The Effects of Repeated Soil Wetting and Drying on Lowland Rice Yield with System of Rice Intensification (SRI) Methods

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Abstract
In lowland rice farming, water control is the most important management practice that determines the efficacy of other production inputs such as nutrients, herbicides, pesticides, farm machines, microbial activity, mineralization rate, etc. Poor drainage that keeps soil saturated is detrimental to crops and degrades soil quality. In many rice irrigation systems, drainage mechanisms and practices are dysfunctional or inadequate because farmers believe that rice grows best when water is supplied in abundance. Rice fields are therefore kept continuously flooded and are drained only at time of harvest. This practice is not only wasteful, but also leads to leaching of soluble nutrients, blocks soil microbial activities, and slows down mineralization and nutrient release from the soil complexes.

The natural nitrogen supply for plants and microorganisms results principally from the mineralization of organic nitrogen compounds. The water management practices proposed for the System of Rice Intensification (SRI), cycles of repeated wetting and drying, were found to be beneficial to rice plant growth through increased nutrient availability leading ultimately to higher grain yields. The phenomenon of having a large flush of nitrogen mineralization occurring after rewetting of dry soil was first reported by Birch in 1958. This intensive pathway of nitrogen mineralization and nitrogen availability has potential to increase lowland rice yields. In a series of lowland rice experiments conducted in a semi-arid region of Africa, repeated wetting and drying increased grain yields by up to three hundred percent in comparison with continuous flooding.

Introduction

Worldwide, nitrogen is considered the most limiting nutrient for rice production; therefore, increased nitrogen availability should translate into yield increases. However, in spite of extensive research and advances in fertilizer management, rice grown in the lowlands generally utilizes less than 40% of applied N, and often as little as 20-30% (Vlek and Craswell, 1979; Schneiders and Scherer, 1998; Kronzucker et al., 1999). The main N losses occur from leaching and denitrification as well as volatilization of NH_3 from the floodwaters after it diffuses from the soil-water interface.

Nitrogen, usually found as ammonium in anaerobic lowland soils, occurs more generally as nitrate (NO_3) in aerobic upland soils. Ammonium ought to be more beneficial as a source of N because metabolizing NH_4^+ requires less energy than does NO_3. It has been thought, however, that at optimum pH, nitrate is equally as effective as ammonia as a source of nitrogen for rice (Tanaka et al., 1984). Recent research has found that, actually, N in nitrate form produces 40 to 70% more yield than an equal amount of N as ammonia, with a combination of NH_4^+ and NO_3^- leading to better yields than provision of either form of N by itself (Kronzucker et al., 1999). SRI methods as discussed below, by repeatedly wetting and drying the soil, would provide N in both forms.

Under aerobic conditions there is a higher rate of N mineralization in the rhizosphere of rice plants compared with under anaerobic conditions. This may be because under aerobic conditions, rice plants may secrete certain enzymes such as protease and/or of organic materials that promote the activity of microorganisms.

Even when a rice crop is fertilized, it obtains the majority of its N requirement (60-80%) from the organic N pool of the soil (Broadbent, 1979). For best plant performance, it is therefore essential not only to optimize mineral N nutrition, but also to achieve integrated N management that makes the best use of all available N sources, both organic and inorganic. The natural nitrogen supply for plants and microorganisms results principally from the mineralization of organic N compounds. This process occurs in two steps: ammonification and nitrification (Runge, 1983; Das et al., 1997). When thinking about N nutrition for rice plants, we must keep in mind that less than 1% of the total soil N is in inorganic form readily available for plant uptake (Das et al., 1997).

The mineralization of N in the field is often offset or neutralized by microbial immobilization. The microbial biomass is an important repository of plant nutrients that is more labile than the bulk of soil organic matter. It can contribute substantial amounts of nutrients, and not only N, to the plant and soil when those nutrients are made available for plant use. Soil microbial biomass is a sensitive indicator of changes in the quality and quantity of soil organic matter (SOM). It responds more rapidly than does SOM to changes in organic inputs to the soil or to changes in soil management (Gijsman et al., 1997).

