GRAIN YIELD PRODUCTION AND ITS RELATION WITH ROOT GROWTH AND NUTRIENT-USE EFFICIENCY UNDER THE SRI SYSTEM AND CONVENTIONAL CULTURAL METHODS

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1.0 INTRODUCTION

Several innovations have been made in rice production systems in order to increase grain yield and better meet the world's food demand. The best-known strategy for meeting such demand was the Green Revolution, which has produced tremendous yield increases in Asia, where many farmers were able to adopt the technology. However, it failed to help many farmers in Africa, where farmers are constrained by their limited infrastructure and financial resources. In recent years, it seems that rice production has reached some yield limitation, and scientists are pursuing methods for further improvement of genetic potential. This raises a new issue of how resource-poor farmers can improve their rice yields and participate in a hunger-relief program.

Lowland rice production has been done under continuously flooded conditions for millennia. All except a few of the studies done on rice have been oriented to genetic and/or management practice improvements on the assumption that rice is best grown under standing water (Obermueller and Mikkelsen, 1974; Senewiratne et al, 1961). Standing water, however, could itself be suppressing yield production since it causes rice to undergo several drastic adaptations in its root system, most notably the creation of aerenchymes and subsequent degeneration of roots. The hypoxic conditions, caused by standing water, limit the ability of the roots to respire and slow their metabolism, ion transport and growth. Furthermore, hypoxia leads to a reduced soil condition (low redox potential) that creates low solubilities of some nutrient ions and high solubilities of others, e.g., Fe, Mn (Ponnamperuma, 1984).

Two decades ago, a System of Rice Intensification (SRI), based on some new insights into how rice can be grown best, translated into certain principles and practices, was developed in Madagascar. It has helped farmers there to increase their grain yield from 2 $t.ha^{-1}$ to 8 $t.ha^{-1}$ or more by changing plant, soil, water and nutrient practices such as planting very young seedlings, wide spacing, mechanical control of weeds, and use of compost with limited use of chemical fertilizers. The system, recognizing that rice has great unattained potential for tillering, seeks to provide an optimum growing environment in order to allow the plant to manifest such potential.

The main components of the SRI are: (1) early transplanting of seedlings at 8-12 days, (2) transplanting of single seedlings with wide spacing, from 25x25 up to 50x50 cm^{-2}, (3) mechanical weeding with a rotary push weeder that aerates the soil as it eliminates weeds, (4) water management with no continuously standing water during the vegetative growth phase, and (5) use of compost. Proponents of SRI claim that these practices appear to work synergistically to give higher yield than conventional rice production systems (ATS, 1992; Vallois, 1996).

The attainment of high yield with these changes in management practices, each of them fairly simple, shows that further understanding is needed for assessing the nutrient dynamics in the whole soil-plant environment.

The study reported here was undertaken (1) to compare the grain yield production of the SRI system with the conventional cultural system and determine how the former affected root development, and (2) to compare the nutrient-use efficiency of plants grown under the SRI system and under the conventional cultural system, holding both farmer and farm-field effects constant.

To test these hypotheses, we undertook two complementary studies.[1] One evaluated the nutrient uptake (nitrogen, phosphorus, and potassium) of rice plants cultivated under different cultural systems in a certain set of Malagasy farmers. For this purpose, an on-farm survey was undertaken during the main growing season in 2000-2001 in four different locations of Madagascar, involving 109 farmers who were using both SRI and conventional methods concurrently on their farms. A second study evaluated the nutrient uptake and nutrient-use efficiency under controlled conditions as discussed below. The following discussion explores possible explanations for the high grain yield obtained with the SRI system. The results reported here can help us develop a more complete understanding of nutrient dynamics for rice under different agro-ecological environments.

2.0 MATERIALS AND METHODS

To better understand the results of rice farming systems in Madagascar, two kinds of studies were conducted, as noted above. One was an on-station evaluation of grain yield production and its relationship with root growth with SRI, SRA (the "improved" rice cultivation system recommended by the national agricultural research agency FOFIFA), and conventional farmer practice. The second was an on-farm study mentioned above of the agronomic factors affecting the SRI and conventional systems.

