Nutrient-use efficiency and nutrient uptake in conventional and intensive (SRI) rice cultivation systems in Madagascar

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Chapter 1

OVERVIEW

Several innovations have been made with rice systems in order to increase grain yield and better meet the world's food demand. One of the well-known achievements for meeting such demand was the "Green Revolution." The "Green Revolution" 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. On the other hand, it seems that rice production has reached its yield potential, and scientists are pursuing genetic research for further improvement. 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 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). The hypoxic condition, caused by standing water, limits the ability of the roots to respire and slows its 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 (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 increase their grain yield from 2 to 8 tons/ha 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 recognizes the rice as having great unattained internal potential for tillering and seeks to provide an optimum 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, (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 for higher yield than conventional rice production systems (ATS, 1992; Vallois, 1996).

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

The present proposed study aims (1) to compare the nutrient-use efficiency of the SRI system and the conventional cultural system, (2) to estimate the nutrient requirements per unit of rice grain produced under SRI and conventional methods for producing a given grain yield, and (3) to compare the yield performance of both systems as affected by socio-economic factors (such as labor use and farmers' level of education).

Moreover, we want to be sure that the system being promoted has a sound scientific basis, on one hand, and is kept as simplified as possible to facilitate more widespread adoption among farmers.

Work done by Witt et al. (1999) 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: (1) other macro-nutrients do not become limiting until a higher grain yield level, compared to conventional cultivation, leading to a more constant internal efficiency (IE), the ratio between grain weight and total nutrient uptake. In such conditions, SRI rice plants would be capable of taking up soil nutrients in balanced amounts compared to crop needs; and (2) internal use of nutrients is relatively high and more efficient for grain production under SRI conditions.

In order to test these hypotheses, we planned two different but complementary studies.[1] One was focused on estimating the nitrogen, phosphorus, and potassium requirements of rice cultivated under SRI conditions. For that purpose, a model called QUEFTS[2] (Quantitative Evaluation of the Fertility of Tropical Soils) was applied to assess the internal-use efficiency of nutrients in tropical and subtropical Asia to test both the conventional and SRI systems. With the QUEFTS model, we could test possible interactions among N, P, and K and determine their effect on internal efficiency. QUEFTS studies the relationship between grain yield and nutrient supply in four different steps and takes into account limitations in supply, acquisition and utilization of N, P and K (Witt et al., 1999). We implemented this model using data

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[1] It should be noted that this research was conducted concurrently and cooperatively with Oloro McHugh, who was at the same time gathering 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.

[2] This model, originally used for calculating tropical maize yield as a function of N, P and K, was used to evaluate the interaction among these 3 elements and its effect on the grain yield. QUEFTS was, then, calibrated by Witt et al. in 1999 to assess the nutrient requirement of irrigated lowland rice in tropical and subtropical Asia.

from an on-farm survey of nutrient-use efficiency undertaken during the main growing season in 2000-2001 in four different locations, involving 109 farmers who were using both SRI and conventional methods concurrently on their farms. This enabled us to minimize the effects on yield and nutrient efficiency of differences between farmers and between farms.

A second study was done to evaluate the nutrient uptake and nutrient-use efficiency under controlled conditions. This on-station trial was done at the Beforona Station (Moramanga), and the performance of three rice cultivation systems was evaluated: SRI, SRA (the system for ‘improved’ rice cultivation recommended by FOFIFA, the national agricultural research agency), and conventional practices.

The following discussion explores possible explanations for the high grain yield obtained with the SRI system. The results reported here will help us to take further steps for a complete understanding of nutrient dynamics for rice under different agro-ecological environments.

Chapter 2

THE SYSTEM OF RICE INTENSIFICATION AND THE FARMING SYSTEMS IN MADAGASCAR

Background on Rice Farming Systems in Madagascar

Despite the recent evolution of industrial and trade sectors, the agriculture sector dominates the Malagasy economy and accounts for about 43% of the gross domestic product (FAO, 2001). Most of all, rice farming dominates the agricultural sector (http://www.buck.com/cntry-cd/bgnotes/ma.htm).

Rice cultivation has been an important component of the Malagasy traditional culture. It dictates farmers' daily life and is the basis of its cropping systems. In fact, one is not considered to be a farmer unless he has a patch of rice, no matter how small it is. Furthermore, farmers allocate much of their time and labor to the rice farming systems to the detriment of the other activities. Given such immeasurable allocation of labor to rice cultivation and the large number of peasant farmers (about 75% of the total population), Madagascar should be exporting a considerable amount of rice. Its /population is, however, still rice-deficient, as the country imports about 180,000 tons of rice to meet consumer demand every year.

This dependence on imports to meet demand for the country's staple food is mainly due to the low national average rice grain yield of only 2 $t.ha^{-1}$ with limits on cultivated area. In fact, only about 30% of the cultivable rice fields are managed each season because of the relatively low soil fertility.

The rice farming systems can be classified into three types:

- Lowland rice, which can be rain-fed or irrigated. This is cultivated lowland areas and its calendar normally follows the growing season from October through April. Rain-fed cultivation may have its calendar delayed since rainfall distribution is extremely variable. There are also rice fields that only depend on the capillary movement of the water in order to provide the water that plants need. The latter is mainly encountered in *baiboho* (alluviums). Lowland rice cultivation constitutes 72% of the rice area.
- Upland rice, which is totally rain-fed and depends entirely upon rainfall. This type of cultivation is very often done on hillsides.
- Slash-and-burn cultivation, which also relies on rainfall. It is different from the previous type of cultivation in that farmers clear a patch of forest land and use fire in order to release nutrients from the biomass. It is an unsustainable system of cultivation and is associated with very short fallow periods.

The System of Rice Intensification

The System of Rice Intensification first originated in Madagascar around Antsirabe in the 1980s. It was developed by a French Jesuit priest, Henri de Laulanie, and it has enabled its practitioners to increase their grain yield from the national average of 2 $t.ha^{-1}$ to now 8 $t.ha^{-1}$ or more just by changing the rice management practices (Association Tefy Saina, 1992).

Rice has been cultivated under flooded conditions for centuries for various reasons. Reasons among others are the control of weeds and the belief that rice performs better under standing water (Reddy and Reddy, 1999). However, rice is only a flood-tolerant plant, not one that benefits from constantly saturated soil (Vartapetian, 1993).

One of the key advantages of flooding a paddy field is to increase low soil pH up to a level of 6.7 to 7.2. Such a condition favors the release of the P element from aluminium or ferrous coated P. The cut off of soil oxygen supply, however, leads to a rapid decrease of the redox potential and thus a gradual appearance of soluble Mn, Fe and methane (Ponnamperuma, 1984).

According to proponents, SRI encompasses a set of five principles, each of them fairly simple, but working synergistically with the others in order to achieve higher grain yield (Uphoff, 2000).

Early transplanting

Recent trends in recommendations for rice cultivation are to increase the density of plant population. Considering the fact that arable land and incoming light are limited (in a land area basis), most research for improving rice yield have been oriented to (1) increasing biomass production by improving radiation and its efficient use, and (2) increasing the harvestable biomass relative to the non-harvestable portion for the sake of a higher Harvest Index (HI), the ratio between grain biomass and total plant biomass.[3] This thinking has led to a breeding strategy that aims to create a cultivar producing more grains but fewer tillers (Khush, 1993).

The growing conditions under SRI facilitate an optimum environment for tillering expression (de Laulanié, 1992).

Before proceeding any further, the term *phyllochron* needs to be introduced since it will be used very often in this thesis. Phyllochron, which has been used to characterize the growth dynamics of cereals, is defined as the interval of leaf emergence (Nemoto et al., 1995). It varies in a function of temperature, day length, nutrition, light intensity, planting density and humidity (Nemoto et al., 1995). The modeling of the phyllochron was first published in 1951 when Katayama presented the growth rules he had worked out for leaf emergence on the main stem and tillers of rice, wheat and

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[3] It should be noted, however, that while the formal definition of HI makes the denominator "total plant biomass," in operationalizing HI, only above-ground biomass is cut and weighed.

barley. This model was used by de Laulanié for explaining the success of the SRI system which he had already developed empirically.

As we can see from the Katayama table, the first tiller off the main stem appears at the fourth phyllochron. De Laulanié had already found that if the rice seedling is transplanted later than the third phyllochron, the resulting plant will lose all of the incoming tillers from this first row of tillers which represents about 40% of the total tillers, and that any further delay of transplantation leads to a bigger loss of tillers (Association Tefy Saina, 1992).[4]

Proponents of SRI recommend transplantation of the seedlings during the third phyllochron, at the stage when the plant has still only two leaves, in order to avoid reduction in subsequent tillering and root growth (Laulanié, 1993). Early transplantation in conjunction with the other practices allows a greater realization of the tillering potential of rice plants (Association Tefy Saina, 1992).

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[4] This process warrants further systematic study. An alternative explanation focuses on changes in phyllochron length as affected by temperature, soil moisture, shading, etc. The impact of transplanting seedlings before the fourth phyllochron, in terms of tillering, root development and yield, is very dramatic as seen from our research and in factorial trials (Randriamiharisoa and Uphoff, 2002). Exactly what physiological processes are involved that produce such a result remains to be determined.