Measurements of microbial biomass have been used to assess the effects of different farming systems on soil fertility (Maire et al., 1990; Hassink et al., 1991; Gijsman et al., 1997). Microbial biomass plays a central role in soil nutrient cycling. Strong positive correlations have been found between the amount of nutrients held in the microbial biomass and the amounts of mineralizable nutrients in the soil, indicating that nutrient cycling is tightly linked to the turnover of microbial biomass (Carter and Macleod, 1987; Smith, 1993; Gijsman et al., 1997).

Birch (1958) reported a flush of N mineralization that occurs after the rewetting of dry soil. This intensive pathway of N mineralization which subsequently increases N availability has become known as 'the Birch effect,' though not much attention has been paid to it for lowland rice. Several factors may contribute to the N flush that follows the rewetting of dry soil. A significant proportion of the soil microorganisms can die during drying and rewetting; the mineralization of dead microbial cells by the remaining microflora can cause part of the observed N flush (Marumoto et al., 1977; Cabrera, 1993; Das et al., 1997). The youthful state of the microbial population that develops after rewetting can also be responsible for part of the enhanced N mineralization (Birch, 1958; Soulides and Allison, 1961; Cabrera, 1993).

Flooded rice soil is a complex of an aqueous phase, a solid phase, an interchangeable gaseous phase, and various flora and fauna. The main chemical changes brought about by the flooding of soil have an impact on the supply of micronutrients; a decrease in redox potential due to the depletion of molecular oxygen leads to reduced Fe and Mn, for example. Soil submergence for 10 to 12 weeks increases Fe^{2+} and Mn^{2+} concentrations in the soil solution, regardless of the soil type (Savithri et al., 1999). The concentrations of Zn and Cu decrease in lowland soils, and Zn deficiency is reported to be a widespread nutritional disorder of wetland rice (Neue and Lantin, 1994; Savithri et al., 1999).

The System of Rice Intensification (SRI), a methodology developed in Madagascar for growing lowland rice, changes plant, soil, water and nutrient management practices, some of them quite radically (Stoop et al., 2002; Uphoff, 2002). These changes cause rice genomes to yield more productive phenotypes: ones with more tillers, much larger root systems, and a positive correlation between tillering and grain filling -- a relationship previously reported in the literature to be negative.[1]

In various countries, use of SRI methods has been producing average yields around 8 t/ha, double the present world average (Uphoff et al., 2002). With good use of these methods and with build-up of soil fertility, in microbiological as well as chemical and physical terms, yields can be surpass 15 t/ha, pushing beyond what has been considered a yield ceiling for rice (Khush, 1996). More needs to be known about SRI before drawing firm conclusions about its potentials and limitations. The research reported here was undertaken to assess the effects of these management methods for improving productivity, and this article reviews one possible explanation for this better performance that can be found in the existing literature.

Materials and Method

Trial Location: The Gambia

The Gambia is a small country on the western coast of Africa. It is surrounded on three sides by Senegal and on the west it opens onto the Atlantic Ocean. It is situated between 13.2 and 13.7^{o} N latitude. It consists of a 50-km-wide ribbon of land extending eastward 475 km from the Atlantic coast and dissected by the River Gambia. The Gambia has an area of 11,700 km^2 and lies within the Sahelo-Sudan climate zone.

The rainy season typically extends from late May to early October; however, both ends of the rainy season have shortened in recent years. The 10-year normal average rainfall was calculated in 2000 as 804.3 mm in the western half of the country, and 700.3 mm in the eastern half. The average annual minimum temperature in this tropical country is 21C°, with an average maximum mean of 33C°.

The Gambia is located in the Senegal sedimentary basin. Its surface formation is tertiary sandstone known as the Continental Terminal. This formation which averages 40m deep is composed mainly of quartz and kaolinite, which are believed to have resulted from erosion of soils formed from granite and gneiss to the east of the country (Dunsmore et al., 1976).