2.1 On-station trial description

This experiment was conducted at the Center for Diffusion of Intensified Agriculture (CDIA) in Beforona in collaboration with the Landscape Development Intervention (LDI) project team during the 2000-2001 main growing season (October through May). The trial

[1] This research was conducted concurrently and cooperatively with Oloro McHugh, who at the same time gathered field data on water management issues, constraints and opportunities with SRI for his M.S. thesis in Biological and Environmental Engineering from Cornell. Having an agronomist and an agricultural engineer do parallel studies with the same on-station and on-farm data sets gave opportunity for cross-checking and cross-fertilization in the research. The work reported here is the author's, but he acknowledges and appreciates the enrichment of research made possible by this cooperation.

was done in a clayey-sandy soil with 43.8 g organic matter kg^{-1}, 27 g organic C kg^{-1}, 1.88 g total N kg^{-1}, 17.8 g available P kg^{-1} (Olsen method extraction), 2.6 cmol(+).kg^{-1} cation exchange capacity, and 0.15 cmol(+).kg^{-1} exchangeable K. The trial plots had been used for traditional rice cultivation until 1999 without any nutrient additions (either manure or plant residues). Then, beans and vegetables such as peppers and cabbage were successively planted from 1999 to 2000 with compost application made from household waste.

Five treatments were arranged in a completely randomized block design with three replications. Plot size was equal to $20m^{-2}$ ($4x5m^{-2}$). Treatments, described in detail below, are labeled as following:

- T1: SRI cultivation method with compost application,
- T2: SRI method without compost,
- T3: SRA method with chemical fertilizer (NPK 11-22-16),
- T4: SRA method without fertilizer, and
- T5: Conventional system.

Table 1: Principal characteristics of the SRI, SRA and conventional systems

System of cultivation	SRI	SRA	Conventional
Age at transplantation	8 days	25 days	45 days
Number of seedlings/clump	1	2-3	4-6
Spacing (cm^2)	25x25	20x20	14x14
Water management	Irrigate at night and drain in the morning	Standing water of 3-5 cm	Standing water of 2-3 cm for first 2 weeks after transplanting; 5 cm for the rest of the season
Fertilization	Compost	NPK and urea	No fertilization

Rice grain yields were measured from a $9m^{-2}$-subplot sample located in the center of the plot. Grains were weighed right after the harvest, and grain moisture content was taken. Grain yield was then adjusted to 14% moisture content.

Yield components (tillers per clump, panicles per clump, and grains per panicle) were also measured. These yield components were determined from 12 hills.plot^{-1} distributed in 3 sub-series of 4 hills. The aboveground measurement was complemented by an evaluation of both root length density (RLD) and root- pulling resistance (RPR) of the rice plants at harvest.

For the determination of the RLD, roots sample were taken at harvesting time. The most representative plants were chosen in each plot, and a circle of 27.5cm for SRI, 21 cm for SRA and 17.5 cm for conventional system were delimited around the rice roots.[2] A trench was then dug, and the soil was cut horizontally at 5, 10, 20, 30, 40 and 50cm. The blocks of soil were washed in a bucket of water in order to separate the roots from the soil. Roots were then separated through repeated filtration with a 1mm and 0.5mm mesh and weighed. A 1g-subsample was spread on graphic paper, and the number of intersections between the root and the paper grids were counted.

In order to evaluate the nutrient content of the rice plant, plant samples were analyzed for macronutrient content (N, P and K) at the maturity stage separated into harvestable biomass (grains) and non-harvestable biomass (straw).

After being oven-dried at 70°C, weighed and ground, N content was measured by micro-Kjeldahl digestion (Bremmer and Mulvaney, 1982), P content by the molybdenum blue colorimetric method (Yoshida et al., 1972), and K content by spectrophotometer atomic adsorption (Yoshida et al., 1972).

In addition, soil samples were collected at the beginning of the growing season from five locations in each plot at a depth of 0-20 cm for the SRA and conventional system, and at a depth of 0-30 cm for the SRI system.

[2] These diameters reflected the observed sizes of the respective root systems.

2.2 On-farm experiment description

2.2.1 Hypotheses

Work done by Witt et al. (1999) **has** showed that grain yield increases linearly in correlation to the increase of nutrient uptake until a certain level where one or more other nutrients become limiting (other factors such as climate, plant water needs, or disease, with micro-nutrients assumed to be optimal). Once the efficient use of a nutrient is limited by others, the marginal increase of grain yield in relation to nutrient uptake starts to decline. Since plants cultivated with SRI methods appeared to be able to produce higher grain yield in the same soil conditions as those cultivated under the conventional system (Andriankaja, 2001), we hypothesized that nutrients taken up by the plants are more efficiently used for grain production under SRI conditions.

2.2.2 Sampling methods

Prior to our survey, a full list of farmers practicing SRI in the area was obtained from the Ministry of Agriculture and Association Tefy Saina. Farmers were interviewed initially in order to characterize their farming systems. They were asked whether they are practicing both SRI and conventional systems, and those using both systems were maintained in our sampling population.