Table 1: Phyllochron table of Katayama as adapted by Laulanié indicating the number and location of tillers being initiated at each stage of development in *Oryza sativa*, provided that growing conditions are optimal

PHYLLOCHRON	0	1	2	3	4	5	6	7	8	9	10	11	12	Total
Main stalk		1												1
First row of tillers					1	1	1	1	1	1				6
Second row of tillers							1	2	3	4	5	6	5	26
Third row of tillers									1	3	6	10	15	35
Fourth row of tillers											1	4	10	15
Fifth row of tillers													1	1
Total number per phyllochron	0	1	0	0	1	1	2	3	5	8	12	20	31	84
Total	0	1	1	1	2	3	5	8	13	21	33	53	84	

Source: Association Tefy Saina, 1992.

Figure 1: Tillering development with SRI-grown plants (top) and conventionally grown plants (bottom) (variety 2787).

Transplanting of a single seedling per clump

Conventional methods are characterized by a transplanting of more than 3 or more seedlings per clump. As far as traditional farming practices in Madagascar are concerned, planting more seedlings per clump is thought to provide farmers assurance that if one plant dies, others can still grow and therefore a lower percentage of hills will be missing.

SRI, however, recommends the transplantating of one seedling per clump (Association Tefy Saina, 1992). Research done in 1998 showed that a single rice plant could express its tillering potential better than a larger number of plants in a clump (Joelibarison, 1998). Transplanting three seedlings together impeded rice growth in that the adjacent plants had to compete for nutrients, space and light. This competition repressed root growth and proliferation. When root systems are poorly developed, the plant devotes its energy for developing the seedlings in height to the detriment of the production of tillers (Joelibarison, 1998).

Mechanical weeding

One of the main purposes for flooding rice paddies with some controlled drainage is for weed control (Sahid and Hossain, 1995). Rice fields are kept under standing water until aquatic weeds develop. Once they start to invade the rice field, the field is drained in order to kill the aquatic weeds. Thereafter, rice field is re-flooded with standing water again when terrestrial weeds start to dominate. This is the traditional way for managing weeds in conventional flooded rice systems.

With SRI, weeds are controlled by the use of mechanical weeding with a rotary pushed weeder – *sarcleuse*. The system relies on early and frequent weeding which varies from 3 to 4 times throughout the cultivation period. The first in the series of weedings is done about 10 days after transplantation and the others in a frequency of 10-20 days (Association Tefy Saina, 1992).

Maintaining moist soil under non-saturated conditions during the vegetative phase

Irrigated rice plants are grown under standing water throughout the season because most farmers and agronomists believe that rice performs well under flooded conditions. Rice and water are all linked together from the field to the pots (Malagasy proverb).

Under flooding, rice roots alter their root cortical cells by the creation of air pockets (aerenchyma) to facilitate oxygen transport to roots since the concentration of soluble oxygen in the water/soil interface is very low and the diffusive transport of oxygen is about 10^4 times lower in water than in air. Such cell lysis leads to the formation of gas-filled cavities or lacunae (Drew, 1997; Puard et al., 1999.; Vartapetian, 1993). These lacunas enhance the transport of oxygen from the shoot to the root tip. Puard noticed the same mechanism when he planted an upland rice variety in a lowland condition with standing water. The lack of oxygen leads to more aerenchymatous spaces in the root systems (Puard et al.,1999). Flooded conditions have been, however, reported to lower yield (Wan Huang et al., 1999).

Rice plants, when grown under saturated condition, develop more hairy, fine and branched secondary adventitious and surficial roots near the root-soil interface in order to absorb the dissolved oxygen in the oxidized layer close to the water-soil interface (Obermueller and Mikkelsen, 1974). The elongation of the root system nutrient uptake is repressed.

When rice is grown under intermittent dry and flooded conditions, the same condition as that of the SRI system, there are fewer surficial roots and more tap roots and primary roots. Such rooting pattern is apparently the result of the soil aeration brought about by the intermittent drainage.

Last but not least, a study done by Kar et al. (1974) showed that 78 % of the roots die back at the flowering stage when rice is grown under flooded conditions as compared to that under aerated conditions.

Compost application

Proponents of SRI recommend the use of organic fertilization (compost) instead of chemical fertilizer. The idea is to capitalize on the biological resources and organic matter in the compost and to maintain optimum biological activity of the soil. This organic fertilization is thought to improve the soil structure and the continual release of nutrients.

After the system was first developed in 1984, de Laulanié and cooperating farmers continued to experiment with the SRI in Antsirabe by varying the age of the plant at transplantation, experimenting with direct seeding, and varying the plant spacing. In 1992, farmers in Fianarantsoa started experimenting with the system under the supervision of the Association Tefy Saina. Later in 1996, the Agricultural School (ESSA) of the University of Antananarivo became interested in the system because of its potential and oriented some of its Masters students to evaluate the system in systematic, scientific terms.

Chapter 3

RESEARCH OBJECTIVES AND HYPOTHESES

Proponents of SRI assert that the synergistic effects of (1) transplantation of young seedlings and (2) single seedlings per clump, (3) mechanical weeding, (4) alternate irrigation and drainage during the vegetative phase of the rice plant to avoid continously saturated, hypoxic and (5) application of compost lead to better tillering development in comparison to the conventional system, more root growth and functioning, and ensuing higher grain yield production.

The attainment of high yield with less application of chemical fertilizer while using the same varieties that farmers are already using in conventional cultivation has prompted us to seek a better understanding of the physiological factors underlying SRI yield.

Research Objectives

- To determine the nutrient uptake of SRI plants and compare this with that attained with the conventional system: evaluate N, P and K uptake, partitioning and recycling at different SRI yield levels, and also to compare this with conventionally grown rice.
- To determine the efficient use of nutrients for grain production with SRI and the conventional system.
- To develop a model of nutrient uptake balance with SRI and conventional systems, and then to estimate N, P and K requirements of rice plants cultivated with either SRI or conventional practice.

Null Hypotheses

The following null hypotheses were formulated prior to our study:

- Nutrient uptake by conventional rice is similar to that of SRI rice. Because the appearance of more tillers with SRI cultivation methods gives a higher number of nodal roots, we have an alternative hypothesis that these roots go deeper and exploit a larger area of soil, which leads to a more balanced nutrient uptake relative to the crop needs.
- N, P and K use efficiency for grain production are similar in SRI and conventional rice. Alternatively, we hypothesize that SRI plants maintain more late-season root activity that facilitates more efficient nutrient uptake during the grain-filling period. The absorbed nutrients during this late stage are more efficiently used in SRI for grain production compared to plants cultivated with conventional methods.
- There will be no difference in Harvest Index between SRI and conventional rice. One would expect that with more tillering, the SRI method leads to an increase of non-harvestable biomass which results in a decrease of the Harvest Index. If, however, there are proportional changes in shoot, root and grain, HI will not change.

These hypotheses are based upon a review of scientific literature and on our own observations of rice plant behavior in Madagascar.

Chapter 4

LITERATURE REVIEW ON RICE MINERAL NUTRITION

Madagascar is one of many countries in the world today that has a rice food deficit. It recorded a drop of the rice consumption per capita from 122.6 kg/year in 1970 to 92.3 kg/year in 1998. Furthermore, the national yield average of 2.17 $t.ha^{-1}$ is slightly lower than the average grain yield of 2.22 $t.ha^{-1}$ in Africa and much lower than the average grain yield of 3.95 $t.ha^{-1}$ in Asia (FAO, 2001).

SRI has led to a remarkable increase of the grain yield production for its practitioners since the1980s (Association Tefy Saina, 2001). Surveys done by Bilger (1996) showed that farmers practicing SRI obtained a grain yield of 6.3 $t.ha^{-1}$ in Antananarivo and 8.0 $t.ha^{-1}$ around Antsirabe whereas those practicing conventional rice cultivation obtained about 3.2 and 3.9 $t.ha^{-1}$ respectively (Bilger, 1996).

Most of the literature on nutrient-use efficiency is oriented to the evaluation of mainly nitrogen-use efficiency (Janssen, 1998). Other nutrients such as P and K, however, influence the efficient use of nitrogen, and nitrogen itself exerts a great influence on the efficiency of others. Inadequate supply and thus uptake of one nutrient impairs the efficient use of other nutrients which are more abundant, and the crop cannot efficiently use the abundant nutrient for plant growth (Jansen et al., 1990).

The factor most largely determining the use-efficiency for a particular nutrient is the nutrient content of the soil. A poor and infertile soil actually alters the physiological activities of the rice plant and therefore constitutes a constraint to the plant’s internal efficiency. Nevertheless, the potential supply of nutrients to the plant also depends on the extent of root growth, as well as microbiological conditions in the rhizosphere. An environment producing a very limited root system offers a lower potential supply of nutrients than one inducing a more proliferated and extended root system. A well developed root system is obviously essential for rice plants to effectively absorb available nutrients.

Janssen mentioned that the efficient use of nutrients is a balancing act. This art of balancing has always been considered to be first influenced by the nutrient potential supply in the soil solution (Janssen, 1998). Several studies have been consequently oriented to the augmentation of the recovery of fertilizer nutrients (Furoc and Morris, 1989; Ockerby et al., 1999). We believe that in addition to this maximization of nutrient recovery, one needs to get a close look at the importance of root growth since the extent of root system proliferation can affect the potential supply of any nutrient. Poor root development impedes rice plants from accessing nutrients available in the soil.

Internal Efficiency

This process, commonly measured in terms of physiological efficiency, represents the amount of grain yield produced per unit of crop nutrient content.

The rice plant utilizes two sources of nutrients in order to satisfy its demand when forming and filling grain:

- One source is the nutrients already contained in the rice shoot. These nutrients are remobilized to the grain sink at the post-anthesis stage. This remobilization leads to less shoot nutrient content at the maturity stage compared to that pre-anthesis.
- The second source is the indigenous nutrient supply. The utilization of this source, however, is closely linked to the capacity of the roots to take up nutrients. That capacity itself is a function of root growth and proliferation.

