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Yield, water productivity and nutrient balances under the System of Rice Intensification and Recommended Management Practices in the Sahel

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ABSTRACT

Consumer demand for rice in sub-Saharan Africa (SSA) is increasing faster than for any other cereal. Governments in the Sahel are responding by promoting double-cropping of irrigated rice in the region's river basins, although rising fertilizer and water costs cast doubt on the future profitability of such systems. Despite controversy, the System of Rice Intensification (SRI) is widely promoted as a potential solution to this dilemma. SRI includes transplanting young, single seedlings at wide spacing, compost application, mechanical weed control, and alternate wetting and drying irrigation. However, independent evaluation of the system in comparison to an appropriate control is lacking in SSA, and the Sahel in particular. Responding to this need, we compared SRI to flooded rice production following regionally Recommended Management Practices (RMP), in a five-season experiment in the Senegal River Valley. Our objectives were to evaluate yield, water productivity, fertilizer nitrogen recovery efficiency, partial macronutrient balances and soil quality under both management systems. But because compost production in the Sahel is constrained by low labor and biomass availability, we replaced these materials with waste rice straw, and compared the impact of sole mineral fertilizer application to rice straw residue incorporation with fertilizer addition, under both SRI and RMP. In seasons 1–3, fertilizer alone significantly increased yield, with no differences found between management systems. In season 4, beneficial effects of straw incorporation and fertilizer addition were observed, as significant additive increases in yield, straw and fertilizer nitrogen recovery were found for each management system. In season 5, additive benefits were found only for SRI, although SRI yields never exceeded any fertility management treatment under RMP. Across seasons, water savings from 16% to 48% were obtained with SRI, resulting in significant (11%–45%) increases in water productivity. Combined straw incorporation and fertilizer application helped stabilize partial nitrogen and potassium balances across management systems. Compared to controls, straw incorporation also increased total soil nitrogen and carbon. In contrast to the literature on SRI in the Sahel, our findings indicate that when nutrient additions are held constant, significant yield increases should not be expected over conventionally recommended rice crop management systems. However, should farmers choose to experiment with SRI to reduce water use, they would be most likely to benefit from combining rice straw incorporation with mineral fertilizer, although several seasons may be required for additive yield effects to occur.

1. Introduction

Among the ecosystems in which rice (*Oryza sativa* L. and *Oryza glaberrima* Steud.) is grown in Africa, the irrigated environments of the Sahel have the highest yield potential (Seck et al., 2010), although large volumes of water are required to offset the evaporative demand of the hot and arid climate (de Vries et al., 2010). In response to the rapidly expanding consumer demand for rice, 200,000 ha of irrigation facilities reliant on diesel or electrical water pumping have been constructed in the Sahel (Balasubramanian et al., 2007 updated with FAOSTAT, 2012). With a per capita rice consumption rate of 111 kg year^{-1}, Senegal is both the Sahel's and Africa's largest rice importer (FAOSTAT, 2012). Cereal import dependency undermines food security, and increases vulnerability to price shocks, underscoring the need to increase domestic rice productivity (Seck et al., 2010). Raising annual rice output requires exploitation of both wet- and dry-season production. However, Senegalese

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farmers face increasing input costs due to reductions in fertilizer subsidies and rising fuel prices. Because of increases in the latter, irrigation costs comprise 21–45% of farmers' budgets (Krupnik et al., 2012). Combined with increasing municipal water demand and predictions of climate-change induced water scarcity (Lahtela, 2003), improving water productivity in Sahelian irrigated rice has become an important objective (de Vries et al., 2010).

Numerous water-saving technologies for rice have been validated in Asia, though they remain relatively untested and are not yet recommended anywhere in Africa. Most notable are aerobic rice (e.g. Bouman et al., 2007), alternate wetting and drying, or AWD (e.g. Belder et al., 2005), and the System of Rice Intensification, or SRI (Uphoff et al., 2010). Of these, SRI has attracted the most attention. SRI techniques include line transplanting of single young seedlings at wide spacing, mechanical weed control, AWD irrigation, and the application of organic soil fertility amendments, preferably compost or manure. SRI's advocates argue these techniques provide very high yields and improve water productivity (Uphoff et al., 2010). SRI is now supported by institutions ranging from farmers' organizations to NGOs and the World Bank, and is promoted in 47 countries globally (CIIFAD, 2011), though its popularity has not come without controversy. For example, McDonald et al. (2006) argued that SRI yields were no higher than Recommended Management Practices (RMP), and this suggestion spurred considerable debate (see McDonald et al., 2008; Uphoff et al., 2008).