The interview focused mostly on the characteristics of their SRI and conventional management practices. Age of seedling at transplantation, number of seedlings per clump, mode of weeding, type of water management, and type of fertilization were asked about. Fields were classified in accordance with two criteria: the age of seedlings transplanted, and the number of seedlings per clump.

Criteria for defining ***Conventional practice***

Age of seedling at transplantation: more than 20 days

Number of seedlings per clump: more than 3

Criteria for defining ***SRI system***

Age of seedling at transplantation::8-12 days

Number of seedlings per clump: 1 seedling

Other factors such as spacing, water management and/or fertilization use were intentionally left out as criteria since we wanted to capture and assess any variability in these other factors. Farmers were selected according to whether they had fields that met these two sets of criteria.

The total number of households in our study area was 109 farmers, and their distribution is as follows:

- Two sites in Ambatondrazaka (around Lake Alaotra): one in the southeastern part of the lake area with a sample size of 40 (Zone I), and another in the northeastern part with a sample size of 30 (Zone II);
- One site in Antsirabe: located to the north and northwest of the city with a sample size of 28 (Zone III); and
- One in Fianarantsoa: located to the northwest with a sample size of 11 (Zone IV).

Once farmers had been selected, a SRI rice plot and a conventional rice plot were *randomly* selected on each farm. As much as possible, adjacent SRI and conventional rice plots were selected for each farmer so as to reduce any effects of geographical variability (soils and topography).

Grain yield production and macro-nutrient content were evaluated using the same methods describes for the on-station trials.

3.0 RESULTS AND DISCUSSION

3.1 Grain yield production and root development in the on-station trial

3.1.1 Grain yield and yield components

Substantial differences were observed in the grain yield production for SRI, SRA and conventional systems (Tables 2 and 3). The highest yield was obtained from those plots where SRI was used and compost was applied, an average yield of 6.26 t.ha^{-1}. This was statistically significantly different from that of the SRA system, yield of 4.92 t.ha^{-1} for NPK and urea fertilized plots, and 4.67 for non-fertilized plots, and of the conventional system, with a yield of 2.63 t.ha^{-1} (Table 3). The higher grain yield with SRI methods was the result of higher panicle and grain numbers per m^{-2} (Table 2). For the SRA treatments, the lack of significance between the fertilized and non-fertilized plots was due to greater effect of blast (*Pyricularia oryzae*) in the fertilized plots during grain filling.

It should be noted that the date of planting for the trials was about one month later than usual in the area because of logistical problems in getting the research started. This could have affected all five treatment results but probably affected the SRI trials most since that method benefits from more profuse tillering.

Table 2: Grain yield components in the on-station experiment

Treatments	Plants/m^{-2}	Panicles/m^{-2}	Grains/m^{-2}	1000-grain weight (g)
SRI with compost	16	242	20,445	29.43
SRI without compost	16	248	18,827	29.22
SRA with NPK and urea	25	212	15,634	29.35
SRA without fertilization	25	152	10,826	29.70
Conventional	53	290	9,237	30.12

Table 3: Group distribution of mean grain yield (LSD test at 5%)

Treatment	Mean	Group
SRI with compost	6.26	A
SRI without compost	5.037	AB
SRA with NPK and urea	4.92	B
SRA without fertilizer	4.68	B
Conventional system	2.63	C

3.1.2 Grain Yield, Root-Pulling Resistance, and Root Length Density

It has been noted that one of the key advantages of the SRI system is the better root growth and proliferation. The test of root pulling resistance (RPR), which is a method used to evaluate the root growth and rooting density (Ekanayake et al., 1986), was much higher for (single) SRI plants (RPR=49.67 to 55.19 kg). For SRA plants, growing in clumps of about 3, RPR averaged 30 to 34.11, and for conventionally grown plants in clumps of 4-6, it was 20.67. On a per-plant basis, these differences are 4- to 10-fold.

Table 4: Comparison of root pulling results (RPR), in kg, at different stages

Treatments	RPR at panicle initiation	RPR at anthesis	RPR at maturity	% decrease of the RPR between anthesis and maturity
SRI with compost	53.00	77.67	55.19	28.69
SRI without compost	61.67	68.67	49.67	28.29
SRA with NPK and urea	44.00	55.33	34.11	38.30
SRA without fertilization	36.33	49.67	30.00	39.40
Conventional system	22.00	35.00	20.67	40.95

These differences are apparently the result of better soil aeration with SRI by keeping the soil wet but not continuously saturated during the vegetative phase and by doing an early and frequent mechanical weeding. This seems to have allowed the SRI plants to have a better access to nutrients and to comply with their nutrient demand at any time. Furthermore, SRI root systems have greater space to grow, in comparison to SRA and conventional root systems, and SRI rice plants were thus able to develop more rooting systems.[3]

Because of spacing differences, the root pulling method is not a sufficient or always accurate measure of better rooting. An in-depth evaluation of root growth and proliferation was done by measuring the root length density (RLD). In all of the treatments, root growth decreased rapidly in relation to the soil depth.