Since most of the literature regarding nutrient-use efficiency is on nitrogen-use efficiency (NUE), the following section will be drawn from NUE studies, which will be applied then to other nutrient-use efficiency in question. It has been proposed that a linear relationship exists between shoot N accumulation and rice grain yield until the N shoot content reaches some certain optimum value. Once that value is reached, the increase of the physiological efficiency does not follow a linear pattern anymore. Any further increase of the shoot N content leads to a relatively lower increase of physiological efficiency. This lower increase is best viewed in terms of marginal physiological efficiency decreases after the attainment of the optimum uptake of N element.

This optimum N uptake is, however, related to the uptake of the other two macro-nutrients (P and K). In fact, a given amount of N becomes the optimum uptake because other nutrients are limiting the efficient use of that nutrient for dry matter production. Once other nutrients are not yield-limiting, rice plants can remove the physiological blockage affecting internal efficiency.

Internal Efficiency and QUEFTS Model

The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model was originally used to calculate attainable maize grain yield when the N, P and K supply from the soil and that derived from fertilizer are known (Janssen, 1990). It was later calibrated by Witt et al. in 1999 to apply to rice crops in Asia in order to determine what constitutes a balanced nutrient uptake for a targeted grain yield.

One of the main features of the QUEFTS model is the possibility of determining the interactions among macro-nutrients that affect the N, P and K internal efficiency (Witt et al., 1999). These interactions are established through four successive steps of analysis.

- Estimation of the existing potential soil nutrient supply. This is estimated either from soil testing or from plant nutrient uptake. Soil potential supply is best quantified from soil analysis since the plant nutrient uptake is influenced by the proportion of the nutrients in the soil and the growth conditions (Janssen et al., 1990).

- Calculation of the actual uptake as a function of the potential supply. The plant uptake of N, P and K (UN, UP and UK) is first calculated as function of the potential supply of the other two nutrients (SN, SP and SK). This leads to two estimations of the plant uptake for each nutrient. Only the minimum uptake for each pair of results is kept to evaluate the final estimate of nutrient uptake (UN, UP, UK). When a nutrient supply is plotted along the abscissa and the potential supply of another nutrient is considered fixed, the actual uptake of this nutrient follows a parabola with 3 distinct situations. The extreme two situations are: (1) a situation where the actual uptake is equal to the low potential supply of the nutrient (U=S) and (2) a situation where the potential supply of the given nutrient is so large that the other nutrients limit its uptake.
- Combination of yield ranges for two nutrients. The third and the fourth steps estimate yield ranges as a function of the actual nutrient uptake. In the third step, yield ranges are combined in pairs such as nitrogen and phosphorus, nitrogen and potassium, and phosphorus and potassium. The yield ranges originated first from the estimation of one nutrient uptake. This nutrient uptake leads to two yield estimates, which lie between YNA (maximum accumulation of the nutrient) and YND (maximum dilution of the nutrient). Note that the nutrient taken as example in this case is nitrogen. The yield estimate for two pairs of nutrients is, thereafter, obtained by combining other nutrient uptake to these yield estimates such as P or K. The resulting yield estimate (YNP) should then lie within the overlap of YNA-YPA and YND-YPD. Furthermore, YNP follows a parabolic pattern where the lower point depicts a situation with large surplus of P and limited supply of N, and the upper peak depicts a situation with large supply of N and limited supply of P (Figure 2).

Likewise, yield estimates of the other combinations are calculated. It, thus, leads to six yield estimates: YNP, YNK, YPN, YPK, YKN and YKP.

- Determination of the yield estimate based on a combination of yield ranges for the three nutrients. This final yield estimate is obtained from the average of the six yield estimates for paired nutrients.

This final yield estimate follows a linear-parabola model when plotted with nutrient uptake, and it is assumed that there is a balanced nutrient uptake. As we already noticed in the third step of the model calibration, this linear-parabola pattern should be enveloped between the maximum accumulation and the maximum dilution lines. The grain yield increase follows linearly the nutrient uptake increase as long as none of the three macro-nutrients has become a limiting factor. Once one or more of the nutrients are not taken up in balanced proportion and the grain yield reaches the yield potential, the grain yield increase follows a parabolic pattern, which plateaus at the yield potential.

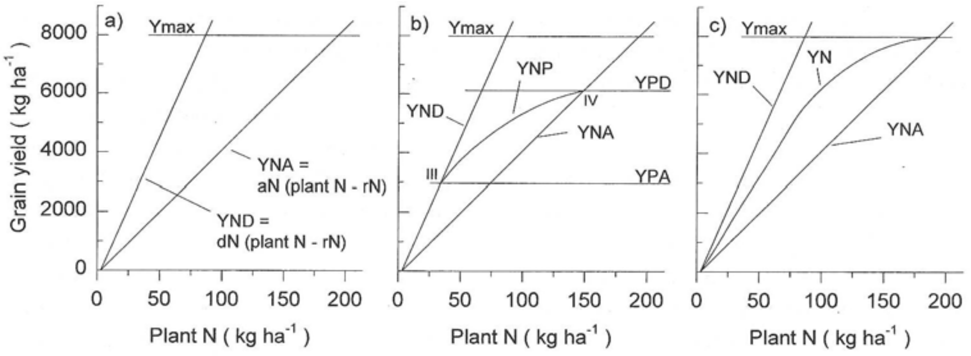

Figure 2: Schematic relationship between grain yield and aboveground total plant N calculated by the QUEFTS model

Source: Witt et al. (1999).

Chapter 5

MATERIALS AND METHODS

For a better characterization of the rice farming systems in Madagascar, two kinds of studies were conducted. One was based on an on-station evaluation of the nutrient dynamics of the SRI, SRA (Improved Rice Cultivation), and conventional systems. The second was an on-farm study of the agronomic and socio-economic factors affecting the SRI and conventional systems.

On-Station Evaluation of Nutrient Dynamics – Beforona

Beforona Study Area

Beforona is located in the eastern part of Madagascar (48° 30'- 48° 58' and 18° 50') at an elevation of 350-750 m (figure 3).

Climate

Rainfall

Beforona is characterized by a *tropical humid climate* (2000-3500 mm/yr^{-1} rainfall) with two very similar seasons that only differ in the temperature variation and the rain frequency:

- A rainy and hot season through December to May, and
- A less rainy and cooler season through June until November

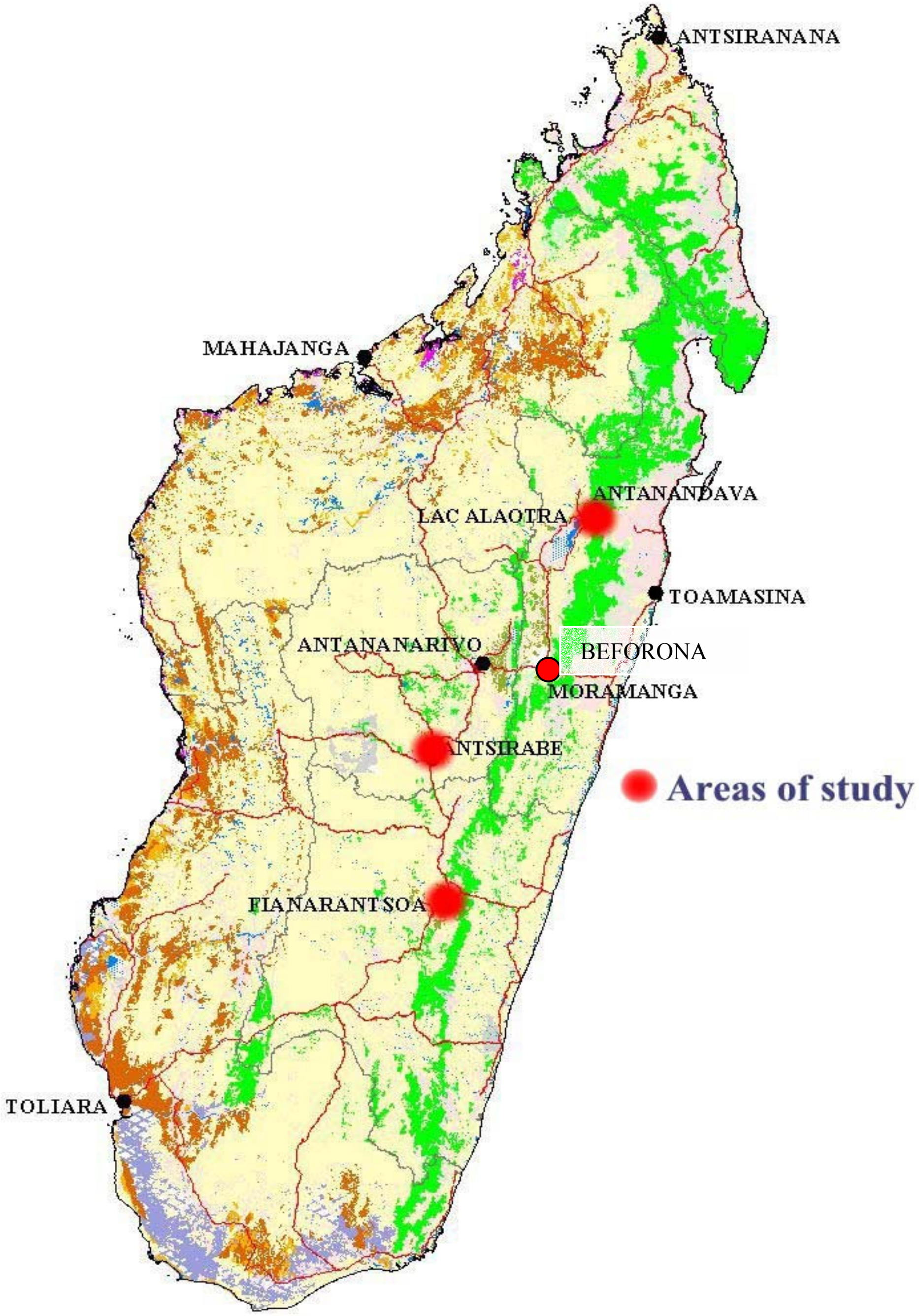

Figure 3: Map of Madagascar showing areas for study

Table 2: Average monthly rainfall at Beforona (year 2000)

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Monthly rainfall (mm)	216	612	738	63	86	184	388	128	56	32	265	451
Frequency of rain (d)	16	26	26	17	13	25	21	23	18	12	18	24

Source: Projet BEMA (2001).