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[1] The literature maintains that strong compensation mechanisms exist between the number of panicles per plant and the number of grains per panicle, producing "a strong negative relationship between these two [yield-determining] components" (Ying et al., 1998) These authors provide evidence to the contrary. SRI methods also contradict this conclusion found in the literature.

Trials were conducted in Eastern Gambia in 2000, at the Sapu research station of the National Agricultural Research Council on the bank of the Gambia River. The experimental design was a split-split plot design with water control as the main plot, spacing as the subplot, and variety as the sub-subplot. The water control treatments were continuous flooding, which is the standard local management practice, and SRI practice which involves repeated wetting and drying. The planting distances between hills were as follows: 20 x 20 cm, 30 x 30 cm, and 40 x 40 cm.

The two rice varieties evaluated, ITA 306 and IET 3137, are commonly grown in The Gambia and in other West African countries including Mali, Côte d'Ivoire and Burkina Faso. The trial sub-subplot sizes were 3 x 5m. All plots were transplanted with 7-day-old seedlings, which represents SRI practice, i.e., planting seedlings before their fourth phyllochron of growth (Stoop et al., 2002). Weed control was carried out mechanically with a rotoweeder at 14, 28 and 48 days after transplanting. No herbicide, insecticide, or chemical disease control measures were used.

Results and Discussion

Except for plant height and tiller ability, no significant varietal effect was seen. Overall, water management practice did have an effect on plant height (Table 1). Although a larger number of tillers per hill was not associated with repeated wetting and drying, as occurred in response to wider spacing, the tillers were remarkably larger in stem diameter and leaf surface area. The number of fertile tillers per hill was 69.5% higher, with a rate of fertile tillering almost twice as high (58.6% vs. 31.8%).

Although high tillering was recorded at 40 cm spacing, 40-50% of these tillers were unproductive. There was highly significant difference between SRI and conventional management practices in several respects. Thousand-grain weight was higher in the SRI treatments (by 6.7%) as well as biomass accumulation (by 20.1%). Average grain weight for ITA 306 for the 3 spacings was greater with SRI management by 5.2g; for IET 3137 is was greater by 3.1g. With ITA 306, the difference in 1000-grain weight between 20x20 and 30x30 cm spacing was larger by 7.45g for SRI methods and by 3.05g for the local practices. **[is this right?]**

Clearly higher yields were recorded with SRI practices. At 20 cm spacing, ITA 306 yielded 7.4 t/ha, while IET 3137 yielded 5.8 t/ha; 30 cm spacing, one-third less productive with ITA 306 yielding 5.5 t/ha, and IET 3137 yielding 4.6 t/ha. These contrasted with the highest yield obtained using standard practices, 2.6 t/ha. SRI recommends wider spacing but with the distance between plants being *optimized*, rather than maximized. Wider spacing is usually more productive than present practice, which in The Gambia is usually about __ cm. **[fill in]** We anticipated that 30 cm spacing would give a higher yield than 20 cm, but under these particular soil, climatic and other conditions, that did not happen.

A good indication of plant productivity is the panicle setting rate. With the conventional practice of continuous flooding, the average panicle setting rate (32%) was only about half that from SRI management (58%) (Figure 1). The highest panicle setting rate (64%) was recorded at 30 x 30 cm spacing with SRI management. While the number of tillers per hill was somewhat higher at 40 x 40 cm spacing with SRI practices, panicle setting was lower, only 51% on average.

Table 1: SRI vs. Standard Practice with Different Varieties and Plant Spacing Sapu, The Gambia, 2000