Interestingly, conventional and SRA systems had greater root growth in the first 20 cm in comparison to the SRI system. Indeed, the most root growth close to the soil surface (0-10 cm) was seen with plants cultivated by conventional methods. However, root growth of conventional, SRA and SRI plants was about the same at a depth of 20-30 cm. Much greater root growth was recorded with SRI plants at lower depths, below 30 cm. This greater root growth in lower depth suggested that plant cultivated with the SRI method, which benefited from the alternate drying and drainage, was capable of developing greater root penetration in comparison to the SRA and conventional plants.

Table 5: Root length density ($cm.\ cm^{-3}$) under SRI, SRA and conventional systems

Treatments	Soil layers (cm)					
	0-5	5-10	10-20	20-30	30-40	40-50
SRI with compost	3.65	0.75	0.61	0.33	0.30	0.23
SRI without compost	3.33	0.71	0.57	0.32	0.25	0.20
SRA with NPK and urea	3.73	0.99	0.65	0.34	0.18	0.09
SRA without fertilization	3.24	0.85	0.55	0.31	0.15	0.07
Conventional system	4.11	1.28	1.19	0.36	0.13	0.06

[3] We could not assess the possible effects on root growth of the production of phytohormones by aerobic bacteria and fungi (auxins, cytokinins, etc.) which are known to stimulate root growth (Frankenberger and Arshad, 1995). These effects should also be considered in further investigation of such differences in root growth and performance arising from alternative systems for plant, soil, water and nutrient management. Soil organisms provide many benefits to plants and plant roots beyond N_2 fixation and P solubilization (Dobbelaere et al., 2003).

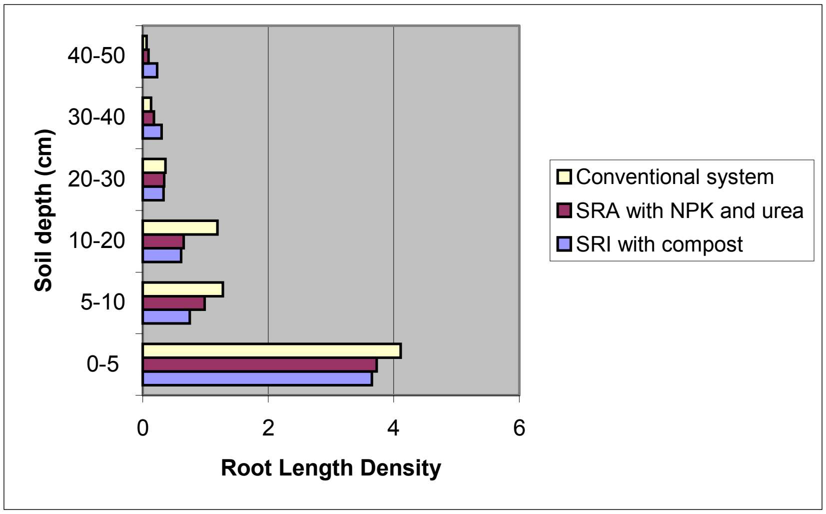

Figure 1: Root distribution for the SRI, SRA and conventional systems

3.2 Grain yield and Harvest Index comparisons in the on-farm experiment

A major concern in plant breeding for more productive rice varieties has been to reduce the non-harvestable biomass in order to increase grain yield production. Such an approach is referred to as increasing the Harvest Index (HI), the ratio between grain yield and total biomass. This objective has led many to the creation of shorter stature cultivars that produce fewer barren tillers and a higher number of grains per fertile tiller (Khush, 1993). This strategy has also been oriented to an increase in planting density. We, however, wondered if the increase of tiller number and reduction of planting density associated with SRI really reduced the Harvest Index.