Temperature

The temperature records slight variation throughout the year. It is moderately high from November until April with a maximum temperature of 32°C. Thereafter, the temperature drops and plateaus at 22°C.

Table 3: Average monthly temperature at Beforona (year 2000)

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Mean monthly temperature (°C)	32	29	28	28	27	23	22	23	25	27	27	31

Source: Projet BEMA (2001).

Topography

Beforona is characterized by its hilly relief with steep slopes of about 30%. Such topography very often leads to erosion of upland soils mainly when the overlying vegetation is removed. The upland has always been subjected to an unsustainable exploitation since the lowland arable surface is very limited (narrow and patchy valleys).

Regarding the parent materials, soils are mostly composed of continuously renewed materials from migmatites and amphiboles, and they all belong to the group of orthic ferrasol and xantic ferrasol.

On-farm trial description

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

(a) SRI cultivation method: The rice plants were transplanted at an age of 8 days. Rice seedlings were carefully transplanted in moist and consistent soil in a grid pattern of $25x25cm^2$ with only one seedling per clump. Plots were all kept under a non-saturated condition during the vegetative phase (only kept under standing water over the night and immediately drained in the morning). Two series of weeding were done with a mechanical rotary-weeder (*houe rotative*) with the first one done 20 days after transplantation and a second 30 days later. Compost-fertilized plots received an incorporation of 10 $t.ha^{-1}$ of compost composed of bush vegetation, pig manure and soil (80 kg N/ha, 0.45 kg P/ha and 92.5 kg K/ha) 8 days before the transplantation.

(b) SRA (*Système de Riziculture Améliorée*) method: This differs with SRI first by age of transplantation, which is about 25 days. Rice seedlings were transplanted in $20x20cm^2$ grid patterns with 2-3 seedlings per clump. SRA plots were all kept under standing water of 3-5cm throughout the growing season with some occasional drainage. Two series of mechanical weedings were done at intervals of 30 days. 300 $kg.ha^{-1}$ of NPK 11-22-16 was applied right before the transplantation for the SRA fertilized plots. It was, thereafter, supplemented by a 67 $kg.ha^{-1}$ of urea at the panicle initiation stage.

(c) Conventional rice system: Rice plants were transplanted at the age of 45 days. Rice seedlings were transplanted in a random pattern with 53 hills per m^2 (approximate spacing of 14x14 cm^2) and the number of seedlings per clump was 4 to 6. Rice plots are kept under standing water of 2-3 cm during the first two weeks after transplantation and 5 cm thereafter. Conventionally managed plots did not receive any kind of weeding given their continuous flooding. Nor did they receive any type of fertilization.

Table 4: 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 first two weeks after transplanting and 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 immediately 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 the evaluation of both the root length density (RLD) and the 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.[5] 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 determine the evolution of the nutrient content of the rice plant, plant samples were taken at panicle initiation, anthesis and maturity. They were analyzed for macro-nutrient content (N, P and K). The whole plant biomass was analyzed altogether for plants sampled at panicle initiation, while harvestable biomass (grains) and non-harvestable biomass (straw) were analyzed separately for plants sampled at the other two stages.

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).

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

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.

On-Farm Study of Agronomic and Socio-Economic Aspects of the SRI and Conventional Systems

To obtain detailed and more exhaustive comparisons between the SRI and conventional systems, the on-station trial was complemented by an on-farm survey which was done in three different rice-growing areas of Madagascar. These three areas are Ambatondrazaka, Antsirabe, and Fianarantsoa (Figure 3). Two different locations in the first area were surveyed as noted below. Agroecological and social variability were taken into account when selecting the sites for study.

Description of the survey

Proponents of SRI have always mentioned the greater grain yield attained in comparison to the conventional system. A survey done by MADR/ATS in 1996 in the high plateau of Madagascar showed that farmers practicing SRI obtained a grain yield of 6.3 $t.ha^{-1}$ in Antananarivo and 8.0 $t.ha^{-1}$ around Antsirabe whereas those practicing Conventional only obtained about respectively 3.2 and 3.9 $t.ha^{-1}$ (Bilger, 1996). Extension of the SRI, however, appears to be slow despite such high yield increases.

The attainment of this high yield, on the one hand, and the relative low adoption of the system, on the other hand, prompted us to conduct on-farm surveys where biological as well as socio-economic factors could be evaluated. From this survey, we could compare the performance of SRI and conventional systems, and also identify any hindrances impeding the adoption of the SRI system.

During our sampling and survey, full collaboration was obtained from Association Tefy Saina (ATS) in Antanananarivo and Antsirabe, from FOFIFA in Fianarantsoa, and the LDI project team in Beforona.

Characterization of Ambatondrazaka – Lake Alaotra

Lake Alaotra is located in the northeastern part of Madagascar (17.8° S, 48.43° E). The region is mostly a large plain at an elevation of 750m above sea level. The plain itself is surrounded by eroded mountain escarpment in the east, north and south and by more stable and solid convex hills in the west. This surrounding hilly relief leads to annual sediment deposits in the bottom of the valley and a continual renewal of the valley topsoil.

Climate

Alaotra has a moderate humid tropical climate and its annual rainfall is about 1025mm (1990 to 1999). The climate is marked by two distinct seasons:

- A rainy and hot season fron December through March, and
- A dry and cold season from April through November.

Table 5: Average monthly rainfall and temperature at Ambatondrazaka, 1990-99

Month	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Rainfall (mm)	320	227	127	34	13	7	17	5	14	35	28	198
Mean temperature (°C)	24	24	24	22	19	18	17	18	19	21	23	24

Source: Center of Meteorology, 2001

Although Ambatondrazaka is the biggest rice producing area in Madagascar, the irrigation infrastructure is inadequate, and many farmers have to rely upon rainfall in order to start their rice calendar. This means that most peasant farmers do not start their soil preparation before December. Furthermore, rice cultivation is drastically affected by the irregular distribution of the rainfall throughout the year.

Topography

Soil in the Mangoro rift is formed of materials rich in laterite and is apparently a ferrasol. Since hills are bare and are always eroded during the rainy season, the upper horizon is formed of very young and recent materials from the original rock. The original rock itself is a basement rock made of metamorphic and igneous rocks belonging mainly to the category of metamorphic rocks with crystalline constituents such as granites, migmatites and schists (http://www.rbgkew.org.uk/herbarium/madagascar/bio_paper_full.html#GEOLOGY).

Soils in the bottom valley itself are more aquents and fluvents since sediments deposit from the upland occur much faster than the horizon differentiation. Soils in the plain, however, denote the same characteristics as the common rice land which are the aquepts and aquic subgroups.

Population and ethnic groups

Populations of Ambatondrazaka belong mostly to the *Sihanaka* ethnic group. They were originally doing slash-and-burn cultivation, but the melting between *Sihanaka* and *Merina* peoples in the 19th century drove them down to the lowland.

Since Ambatondrazaka has been considered the granary of Madagascar, there have been several government extension projects focused mainly on rice farming system, and this has influenced the current farming systems. It is the only region where farmers use animal traction and motor-driven equipment.

In regard to the rice farming systems (rice growing season December through June), farmers practice little off-season cropping since their rice calendar does not end until June. Cultivation is quite difficult because not only does the lake receed but also the rain is not enough for cropping.

Characterization of Antsirabe

Antsirabe (9.87° S, 48.03° E) as part of the high plateau of Madagascar is comprised of hilly and mountainous areas with a relatively high elevation, up to 1600m.

Climate

The area has a humid tropical environment with more accentuated cold season (minimum temperature goes down to 4°C in June). The climate is delimited by two seasons:

- A rainy and hot season from October until April, and
- A dry and cold season from May until September

Table 6: Average monthly rainfall and temperature at Antsirabe, 1990-99

Month	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Rainfall (mm)	345	225	164	103	24	5	9	5	20	74	116	195
Mean temperature (C)	20	19	19	18	16	14	13	14	17	19	19	20

Source: Center of Meteorology, 2001

The average annual rainfall in Antsirabe is about 1,285 mm. Even if the rainfall is higher in comparison to the rainfall in Ambatondrazaka, its distribution is irregular throughout the year, and there are periods where rain comes more often than at other times. As shown in the above table, it comes most often in December and January. Such late rain means that any kind of cultivation needing the rainfall in order to start (mainly rice) might be delayed when no irrigation scheme is available. Furthermore, problems of inundation and submergence are major constraints for rice land that is near streams.