Practice	Variety	Spacing	Plant Ht (cm)	Tillers per hill	Panicles per hill	1000 Grain Wt (g)	Stover T/Ha	Yield T/Ha
Standard	ITA 306	20 x 20	100.3	29	10	20.0	5.4	2.4[de]
	IET 3137	20 x 20	83.7	30	12	25.7	4.4	2.6[d]
	ITA 306	30 x 30	97.0	47	15	20.0	5.2	1.4[fg]
	IET 3137	30 x 30	82.7	43	12	25.3	4.6	1.9[ef]
	ITA 306	40 x 40	88.7	49	12	24.7	5.2	0.9[g]
	IET 3137	40 x 40	71.0	44	16	21.0	4.9	1.7[ef]
SRI	ITA 306	20 x 20	108.3	23	18	27.7	3.5	7.4[a]
	IET 3137	20 x 20	101.3	25	13	22.8	4.4	5.8[b]
	ITA 306	30 x 30	108.0	41	24	27.2	6.5	5.5[b]
	IET 3137	30 x 30	103.0	29	21	22.1	6.4	4.6[c]
	ITA 306	40 x 40	107.7	59	28	25.5	6.4	4.4[c]
	IET 3137	40 x 40	99.7	46	26	20.7	7.7	4.1[c]
$LSD_{.05}$			10.6	13	11	1.5	3.6	0.7
CV(%)			6.9	20.8	34.9	4.2	29.5	13.8

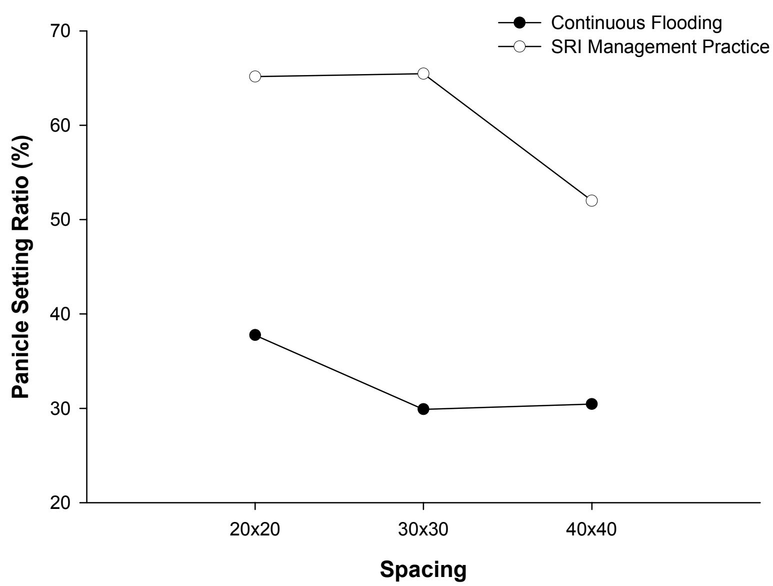

Figure 1: Panicle Setting Ratio with Continuous Flooding vs. SRI Water Management

Table 2 summarizes the trial results with regard to the different water management regimes. Averaging the two varieties, the biggest difference between continuous flooding and SRI intermittent irrigation was 4.1 t/ha, with 20 x 20 cm spacing (2.5 vs. 6.6 t/ha). At 30 x 30 cm spacing, the difference was 3.4 t/ha; and at 40 x 40 cm spacing, it was 2.95 t/ha. Clearly, the rice plants responded better to alternate wetting and drying of the soil compared to conventional continuous saturation.

Table 2 Grain Yield (t/ha) for SRI and Standard Practice, Averaged for Two Varieties and Three Plant Spacings, Sapu, The Gambia, 2000

Spacing	Average Yields (t/ha), Two Varieties		
	Local Practice	SRI Practice	Difference
20x20	2.50	4.60	4.10
30x30	1.65	4.95	3.30
40x40	1.30	4.25	2.95
Average	1.81	5.26	3.45

The yield increase with SRI practices must be attributable at least in part to higher nutrient availability. Inubushi and Wada (1987) found that drying and rewetting Japanese soils not only generated or enlarged a nutrient pool that mineralized rapidly according to first-order kinetics, but also it increased the size of a more stable N pool which mineralized more slowly. This could be explained by an increase in the availability of organic substrates through desorption from soil surfaces (Seneviratne and Wild, 1985; Cabrera, 1993) as well as through an increase in organic surfaces exposed (Birch, 1959; Cabrera, 1993).