Comparison between the SRI system and the conventional system in farmer-surveyed plots at yield level indicated that SRI grain yield was significantly higher (Table 7). Farmers who used the SRI method on their rice plots obtained an average yield of 6.36 $t.ha^{-1}$ compared to an average grain yield of only 3.36 $t.ha^{-1}$ with conventional methods. This 89% increase over the conventional grain yield was actually 218% higher than the national average grain yield of 2 $t.ha^{-1}$.[4]

[4] That farmers in our sample had higher average yield with conventional methods than the national average can be explained partly by the fact that the sample had a disproportionally large number of farmers from the Ambatondrazaka area, where more "modern" methods are already being used as part of their standard

This grain yield increase was accomplished with rice plants that had significantly higher numbers of tillers than conventionally grown rice plants but a similar Harvest Index. While the Harvest Index with conventional methods averaged 0.49, with SRI methods the HI was 0.48 (Table 7). When considering the range between the first quartile and the third quartile, the conventional HI ranged from 0.32 to 0.63, while the SRI HI varied from 0.33 to 0.67. Furthermore, comparison on the nutrient harvest index indicated very similar relationships. Specifically, nutrient harvest index was 0.68g $N.g^{-1}$, 0.71g $P.g^{-1}$, and 0.27g $K.g^{-1}$ for SRI, and 0.65 $gN.g^{-1}$, 0.72 g $P.g^{-1}$, and 0.25 g $K.g^{-1}$ for the conventional system (Table 6).

These numbers indicate that despite the higher number of tillers with SRI plants, which normally results in higher non-harvestable biomass, the HI for SRI treatments was similar, and in some cases even higher than for conventionally grown rice. It appears that SRI plants were benefiting from greater root development. The appearance of nodal roots with every newly formed tiller led to more developed root system, probably due to the conjunction effect of soil aeration by non-flooding water management and early transplantation. Larger root systems can exploit a greater volume of soil and potentially access greater amounts of nutrients.

3.3 Nutrient concentration and uptake by the rice plant

One of the variations that could occur with an increase of grain yield is the dilution of the nutrient concentration of the rice shoot and sink. Regarding nutrient foliage content, plants cultivated with SRI methods accumulated 4.97 g $N.kg^{-1}$ of straw, 0.93 g $P.kg^{-1}$, and 14.97 g $P.kg^{-1}$ of straw (Table 7). The average straw nutrient content with the conventional system was slightly higher (and significant for both N and P) with a respective accumulation of

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cultivation regime. Possibly also those farmers who were using both conventional and SRI practices were more dedicated and serious farmers than average. In evaluating SRI against present practices in Madagascar, it should be noted that the norm with which SRI performance was compared in this study was higher than the typical situation in the country.

5.39 g $N.kg^{-1}$, 1.16 g $P.kg^{-1}$, and 15.29 g $K.kg^{-1}$. Both sets of numbers are slightly different from the ones that Witt et al.(1999) found in tropical and subtropical Asia, which averaged 7.1 g $N.kg^{-1}$, 1.0 g $P.kg^{-1}$, and 14.5 g $K.kg^{-1}$. This difference is assumed to be due to variations in agroecological conditions, varieties, and cultural methods.

When considering the 89% grain yield increase and the negligible difference in the nutrients accumulated by SRI plants relative to conventionally grown rice plants, this means that plant nutrients were not diluted by the higher grain yield with SRI.

Furthermore, grain nutrient accumulation averaged 10.17 g $N.kg^{-1}$, 2.35 g $P.kg^{-1}$, and 3.96 g $K.kg^{-1}$ for plants cultivated with SRI methods, while their accumulation was 9.89 g $N.kg^{-1}$, 2.69 g $P.kg^{-1}$, and 3.54 g $K.kg^{-1}$ with conventional methods. This almost similar N and K concentration in the sink storage while SRI grain yield was significantly higher indicates that plants cultivated with conventional methods had a lower root capacity to take up nutrients at a later stage and/or a lower remobilization of previously stored shoot nutrients.

Further breakdown of the nutrient accumulation showed that the conventional rice plant is somewhat impaired by its poor rooting pattern at the post-anthesis stage of development. Nutrient translocation (the ratio between nutrients in the grain and total above-ground nutrients) for both SRI and conventional systems was almost the same with respective values of 68% N, 71% P, and 27% K for SRI, and 65% N, 72% P, and 25% K for conventional growing methods.

This observation was confirmed when considering the nutrient accumulation in the aboveground biomass. Total aboveground nutrient accumulation averaged 95.07 kg $N.ha^{-1}$, 21.03 kg $P.ha^{-1}$ and 108.64 kg $K.ha^{-1}$ for the SRI system, while that of the conventional system averaged 49.99 kg $N.ha^{-1}$, 12.69 kg $P.ha^{-1}$ and 56.77 kg $K.ha^{-1}$ (Table 6). This showed that modification of the management practices could enhance plant uptake by 91% for N and K, and by 66% for P.