Topography

Antsirabe is characterized by metamorphic and igneous rocks rich in volcanic materials and eruptive rocks such as gabbros and basalts. Since the area was under recent volcanic activity, its soils are more composed of brown-dark and very fertile soils. Such fertile soils have favored Antsirabe farmers, and they are wealthier than the others because they can practice many kinds of cultivation such as rice, maize, wheat, carrots, beans. etc.

Population and ethnic groups

Most inhabitants of the Antsirabe region belong to the *Merina* group. They are as hard-worker as the *Betsileo* tribe, described below, and use *angady* (hand hoes) and some small animal traction for soil preparation.

Peasant farmers diversify their cropping system in addition to their rice cultivation. Since they are favored by better agroecological conditions, their diversification is far more complex than in the rest of the country. Every single farmer is cultivating not only rice in the lowland but also maize in association with beans in the upland during the main growing season (October through March) and wheat or potato in lowland areas during the inter-season.

Characterization of Fianarantsoa

Fianarantsoa (21.45° S, 47.07° E) is located in the middle southeastern part of Madagascar. Still part of the high Malagasy plateau, it is notable for its hilly and mountainous relief with a 1500m elevation.

Climate

Fianarantsoa has a tropical humid climate with two distinct seasons:

- A rainy and hot season from October through April, and
- A dry and cold season May through September.

Table 7: Average monthly rainfall and temperature at Fianarantsoa, 1990-99

Month	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Rainfall (mm)	244	210	125	42	30	10	23	13	14	46	101	212
Mean temperature (°C)	22	22	21	20	18	16	15	16	18	20	21	22

Source: Center of Meteorology, 2001

Average annual rainfall of Fianarantsoa is about 1070mm (1990-99 data). The rain starts in November, and farmers can fairly reliably follow their cultural calendar. In addition, the rain is well distributed throughout the growing season (November to March), so farmers have few problems of water deficit nor inundation.

In contrast to the climatic condition of Antsirabe, there is no steep drop of temperature in Fianarantsoa. Temperature is almost constant from November until April, and farmers can even extend their rice calendar until May without harming their production. They, however, prefer to advance their calendar since most of them practice off-season cropping.

Topography

As part of the high plateau, the Fianarantsoa region is formed of hilly areas with a highly contrasted relief. Its basement rocks are also formed of metamorphic and igneous rocks, and the rocks themselves are mainly constituted of granite. The basement rocks are more consolidated, and although relief is uneven, problems of deep gullies and landslides (*lavaka*) do not occur that much.

Lowland surf[6]ace is very limited in Fianarantsoa. The only exploitable area is the basin of Fianarantsoa and some patched inland narrow valleys. Regarding the rice land itself, soils generally belong to the aquepts and aquic categories with low base status and considerable levels of soluble iron.

Population and ethnic groups

Inhabitants of Fianarantsoa belong mostly to an ethnic group called the *Betsileo*. They are reputed to be the hardest workers in Madagascar. They usually use *angady* (hoes) for the soil preparation in addition to a few using animal traction. The area is widely known to possess the most rice terraces in Madagascar, terraces that could only be formed by *angady*.

Because of the better climatic conditions and their own disposition, farmers in Fianarantsoa diversify their cropping system by practicing cultural rotation. Right after the rice growing season, they plant an off-season crop such as potatoes, beans etc.

Sampling Methods

Prior to our survey, a full list of farmers practicing SRI 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 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

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[6] Note that the preoccupation with rice is so strong that growing other crops is considered 'off-season' or 'counter-season' (*contra-saison*).

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 variability of these other factors. Farmers were selected according to whether they had fields that met these 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 one 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 28 sample size (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 for the sake of reducing any effect of geographical variability (soils and topography).

When conducting our initial nterviews, it was observed that there was considerable variability in farmer's common practices. These had been influenced by previous rural development activities in the region, and each region has its own set of practices that were ‘conventional.’Ambatondrazaka, on one hand, has received much extension work in the area, introducing in-row transplantation, mechanization, chemical fertilizers and pesticide application, and lately, younger transplantation and direct broadcast seeding with herbicide application. It has, therefore, a more modernized kind of agriculture compared to that in the rest of the country. One example is the fairly wide adoption of younger seedling transplantation in Zone I. Another expression of this influence of rural development action is the wide adoption of in-row transplantation even with more traditional practices.

Chapter 6

RESULTS AND DISCUSSION

To give a systematic picture of agronomic and physiological aspects of the SRI and conventional systems, this section is divided into an evaluation of nutrient dynamics based on on-station trials and an evaluation of the nutrient-use efficiency in the on-farm study.

Nutrient Dynamics in the On-Station Trials

Grain yield comparison

Grain yield and yield components

Substantial differences were observed in the grain yield production for SRI, SRA and conventional systems (Tables 9 and 10). The highest yield was obtained from those plots where SRI was used and compost was applied, a yield of 6.26 $t.ha^{-1}$. The difference was statistically significantly different from that of the SRA system, with yields 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 8, p=0.001, ANOVA test). This higher grain yield with the SRI cultivation method was the result of a higher panicles and grains per m^2 (Table 8). For the SRA treatments, the lack of significance between the fertilized and non-fertilized plots were due to a greater attack of blast (*Pyricularia oryzae*) in the fertilized plots at the grain filling period.

Table 8: Grain yield components in the on-station experiment

Treatments	Plants/m2	Panicles/m2	Grains/m2	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 9: ANOVA table of the grain yield in the on-station trial in Beforona

Source	Degree of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	20.68	5.171	11.23	0.001
Error	10	4.6	0.46		
Total	14	25.29			

Table 10: 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

Table 11: ANOVA table of weeds dry weight in the five treatments

Source	Degree of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	124.4	31.11	8.91	0.002
Error	10	34.9	3.49		
Total	14	159.35			

Table 12: Distribution of weeds dry weight in g.m^{-2} (LSD test at 5%)

Treatment	Mean	Group
SRI with compost	6.00	A
SRI without compost	6.21	A
SRA with NPK and urea	0.49	B
SRA without fertilizer	0.22	B
Conventional system	0.00	C

When compared to the study we last conducted in Ranomafana in 1998, where the grain yield of SRI plots averaged 7.75 $t.ha^{-1}$, the present experiment produced lower grain yield (Joelibarison, 1997). This could be due to soil texture and structure difference sbetween the two regions (Beforona and Ranomafana). While soil types are more clayey in Ranomafana, they are much sandier and loamier in Beforona. The latter can repress the tillering performance of SRI plants and thus lead to a lower number of tillers bearing grains that affects the grain yield. This drop of grain yield can be as much as 81% for a clayey vs. loamy soil (based on data from Andriankaja, 2001). There could also be an effect from date of planting.[7]

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 SRI plants, grown singly (RPR=49.67 to 55.19 kg), while it averaged 30 to 34.11 for SRA plants, growing in a clump of 2-3, and 20.67 for conventionally grow plants in clumps of 4-6. On a per-plant basis, these differences are 4 to 10 fold.

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.

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[7] The date of planting for these trials was about one month later than usual in the area, due to logistical problems in getting the research started. This could have affected the absolute as well as relative yields but probably affected the SRI trials most, since that method benefits from having time for more profuse tillering before PI. Trials at Beforona the previous year produced an average SRI yield of 10.2 $t.ha^{-1}$ (Raobelison, 2000). SRA yield was 4.5 $t.ha^{-1}$ and conventional yield was 2.2 $t.ha^{-1}$.

Because of spacing differences, however, the root pulling method is not a sufficient or always accurate measure of better rooting. A 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 13: 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

Another reported phenomenon is rice root degeneration in flooded paddy soil. Kar et al. (1974) found that about 78% of roots growing under flooded (hypoxic) soil conditions had degenerated by the flowering stage of the rice plant. We were not able to do any direct measurement on root degeneration, but we measured RPR at three different stages (panicle initiation, anthesis, and maturity) and compared the RPR measure at the anthesis and maturity stages. The spacing effect is not importanthere since the RPR measurement was done on plants with same spacing but at different stages of growth. We found a drop in RPR of only 27% with the SRI plants while the decline was up to 38% for both the SRA and conventionally grown plants. Less root die-back is definitely an advantage for the SRI plants to get better grain yield since the root extension post-anthesis influences nutrient uptake during the critical grain-filling period. This nutrient uptake will be discussed in more detail in a following section.

Table 14: 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

Table 15: ANOVA table of RPR at maturity

Source	Degrees of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	2433	608	13.14	0.001
Error	10	463	46		
Total	14	2896			

Table 16: Group distribution of RPR (LSD test at 5%)

Treatment	Mean	Group
SRI with compost	55.19	A
SRI without compost	49.67	A
SRA with NPK and urea	34.11	B
SRA without fertilizer	30.00	B
Conventional system	20.67	B

Figure 4: Root growth of conventionally grown plant transplanted at 28 days with 3 seedlings/clump (left) vs. root growth of an SRI plant transplanted at 8 days with 1 seedling/clump (right)

Plant nutrient dynamics

The N concentration in foliage decreased from panicle initiation stage until maturity in all of the five treatments (Table 17). This indicates that the rice plants began to translocate their N content into the sink organs for grain formation.

