater water productivity will become ever more important. SRI experience shows that this is possible to achieve with existing genotypes.

3. Atmospheric and water quality benefits

Reducing reliance on mineral fertilizers and other agrochemicals, as well as keeping rice fields unflooded, will also contribute to diminishing net greenhouse gas emissions from rice paddies as seen in studies from India (Rajkishore et al., 2013; Jain et al., 2014; Gathorne-Hardy et al., 2016), Vietnam (Dill et al., 2013) and Korea (Choi et al., 2014). Pollution in paddy water runoff has been found diminished as well (Choi et al., 2014). Jain et al. (2014) calculated that with SRI production management, there was a 62% reduction in CH_4 emission accompanied by a 23% increase in N_2O emission, with a net overall reduction of 28% in global warming potential.

SRI management contributes to this result in part by creating favorable soil conditions for the growth and diversity of arbuscular mycorrhizal fungi (Watanarojanaporn et al., 2013). These microbes which symbiotically inhabit plant roots have suppressive effects on N_2O emissions as well as increasing plant roots' access to water, phosphorus and other nutrients (Bender et al., 2014). A multidisciplinary evaluation of SRI in India calculated that SRI's average yield increase of 60% was accompanied by 40% lower net GHG emissions ha^{-1}. It also measured 60% less ground-water depletion and 74% less fossil-energy use kg^{-1} of rice produced (Gathorne-Hardy et al., 2016).

4. Tolerance to climate-related stresses

The more-robust plants resulting from SRI production management are better able to tolerate water stress (Zheng et al., 2013; Thakur et al., 2015) and to withstand pests and diseases (Pathak et al., 2012; Visalakshmi et al., 2014). Namara et al. (2008) found in Sri Lanka that under drought conditions, SRI plants produced and stored more photosynthates, with 30% more grain-bearing tillers per m^2, more grains per panicle, and 38% higher grain yield.

SRI plants have been found to better tolerate strong winds and rain with less lodging (Chapagain and Yamaji, 2010), as well as cold stress (Sudhakar and Reddy, 2007). Further, a shorter crop cycle with SRI management (Uzzaman et al., 2015) reduces exposure of rice plants to both biotic and abiotic stresses that can badly affect crops at the end of their season, when they are maturing and particularly vulnerable to losses. Greater tolerance to climate-related stresses can be attributed to the positive effects that SRI management practices have on greater root growth and more abundant and diverse life in the soil, having stronger and more prolific shoot growth with more grain-bearing tillers.