Interestingly, the relatively high increase of accumulated N and K, on one hand, and the lower increase of accumulated P, on the other hand, indicated that conventional plants had possibly either a lower N and K uptake or a higher P uptake. For the sake of getting a clearer picture of nutrient uptake constraints on yield, one needs to compare the grain yield with nutrient content and concentration differences between SRI and conventional systems. SRI grain yield averaged 6.36 $t.ha^{-1}$ and that of conventional rice was about 3.36 $t.ha^{-1}$, an increase of 89.5% in grain yield. (This was reflected in an increase in N and K concentrations and in their content in the rice plants and grain.)

It is possible that the increase of grain yield in SRI relative to conventionally grown crops is due to farmers allocating their best sites to SRI or to more application of compost to SRI plots. Results from our soil analyses, however, showed that SRI and conventional plots had similar soil fertility . The average nutrient content was 0.16% N, 8.51 ppm P-Olsen, and 0.08 cmol $(+).kg^{-1}$ K where SRI methods were used, and 0.17% N, 9.39 ppm P, and 0.09 cmol$(+).kg^{-1}$ K where conventional rice was grown (Table 6). Moreover, only about 6 farmers in our sample used compost, and excluding their grain yield did not influence our comparison (grain yield of 6.35 $t.ha^{-1}$ with SRI, compared with 3.36 $t.ha^{-1}$ with conventional methods).[5]

The greater nutrient uptake with the SRI cultivation method suggests that rice plants grown with such practices were capable of taking up significantly more nutrients. Such uptake indicates that there might be some possible increase of available N due to a higher mineralization of organic-N (alternate aerobic and anaerobic environment). Furthermore, greater activity of nitrogen-fixing bacteria such as N_2-fixing endophytes within the root cells and in the root rhizosphere might also be present in the SRI plant-soil environment. We did not evaluate N-fixation but hypothesize that the greater uptake is

[5] That so few farmers used compost with their SRI practices indicates that the success of SRI does not depend on compost use. Association Tefy Saina, the main proponent and promoter of SRI in Madagascar, considers use of compost to be an "accelerator," giving better results when used with the other practices, rather than as something necessary for SRI to give higher yields.

attributable to the better root growth and root activity in conjunction with increased microbial activities. This hypothesis remains to be experimentally tested through evaluation and assessment of the composition and dynamics of the microbial population under the SRI system.

Regarding the indigenous soil P supply, there was similar P content of the soil for both SRI and conventional rice, on one hand, and yet a 66% increase in the P accumulated in the above-ground biomass, on the other. This reflected a greater capacity of plants cultivated with SRI method to access and take up P. It is possible that in addition to better nutrient supply, the enhanced root growth with SRI allows the plants to access sub-soil P which was not available with the conventional system. It is also possible that SRI soil and water management practices, with alternate flooding and drying, could increase microbial solubilization of P (Turner and Haygarth, 2001). We should recall that most reported measures of P in soil samples are for 'available' P, and the total amount of 'unavailable' P, complexed in forms not accessible to plants can be 20 times greater than what is 'available.' Microbial activity supported by different soil and water management practices could be making 'unavailable' P available to the plants.

Table 6: Soil characteristics in the on-farm survey, 2001

Parameters	Unit	Mean		Standard deviation	
		Conv.	SRI	Conv.	SRI
Soil N content	%	0.17	0.16	0.12	0.09
Soil P content	ppm	9.38	8.51	6.22	5.34
Soil K content	$Cmol(+).kg^{-1}$	0.09	0.08	0.06	0.05
Soil organic matter	%	3.71	3.72	2.61	2.03
Total carbon	%	3.78	2.16	15.05	1.18

Table 7: Grain and straw yield, harvest index, nutrient concentration, nutrient accumulation in the above-ground biomass in the on-farm survey, 2000-2001

Parameters	Unit	Number of observations		Mean		Standard deviation	
		Conv.	SRI	Conv.	SRI	Conv.	SRI
Grain yield	$t.ha^{-1}$	90	94	3.36	6.36	3.37	1.80
Harvest Index	$g.g^{-1}$	90	94	0.49	0.48	0.07	0.08
[N] grain	$g.kg^{-1}$	90	94	9.90	10.18	3.10	2.12
[P] grain	$g.kg^{-1}$	90	94	2.69	2.35	0.81	1.01
[K] grain	$g.kg^{-1}$	90	94	3.54	3.96	1.05	1.10
[N] straw	$g.kg^{-1}$	90	94	5.39	4.98	1.29	1.31
[P] straw	$g.kg^{-1}$	89	94	1.16	0.93	0.59	0.34
[K] straw	$g.kg^{-1}$	90	94	15.29	14.98	8.96	9.63
N uptake	$kg.ha^{-1}$	90	94	49.99	95.07	15.73	30.96
P uptake	$kg.ha^{-1}$	90	94	12.69	21.03	4.55	9.84
K uptake	$kg.ha^{-1}$	90	94	56.77	108.64	28.12	46.87
N in grain	$kg.ha^{-1}$	90	94	33.14	63.86	11.75	20.44
P in grain	$kg.ha^{-1}$	90	94	9.07	15.23	3.24	8.51
K in grain	$kg.ha^{-1}$	90	94	11.82	25.37	4.02	10.05
N in straw	$kg.ha^{-1}$	90	94	16.85	31.22	6.99	15.41
P in straw	$kg.ha^{-1}$	90	94	3.66	5.80	2.18	2.92
K in straw	$kg.ha^{-1}$	90	94	44.95	83.27	27.30	43.88