When looking at the evolution of the N foliage concentration from anthesis to maturity, the treatment showing the highest drop of N was with the SRA fertilized rice. Concentration of leaf N decreased drastically. This abrupt N dilution implies that most of the shoot N content at the anthesis stage is remobilized for grain production at a later stage. Such remobilization is undertaken by the rice plant in order to complement the relatively low capacity of the plants to take up N. To some extent the root degeneration, expressed here by a 38% decrease in RPR, impairs the rice plants cultivated with SRA methods in their N uptake. In contrast, SRI non-fertilized plots recorded less steep decrease of the N foliage content with a relatively higher shoot N concentration at the maturity stage. This higher N concentration reflects less remobilization of nutrients to the grains and a better uptake at the later stage (N uptake during the post-anthesis stage was equal to 79.98 $kg.ha^{-1}$).

Table 17: N concentration (%) of the plant at different stages

Treatments	Panicle initiation	Anthesis (straw)	Anthesis (grains)	Maturity (straw)	Maturity (grains)
SRI with compost	1.23	1.08	1.47	0.88	1.51
SRI without compost	1.04	1.12	1.43	0.91	1.59
SRA with NPK and urea	1.14	1.28	1.43	0.90	1.51
SRA without fertilization	1.33	1.09	1.19	0.82	1.35
Conventional	1.17	1.01	1.42	0.83	1.27

Table 18: ANOVA table of straw N concentration at maturity in Beforona trial

Source	Degrees of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	0.022	0.006	0.61	0.67
Error	10	0.092	0.009		
Total	14	0.115			

Table 19: ANOVA table of grain N concentration at maturity in Beforona trial

Source	Degrees of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	0.207	0.052	0.57	0.69
Error	10	0.914	0.091		
Total	14	1.121			

Table 20: P concentration (%) in the plant at different stages

Treatments	Panicle initiation	Anthesis (straw)	Anthesis (grains)	Maturity (straw)	Maturity (grains)
SRI with compost	0.25	0.23	0.27	0.12	0.38
SRI without compost	0.24	0.24	0.26	0.14	0.43
SRA with NPK and urea	0.29	0.26	0.25	0.17	0.39
SRA without fertilization	0.29	0.23	0.25	0.16	0.39
Conventional	0.24	0.22	0.28	0.12	0.35

Table 21: ANOVA table of straw P concentration at maturity in Beforona trial

Source	Degrees of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	0.005	0.001	3.60	0.46
Error	10	0.003	0.003		
Total	14	0.008			

Table 22: ANOVA table of grain P concentration at maturity in Beforona trial

Source	Degrees of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	0.011	0.003	3.82	0.39
Error	10	0.007	0.001		
Total	14	0.017			

Table 23: K concentration (%) in the plant at different stages

Treatments	Panicle initiation	Anthesis (straw)	Anthesis (grains)	Maturity (straw)	Maturity (grains)
SRI with compost	1.77	1.61	0.76	1.44	0.45
SRI without compost	1.90	1.57	0.76	1.39	0.50
SRA with NPK and urea	1.76	1.53	0.68	1.41	0.40
SRA without fertilization	2.07	1.59	0.73	1.29	0.41
Conventional	1.78	1.57	0.80	1.30	0.42

Table 24: ANOVA table of straw K concentration at maturity in Beforona trial

Source	Degrees of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	0.053	0.013	0.21	0.93
Error	10	0.644	0.064		
Total	14	0.697			

Table 25: ANOVA table of grain K concentration at maturity in Beforona trial

Source	Degrees of freedom	Sum of squares	Mean square	F	P-value
Treatments	4	0.019	0.005	4.76	0.02
Error	10	0.010	0.001		
Total	14	0.028			

The pattern of plant N uptake differs for the five treatments, with the highest nutrient uptake recorded from the SRI plots. When breaking down the pattern of N uptake over time, there was a sharp increase of N uptake from anthesis until the maturity stage. Such uptake was efficiently used for grain production.

The SRA treatment showed a different pattern. The NPK-fertilized SRA plots showed a linear relationship for N uptake kinetics. This N uptake trend suggests that SRA and fertilized rice plants rely more on the remobilization of shoot N for their grain production. The lowest uptake occurred with the conventional treatment where N uptake not only varied very little from panicle initiation until anthesis but also its increase at a later stage was relatively low compared to the other treatments. Nutrient uptake in plants cultivated with conventional methods may be constrained by the low root growth (RPR = 22 kg at panicle initiation) and the high root die-back (40% RPR decrease between anthesis and maturity).

Table 26: Total N aboveground uptake (kg.ha^{-1}) of the plant at different stages

Treatments	Panicle initiation	Anthesis	Maturity
SRI with compost	62.38	95.32	176.74
SRI without compost	52.85	79.41	159.39
SRA with NPK and urea	53.01	77.38	133.63
SRA without fertilization	32.16	55.17	122.62
Conventional	20.18	27.87	62.95

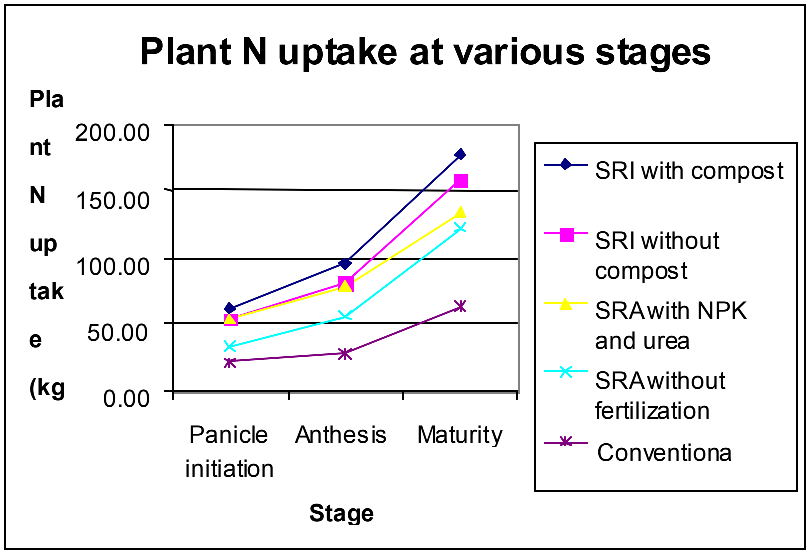

Figure 5: Total aboveground N uptake at different stages of the rice plant

Table 27: Total aboveground P uptake (kg.ha^{-1}) of the plant at different stages

Treatments	Panicle initiation	Anthesis	Maturity
SRI with compost	12.85	19.79	35.89
SRI without compost	11.07	17.61	34.84
SRA with NPK and urea	12.12	16.99	30.08
SRA without fertilization	6.94	11.62	29.24
Conventional	4.16	6.02	13.34

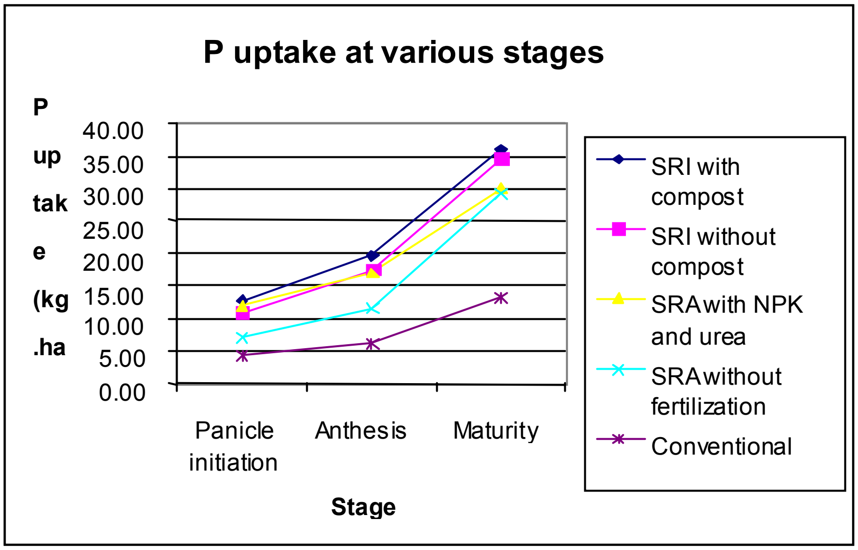

Figure 6: Total aboveground P uptake at different stages of the rice plant

Table 28: Total aboveground K uptake (kg.ha^{-1}) of the plant at different stages

Treatments	Panicle initiation	Anthesis	Maturity
SRI with compost	89.45	125.38	153.33
SRI without compost	87.76	108.21	136.92
SRA with NPK and urea	73.02	93.33	113.37
SRA without fertilization	49.76	75.03	116.17
Conventional	30.98	38.12	55.86

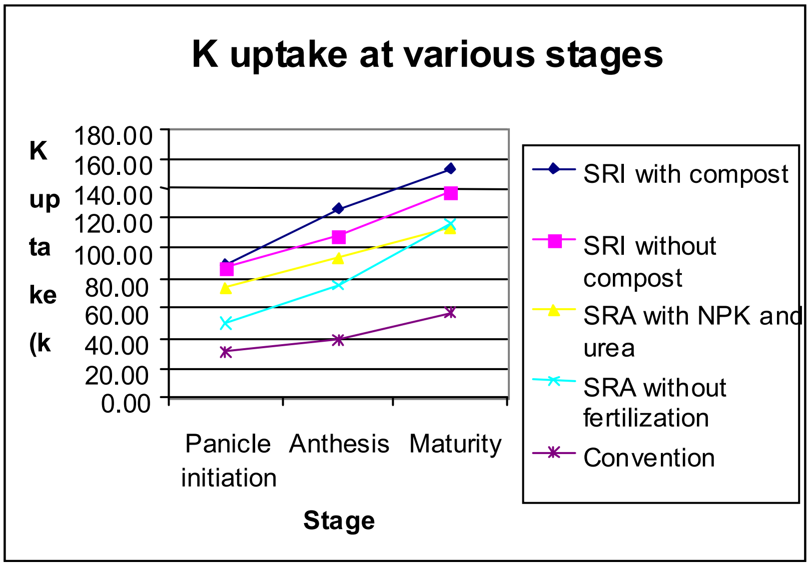

Figure 7: Total aboveground K uptake at different stages of the rice plant

In regard to the P uptake, there is a significant difference of the P uptake along the three different stages with the highest uptake recorded with SRI treatments. The variation of the P uptake is relatively the same for all treatments between the panicle initiation and anthesis stage. SRI treatments, however, showed a rapid and much sharper increase of P uptake from panicle initiation to anthesis. Once the plant was beyond the anthesis stage, its P uptake largely varies as a function of the methods of cultivation. The largest variation occurred in the SRI treatments and the SRA non-fertilized treatment. The true P uptake during the post-anthesis period (P in the plant biomass that comes from the uptake at that given stage) is about 17.62 kg.ha^{-1} for the non-fertilized SRA treatment, 17.23 $kg.ha^{-1}$ for the non-fertilized SRI treatment and 16.11 $kg.ha^{-1}$ for the compost-fertilized SRI treatment.