This suggests that wetting-and-drying cycles are one of the mechanisms by which the soil N pool is replenished from successively more recalcitrant or physically protected N pools (Elliot, 1986). All this supports the hypothesis the SRI water management practice of drying-and-wetting cycles is beneficial to plant growth through increased nutrient availability. Drying and rewetting of soils as practiced in SRI is comparable to inducing a series of Birch effects during a single cropping season.

Under flooded conditions, despite the fact that ample water is available to the rice plant, there are numerous constraints is terms of nitrogen supply. Lowland rice generally loses more than 60% of applied N via NH_3 volatilization from the floodwater. Microbial activity is reduced, and as a result decomposition of soil organic matter is reduced by 50% under anaerobic conditions. Zn deficiency has been reported as a widespread nutritional disorder in flooded rice.

The microbial biomass N is an important repository of plant nutrients that is more labile than the bulk of soil organic matter and able to contribute substantial amounts of nutrients in the soil. Of the factors that contribute to high N availability and high N use efficiency under SRI management practice, repeated wetting and drying process maybe have the greatest influence.

A large flush of N is known to result from rewetting dry soil, known as the Birch effect, discussed above. Drying and rewetting soils not only generates or enlarges a N pool that mineralizes rapidly, but also increases the size of a more stable N pool that mineralizes more slowly. Cycles of drying and rewetting break down 2:1 clay minerals, and a large soil N pool is made available from successively more recalcitrant or physically protected N pools.

Conclusions
SRI management practices are capable of producing higher rice yields than conventional management practices. Yields with this set of management practices are 2 to 3 times higher than the national rice yield averages in The Gambia and the Sahel generally. This article has addressed issues of soil nutrient availability, focusing on N, that could be attributed to soil and water management practices associated with SRI that could account for the better plant performance.

There could be, of course, other processes and mechanisms involved.

- Biological N fixation (BNF) in the roots and rhizosphere of rice could be contributing to the increased yield (Döbereiner, 1987; Boddy et al., 1995). There is evidence that BNF is increase by the mixing of aerobic and anaerobic soil horizons (Magdoff and Bouldin, 1970).
- There is also evidence that P solubilization and availability are increased by alternate wetting and drying of soil (Turner and Haygarth, 2001).
- Mycorrhizal associations may also be contributing to plant nutrition with SRI practices as these symbiotic fungi, which require aerobic soil conditions, can greatly increases the volume of soil from which plant roots can acquire nutrients (Sieverding, 1991; Pinton et al., 2000).
- Recent research has shown the *Rhizobia* in the rhizosphere of rice increase both yield and protein ha^{-1}, however, not through BNF, as which these bacteria accomplish in legumes, but through increases in the production of auxin and other growth-promoting substances (Yanni et al., 2001).
- It is also known that the roots of rice plants growing in continuously saturated soil remain shallow in the soil (3/4 remain in the top6 cm according to Kirk and Solivas, 1997) and under hypoxic conditions they deteriorate. By the time of flowering, a majority have degenerated, 78% in the particular experiment reported by Kar et al. (1974). This physiological process presumably has some limiting effect on rice plant performance.

This means that there are a number of possible explanations, into addition to soil N availability processes, that warrant evaluation for understanding the effects of SRI methods (Uphoff, 2003).

No matter what soil chemical, physical and/or biological reasons underlie the effectiveness of SRI practices, this production methodology addresses some key constraints for rice production in many countries. It can reduce water requirements production (while increasing yield) and also the need for use of agrochemicals, often unavailable or beyond the financial reach of small producers. Water scarcity is likely to become a more significant problem around the world, so adopting cultivation practices that use less water can become very important.

In The Gambia and the semi-arid Sahel, increases in the area under rice cultivation are presently constrained by the amount of irrigation water available to support production. There is a high demand for water throughout the region, and in some cases, the rivers and distribution systems are already failing to suffice for existing irrigation schemes. Sustainable agriculture will need to find ways to economize on water requirements. SRI offers opportunities to raise production with less water. By reducing the need for and use of agrochemical inputs, it can also contribute to food security and environmental quality. But many questions about SRI remain unanswered, which should attract researchers from many disciplines.

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