Estimation of the plant above-ground nutrient accumulation by Witt et al. in subtropical and tropical Asia in 1999 showed a nutrient uptake of 91 kg $N.ha^{-1}$, 16 kg $P.ha^{-1}$ and 88 kg $K.ha^{-1}$ with an average grain yield of 5.2 $t.ha^{-1}$. When compared to our estimate, N uptake was quite similar while P and K uptake were much higher with our estimation on the SRI system. Furthermore, the average SRI grain yield was also much higher. This difference reflects not only the variation of agroecological conditions but also apparently the methods of cultivation used.

3.4 Internal nutrient efficiency

The average internal nutrient efficiencies (IEs) for the SRI system were 69.20 kg grain per kg plant N, 347.3 kg grain per kg plant P, and 69.70 kg grain per kg plant K. This is equivalent to 14.5 kg N, 2.9 kg P and 14.3 kg K per 1000 kg grain. The average IEs for the conventional system were, on the other hand, 74.89 kg grain per kg plant N, 291.1 kg grain per kg plant P and 70.41 kg grain per kg plant K, which is the equivalent of 13.4 kg N, 3.43 kg P, and 14.2 kg K per 1000 kg grain (Table 7). Although the nitrogen IE of the conventional system was much higher in comparison to that of the SRI system, our t-test indicated that it was not significant at 5% degree of confidence (p=0.197).

A significant difference was noticed with regard to the P use efficiency. Table __ shows that there is a more efficient use of the P element for grain production with the SRI cultivation method. This better use of P is apparently the result of a higher N uptake by the SRI plants, which is evident from the measured N:P:K ratios (the ratio of N to P and K to P). For the SRI system, the nutrient ratio is considerably higher – 5.0:1.0:4.9 -- than that of the conventional system -- 3.9 :1.0:4.1.

A breakdown of the regression between N uptake and grain yield of the SRI system and conventional systems, assuming a parabolic relationship, indicated that the decrease of internal efficiency in relation with N uptake is much faster with the conventional system. This decrease is expressed by the second degree of the parabolic equation showing an NU^2 coefficient of -0.229 for conventional and -0.064 for SRI methods. Furthermore, the coefficient of the first degree parabola, which is 58.849 for SRI and 45.631 for conventional, reflected a steeper increase of the SRI grain yield as a function of the N uptake.