Such numbers, significantly higher than the 13.1 $kg.ha^{-1}$ for SRA-fertilized treatment, imply a higher capacity of the rice plant to take up the P nutrient with the SRI and non-fertilized SRA treatments. The P uptake for the conventional system, on the other hand, is relatively low throughout the rice season. Its uptake, which is already low at the panicle initiation stage, may be somewhat impaired by its lesser root growth that subsequently leads to a very low P uptake of only about 13.34 $kg.ha^{-1}$.

Regarding the kinetics of K uptake, the evolution of the uptake basically follows that of N and P pattern. Figure 5, 6 and 7 showed that the highest uptake occurred in the SRI plots with plots receiving compost fertilization.

Interestingly, SRA non-fertilized treatments have a lower K uptake at panicle initiation and anthesis than SRA plots fertilized with NPK and urea, but then started to offset the K deficit compared to that of the SRA fertilized plants. In fact, the application of 32 $kg.ha^{-1}$ of K affected the plant K uptake at panicle initiation by a difference of 23.3 $kg.ha^{-1}$. Such higher uptake was, thereafter, offset by the non-fertilized SRA plots with an uptake of about 116 kg K/ha. Compared to the two improved cultivation methods, the conventional method resulted in rice plants with very low K uptake not only in the vegetative phase but also during the later stages of development of the rice plant.

Nutrient-Use Efficiency in the On-Farm Survey

This section focuses on the general concept of the nutrient internal efficiency. Then, a following section presents the estimation of what constitutes balanced nutrient uptake by using the QUEFTS model.

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

A recent trend for breeding more productive rice is to reduce the non-harvestable biomass in order to increase grain yield production. Such an approach is widely known in the scientific community as an increase of the Harvest Index (ratio between grain yield and total biomass), and it 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). Furthermore, recommendations have been oriented to the increase of planting density. We, however, wondered if the increase of tiller number and the reduction of planting density that are 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 30). 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 represents an increase of 218% more than national average grain yield of 2 $t.ha^{-1}$.[8]

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, that with SRI methods was 0.48 (Table 30). When considering the range between the first quartile and the third quartile, 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, the 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

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[8] That farmers in our sample had higher average yield with conventional methods than the national average can be explained partly by the fact that those farmers in it from the Ambatondrazaka area were already using more "modern" methods as part of their standard 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.

g P.g^{-1} for the conventional system (Table 29). 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 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, due to the conjunction effect of soil aeration by water management and early transplantation, which can exploit a greater volume of soil and potentially access greater amounts of nutrients.

Nutrient concentration and uptake by the rice plant

One of the variations that might occur with an increase of grain yield is the dilution of the nutrient concentration of the rice shoot and sink. Regarding nutrient foliage content, plant 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 30). The average straw nutrient content with the conventional system was slightly higher (and significant for both N and P) with a respective accumulation of 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, plant nutrients were not diluted by the higher grain yield production in 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 about 9.89 g N.kg^{-1}, 2.69 g P.kg^{-1}, and 3.54 g K.kg^{-1} for conventional methods. This almost similar N and K concentration in the sink storage while SRI grain yield was significantly higher indicated 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, however, showed that the conventional rice plant is, somewhat, impaired by its poor rooting pattern at the post-anthesis stage of development (Chapter 6, p. 40). Nutrient translocation (ratio between nutrient in the grain and total aboveground nutrients) for both SRI and conventional systems was almost the same with a respective value 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 29). This showed that modification of the management practices could enhance plant uptake by 91% for N and K and 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 possibly conventional plants had 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 and 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 with SRI, and 0.17% N, 9.39 ppm P, and 0.09 cmol(+).kg^{-1} K with conventional rice (Table 29). 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).[9]

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 N2-fixing endophytes within the root cells and in the root rhizosphere might also be present in the SRI plant-soil environment. I did not evaluate N-fixation but hypothesize that the greater uptake is 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 hand. 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).

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[9] 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,

Table 29: 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 30: 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

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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 “work.”

Estimation of the plant aboveground 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.

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 30). Although the nitrogen the N 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, however, noticed with regard to the P use efficiency. Table 31 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 much more evident when seen in the N:P:K ratio (ratio of N to P and K to P). The nutrient ratio for the SRI system – 5.0:1.0:4.9 -- is considerably higher than that of the conventional system -- 3.9 :1.0:4.1.

Breakdown of the regression between N uptake and grain yield of the SRI system and conventional systems, if assumed to be a parabolic relation, 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.

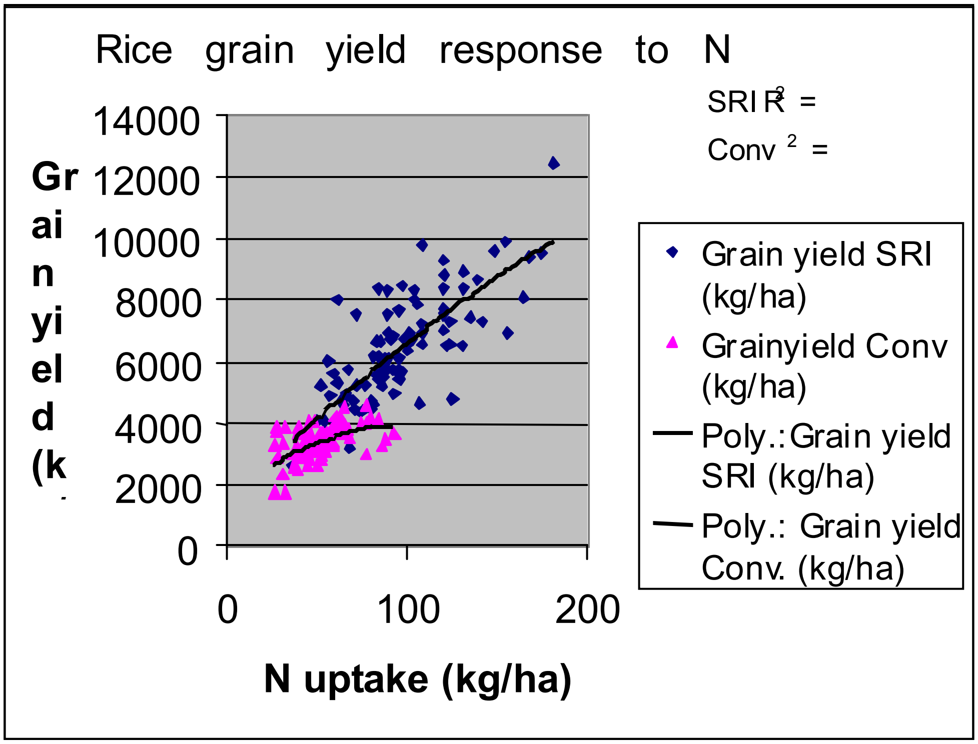

Figure 8: Linear regression relationship between N uptake and grain yield for SRI and conventional methods

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 results, both on-station and on-farm (Chapter 6, Tables 13, 14 and 30), suggest it may be more related to the activity of the root system and its deeper and more extensive proliferation.

Table 31: 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

Development of the QUEFTS Model

Data selection for the QUEFTS analysis

Data from the on-farm survey were collected and assembled in order to elaborate the QUEFTS model. The regions where we collected these data were Ambatondrazaka southeastern side, Ambatondrazaka northeastern side, and Antsirabe. The sample size for Fianarantsoa (N = 11) was too small for use in such regression analysis.

Plant and soil measurements were done in 98 farmers' fields where each farmer was practicing both conventional and SRI systems of rice cultivation. The annual cropping systems differed somewhat in that farmers in Antsirabe cultivate an off-season crop such as potato, peas and vegetables between rice seasons. This practice, widely adopted in Antsirabe, constitutes the main cash source for farmers during the inter-rice season period.