In addition to yield performance, SRI promotion focuses on assertions of increased water and nutrient use efficiency. However, peer-reviewed studies presenting scientifically sound data to support these claims are scant in Africa, while the little work that has been done entails conflicting results. In Mozambique, for example, Menete et al. (2008) recorded a 41–46% yield depression on salt-affected soils with SRI; while in Madagascar, Barison and Uphoff (2010) documented higher macronutrient recovery and yield compared to farmers' practices. In another study in the same location, SRI yields as high as 9.9 t ha^{-1} were recorded, though rather than attributing them to SRI *per se*, Tsujimoto et al. (2009) suggested they resulted from repetitive, deep tillage and incorporation of up to 35 t compost ha^{-1} (dry weight equivalent). In the Sahel, interest in SRI has grown following reports of 66% yield increases, 10% water savings, and a doubling of farmers' revenues in Mali (Styger et al., 2010), though they compared SRI to current, lower-bound farmers' practices alone, thereby avoiding comparison to an upper-bound RMP control. As McDonald et al. (2006) suggested, the latter practice could have given similar, if not more favorable results than SRI.

To make such a comparison, we present five seasons of results from an experiment evaluating yield, water productivity, nitrogen recovery efficiencies, partial macronutrient balances and soil quality effects of both SRI and RMP. Manure or compost are preferred fertility inputs in SRI. In Mali, for instance, single-season evaluations of SRI have used up to 13 t ha^{-1} of manure in addition to chemical fertilizers (Styger et al., 2010). However, in the broader Sahel, where compost production and manure application are constrained by low biomass and labor availability, the season-to-season sustainability of such high application rates is questionable.

In order to adapt this SRI component to local circumstances, we instead compared the impact of sole fertilizer application, to fertilizer combined with waste rice straw incorporation as an organic matter input, in both SRI and RMP. We hypothesized that with equal nutrient additions, yields in the first few seasons of the experiment would not differ significantly between crop management systems. However, we expected that SRI would demonstrate higher water productivity, with stronger yield benefits resulting from straw incorporation and fertilizer addition in the long term, due to increased soil aeration and more rapid residue decomposition under AWD.

2. Materials and methods

2.1. Site description

A field experiment was conducted at the Africa Rice Center's Regional Sahel Station at Ndiaye in the Senegal River delta (16°11′N, 16°15′W). Trials were conducted in both the dry and wet season, spanning the 2007–2009 wet seasons. Climate data were collected 300 m from the experiment in a cropped rice field (Fig. 1). Ndiaye's soil is an Orhithionic Gleysol (FAO, 2006), and is comprised of oceanic sediments overlain by alluvial deposits. Texture (0–20 cm) is 16–44–40% sand, silt and clay (Haefele, 2001). Although subsoil materials of marine origin can cause serious soil salinity problems in the region (Ceuppens et al., 1997), initial electrical conductivity was low. Soil properties before the experiment were 0.87 g total N kg^{-1} and 9.6 g total C kg^{-1} (analysis with a Vario Max Dry Combustion Analyzer, Elementar Americas, Mt. Laurel, NJ following the IOS (1998)), 5.81 kg P-Olsen kg^{-1} (measured following extraction in 0.5 M $NaHCO_3$ at pH 8.5 (Olsen et al., 1954)), 0.47 cmol exchangeable K kg^{-1} (atomic absorption spectroscopy after extraction in 1 M NH_4OAc at pH 7), pH of 4.76 (1:2.5 H_20 saturated paste) and EC 0.33 dS m^{-1} (1:5 H_20 saturated paste).

2.2. Experimental design and establishment

A split-plot experiment with four replicates was established. Main plots were crop management systems, RMP and SRI (Table 1). Sub-plots measured 25 m^2, and consisted of four randomized treatments:

1. A no straw or mineral fertilizer additions control treatment (−ST−F).
2. A straw-only control treatment with 5 t ha^{-1} (dry weight) rice straw incorporated before transplanting, but without mineral fertilizer (+ST−F).
3. Mineral fertilizer only (−ST+F).
4. Rice straw incorporation at the same rate and timing as the straw only control followed by mineral fertilizer application (+ST+F).

In plots receiving fertilizer, DAP was applied basally (19.3 and 21.5 kg N and P ha^{-1}), and three urea splits were broadcasted into 1–5 cm of water (101.3 kg N ha^{-1}; 40% at early-tillering, 40% at panicle initiation, and 20% at heading). Fertilizer K is generally not recommended by extension officials because of high soil-K reserves (Haefele et al., 2004), and was therefore excluded. Before the experiment, soils were ploughed and disk-harrowed, after which bunds were constructed to isolate main plots. An additional bund was built to contain sub-plots within main plots, and plastic sheeting was installed over all main and sub-plot bunds to 0.5 m depth to eliminate seepage. A 4 m space was also maintained between main plots to prevent lateral water movement.

In the 2007 wet season, rice straw obtained from a neighboring farm was incorporated (0–15 cm depth) into damp soil with a hoe 15 days before transplanting, after which plots were leveled. In subsequent seasons, straw was incorporated 19–21 days before transplanting. Straw N and C concentrations were determined by combustion (Vario Max N/C Analyzer, Elementar Americas, Mt. Laurel, NJ, Table 2). Phosphorus and potassium were determined following Yoshida et al. (1976) and Walinga et al. (1989). The short-duration *O. sativa* cultivar Sahel-108 (IR-13240-108-2-2-3) was grown during all seasons. Transplanting for both