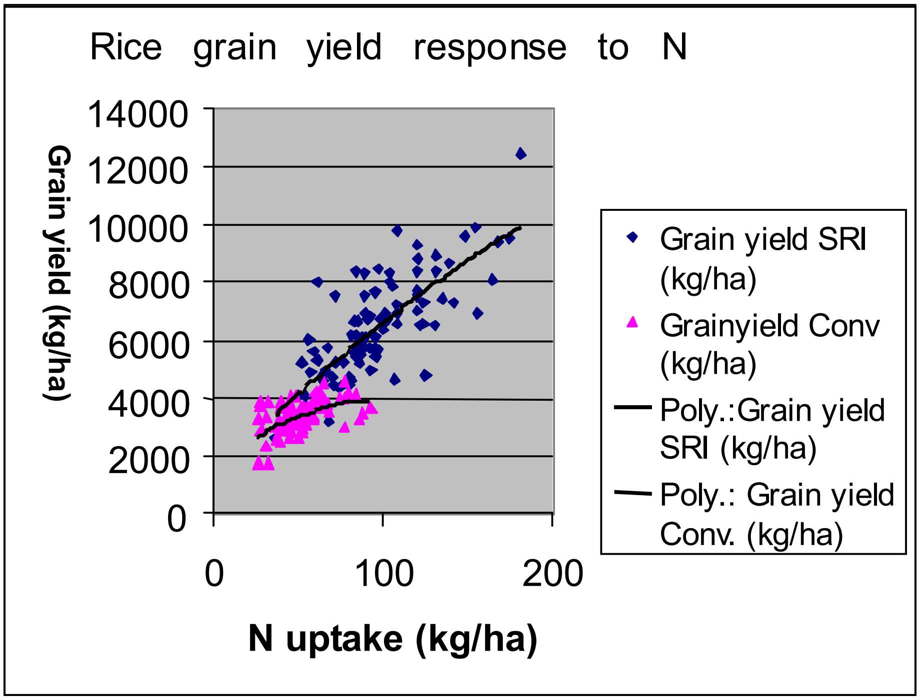

Figure 2: Linear regression relationship between N uptake and grain yield for SRI and conventional methods

Overall, the higher grain yield with SRI appears related to a more balanced nutrient uptake. While this balanced nutrition may be due to the indigenous nutrient supply in the top soil, our on-station and on-farm results suggest it may be more related to the activity of the root system and its deeper and more extensive proliferation.

Table 8: Evaluation of internal efficiency (IE) for SRI and conventional systems

Parameter	Unit	Sample size	Mean	Two-sample t test	
			Conv.	SRI	p-value
N IE	$kg.kg^{-1}$	94	74.89	69.20	0.197
P IE	$kg.kg^{-1}$	94	291.1	347.2	0.001
K IE	$kg.kg^{-1}$	94	70.41	69.70	0.884

4.0 CONCLUSIONS

Results from both our on-station experiment and on-farm survey have shown a consistently and significantly better performance of SRI rice plants relative to those grown with conventional rice practices in Madagascar. The SRI cultivation method appears to result in better nutrient access and/or uptake by the rice plants. The higher nutrient uptake is attributable to greater root growth and penetration in the soil sub-surface (higher root length density below 30 cm in depth), thus enabling the plant to exploit a greater volume of soil in comparison to that of plants grown with conventional methods. It is also very likely that the flooding and draining results in faster mineralization of soil organic matter which results in a greater supply of nutrients relative to conventional rice management.[6]

Two important conclusions are suggested by this study. Despite the greater tillering and grain yield of SRI rice, there was no difference in Harvest Index between SRI and conventional rice. Second, nutrient use efficiency under the SRI cultivation method was significantly higher, especially with respect to P. Both observations, in conjunction with our measurement of root length density and root-pulling resistance suggested that the performance of rice with SRI management practices was particularly related to a proliferation of the root system under SRI cultivation methods and thus to better plant access to soil nutrients.

In any case, the attainment of higher yield with SRI cultivation methods requires higher nutrient uptake. Results from our on-farm survey indicated a doubling of N uptake with the SRI method in comparison to conventional methods even though SRI and conventional rice plots had similar soil fertility. This suggests that the SRI management practices, especially the alternate irrigation and drainage of soil, favors the release of more available N through mineralization processes. This mineralization, however, may lead to a possible mining of the organic-N pool of the soil. Furthermore, the alternate irrigation and drainage may lead to a fluctuation of NH_4^+ and NO_3^- in the soil solution, which might render the SRI soil environment more prone to N loss. The high N uptake with SRI cultivation

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[6] Soil microbial populations are also likely to have been changed by the different plant, soil, water and nutrient management practices, with beneficial effects on plant performance, but this set of variables was not studied here.

method suggests greater activity of nitrogen-fixing bacteria such as N_2-fixing endophytes within the root cells and in the SRI rhizospheres.[7]

Finally, greater P uptake was also observed with the SRI system. This suggests that the better root growth and penetration enabled SRI plants to explore bigger volumes of soil and thus to gain better access to P and possibly sub-soil P.[8]

This paper provides some detailed measurements and comparisons that begin to document the effects of SRI practices in comparison with conventional ones for growing irrigated rice. One cannot draw definitive conclusions about the mechanisms for the observed differences, which are reported from more than 15 countries now (Uphoff et al., 2002). This paper identifies some issues with SRI that should be further investigated, to develop a better understanding of the physiological, nutritional, edaphic, microbiological and other scientific aspects underlying this cultural system. So far, few scientific studies have been done on SRI. We hope that more scientists will undertake studies on the underground and above-ground dynamics and capacities of the System of Rice Intensification.

5.0 REFERENCES (to be completed)

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[7] We do not know to what extent such losses are offset by biological nitrogen fixation made greater with a mixing of aerobic and anaerobic soil conditions which Magdoff and Bouldin (1970) documented was possible.

[8] The mixing of aerobic and anaerobic soil conditions could also increase the pool of available P through P solubilization by aerobic bacteria as reported by Turner and Haygarth (2001).