The following procedure has been inspired by the work of Witt et al. (1999) on evaluation of the internal efficiencies of irrigated lowland rice in tropical and subtropical Asia. The first step required for calibration of the QUEFTS model was the estimation of the two borderlines (maximum dilution and maximum accumulation) for N, P and K. Since we only used on-farm data for such purpose, and thus had observational data influenced by exogenous factors (climatic conditions, pests and diseases, variation of soil fertility), an HI of 0.40 was established to be the minimum value for any further analysis. Nutrient uptake resulting in a lower HI was excluded from the data set. In fact, we needed to have a data set in which rice growth was not limited by factors other than N, P and K supply. Since drought, lodging, pests, disease or low solar radiation might impede grain formation, thus lowering HI, excluding cases with HI lower than 0.40 allowed us to minimize the effect of such external conditions.

Once this exclusion was done, the total number of observations for the SRI system was 81 and that for the conventional system was 83. About 46% of the excluded ones for the SRI system had a grain yield over 6.5 $t.ha^{-1}$, while none of the excluded conventional HI cases had yields more than $4t.ha^{-1}$.[10]

Estimation of the envelope of the nutrient uptake-grain yield relationship

Our analyses were based upon a data set with HI>0.40, as explained above. Witt et al. have proposed that an appropriate method for estimation of the two borderlines is effected by excluding the upper and lower 2.5 percentile, to minimize the effect of outlying cases. The maximum accumulation line and the maximum dilution line were thus evaluated in this study by excluding the lower 2.5 percentile and the upper 97.5 percentile. The lower 2.5 percentile represents the line where the given nutrient was only accumulating in the rice plant and other nutrients were limiting its efficient use; the upper 2.5 percentile, on the other hand, represents a line where the nutrient is diluted in the plant and constitutes a yield-limiting factor.

The following envelopes were obtained after elimination of the upper and lower 2.5 percentiles. The coefficients a and d respectively represent the nutrient maximum accumulation and maximum dilution in the rice plant.

Table 32: Constants a and d of the borderlines in the nutrient uptake-grain yield relationship for the SRI system

	a (2.5th)	**d** (2.5th)	r
N	47	106	0
P	178	596	0
K	34	153	0

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[10] This methodological decision thus did not bias the data set toward high-yield SRI cases and low-yield conventional cases.

Table 33: Constants a and d of the borderlines in the nutrient uptake-grain yield relationship for the Conventional system

	a (2.5th)	**d** (2.5th)	r
N	50	142	0
P	185	494	0
K	32	137	0

A quick comparison of the two borderlines of both systems showed that greater variation of IE was observed with conventional system in regard to the N and K elements. Furthermore, the maximum dilution point of the conventional system was much higher. This led us to conclude that while N is somewhat more efficiently used in the conventional system, its higher value suggests that N is more limiting with that system. The existence of such limitation in a system using fertilizer as recommended implied a substantial loss of applied N by leaching, denitrification and other processes.

For comparison, the two borderlines proposed by Witt et al. for tropical and subtropical Asia were aN=42, dN=96; aP=206, dP=622; and aK=36 and dK=115. If we only consider the dilution point for N and P nutrients, we notice a higher d coefficient for N and a lower one for P. This difference is possibly due to the significantly higher use of fertilizers in rice systems of Asia relative to Madagascar. The lower maximum P IE (maximum dilution) for Malagasy rice system is probably due to the significantly lower P contents of the Malagasy soils relative to the Asian soils.

As seen in the above table, the r-values representing the minimum nutrient uptake for producing any measurable grain yield were set to zero. If we consider a minimum nutrient uptake of 3.0, 0.1 and 3.0 for N, P and K, there is a slight difference in the maximum accumulation and dilution borders.

We will, however use the zero r-values for our QUEFTS model since the previous studies done by Witt et al. indicated that the r-values did not affect the nutrient requirement of the plant and the use of such values might underestimate the nutrient IE at a grain yield level less than 3 $t.ha^{-1}$. Once these borderlines are defined, balanced nutrient uptake with the respective IE can be estimated using the QUEFTS spreadsheet as elaborated by Witt et al. (1999).

Table 34: Constants a and d of the borderlines in the nutrient uptake-grain yield relationship for the SRI system

	a (2.5th)	d (2.5th)	R
N	49	110	3.0
P	179	600	0.1
K	35	171	3.0

Table 35: Constants a and d of the borderlines in the nutrient uptake-grain yield relationship for the conventional system

	a (2.5th)	d (2.5th)	R
N	52	158	3.0
P	186	503	0.1
K	33	154	3.0

Evaluation of balanced nutrient uptake

The QUEFTS model predicts the necessary balanced uptake that the rice plant needs to achieve a certain given grain yield. In the present case, besides the prediction of the balanced nutrient uptake, the model will also be used to establish a cross-system comparison between SRI and conventional systema. Prior to any comparison, it is noteworthy to mention that nutrient IE remains constant until the targeted grain yield comes close to the yield potential. Thereafter, the nutrient IE decreases as a function of the increase of the grain yield.

A decrease of IE occurs at a grain yield level of 7,500 kg.ha^{-1} with the SRI system. For grain yields below 7,500 kg.ha^{-1}, the IE curves are linear and nutrients are taken up in balanced ratio of about 4.3 N:1 P:5 K. Our estimation from the QUEFTS model indicated that SRI plant would take up 13 kg N, 3 kg P, and 15 kg K in order to produce 1000 kg of grain , and the corresponding nutrient IE was 77 kg of grain kg^{-1} of N, 347 kg of grain kg^{-1} of P, and 67 kg of grain kg^{-1} of K.

Regarding the conventional system, a decrease of IE occurs at a grain yield level of 3,500 kg.ha^{-1}. In the linear part of the IE curve, the balanced nutrition ratio was about 4 N:1 P:4.7 K. The QUEFTS model predicted an uptake of 12 kg N, 3 kg P, and 14 kg K for producing 1000 kg of grain yield with a corresponding IE of 84 kg of grain kg^{-1} of N, 328 kg of grain kg^{-1} of P, and 74 kg of grain kg^{-1} of K. This figure reflects that for the same grain yield, the uptake of N and K in conjunction with the uptake of a unit of P is less in the conventional system. This widening of the N:P and K:P ratio from, respectively, 4:1 and 4.7:1 to 4.3:1 and 5:1 indicated that P supply was a major yield constraint for the conventional system. SRI rice appears to access a higher amount of P, likely through its better root development and/or greater supply of P due to flooding/draining, thus removing this as a yield-limiting factor.

SRI appears to be successful because its nutrient uptake balance ratio is higher than that of the conventional system. This higher ratio uptake indicated that SRI plant is capable of performing under relatively very poor soil conditions such as those found in much of Madagascar (average nutrient content of both the SRI and conventional plots: 0.17% N, 8.94 ppm P-Olsen, and 0.08 cmol(+)/kg K).

Tables 36 and 37 showed that the nonlinear range of the grain yield-nutrient uptake relationship occurred at a much lower nutrient uptake level with the conventional system. Its rice plants could only take up the nutrients in a ratio of 4N: 1P: 4.7K until the grain yield level reached 3,500 t.ha^{-1}. Thereafter, the internal efficiency declined due to the lower capacity of the plant to take up nutrients in a balanced manner. The worst case occurred at the highest yield level of 5,000 t.ha^{-1} where the IE of N, P and K were reduced by 42%. It indicated that there was a rapid alteration of the IE with the conventional system while this occurred with the SRI system only at a yield level of 7,500 kg.ha^{-1}. This rapid alteration of the IE with conventional system was mainly due to the inability of the aboveground canopy to keep pace with the increasing demand of nutrients for grain production. In other words, the higher amount of N needed to produce 1000 kg of grain with SRI (13.6 kg N, 3.0 kg P, and 15.8 for K kg SRI vs. 12.6 kg, 3.2 kg P, and 14.1 kg K) likely resulted to a lower capacity of the shoot to comply with the nutrient requirement of the sink organs. Moreover, the early decrease of the IE could also be interpreted as a result of one or more nutrients limiting the efficient use of the given nutrient for better grain production.

Table 36: Estimation of balanced nutrient uptake for the SRI system of cultivation

Grain yield ($kg.ha^{-1}$)	Required nutrient uptake			Internal efficiency		
	$kg.ha^{-1}$	$kg.ha^{-1}$	$kg.ha^{-1}$	$kg.kg^{-1}$	$kg.kg^{-1}$	$kg.kg^{-1}$
1000	13	3	15	77	347	67
2000	26	6	30	77	347	67
3000	39	9	45	77	347	67
4000	52	12	60	77	347	67
5000	65	14	75	77	347	67
5500	72	16	82	77	347	67
6000	78	17	90	77	347	67
6500	85	19	98	76	344	66
7000	93	21	107	75	341	66
7500	102	23	117	73	331	64
8000	114	25	130	70	319	61
8500	126	28	145	67	304	59
9000	142	31	163	63	286	55
9500	164	36	188	58	262	51
9600	169	37	195	57	256	49
9800	184	41	212	53	240	46
9900	196	43	225	51	228	44
10000	255	56	293	39	117	34

Table 37: Estimation of balanced nutrient uptake for the conventional system

Grain yield ($kg.ha^{-1}$)	Required nutrient uptake			Internal efficiency		
	$kg.ha^{-1}$	$kg.ha^{-1}$	$kg.ha^{-1}$	$kg.kg^{-1}$	$kg.kg^{-1}$	$kg.kg^{-1}$
1000	12	3	13	85	325	74
2000	24	6	27	85	325	74
3000	36	9	40	85	325	74
3500	43	11	49	81	314	72
4000	53	14	63	76	292	67
4500	66	17	75	68	262	60
4600	70	18	79	66	254	58
4800	79	20	90	61	235	54
4900	86	22	97	57	220	50
5000	102	27	116	49	188	43

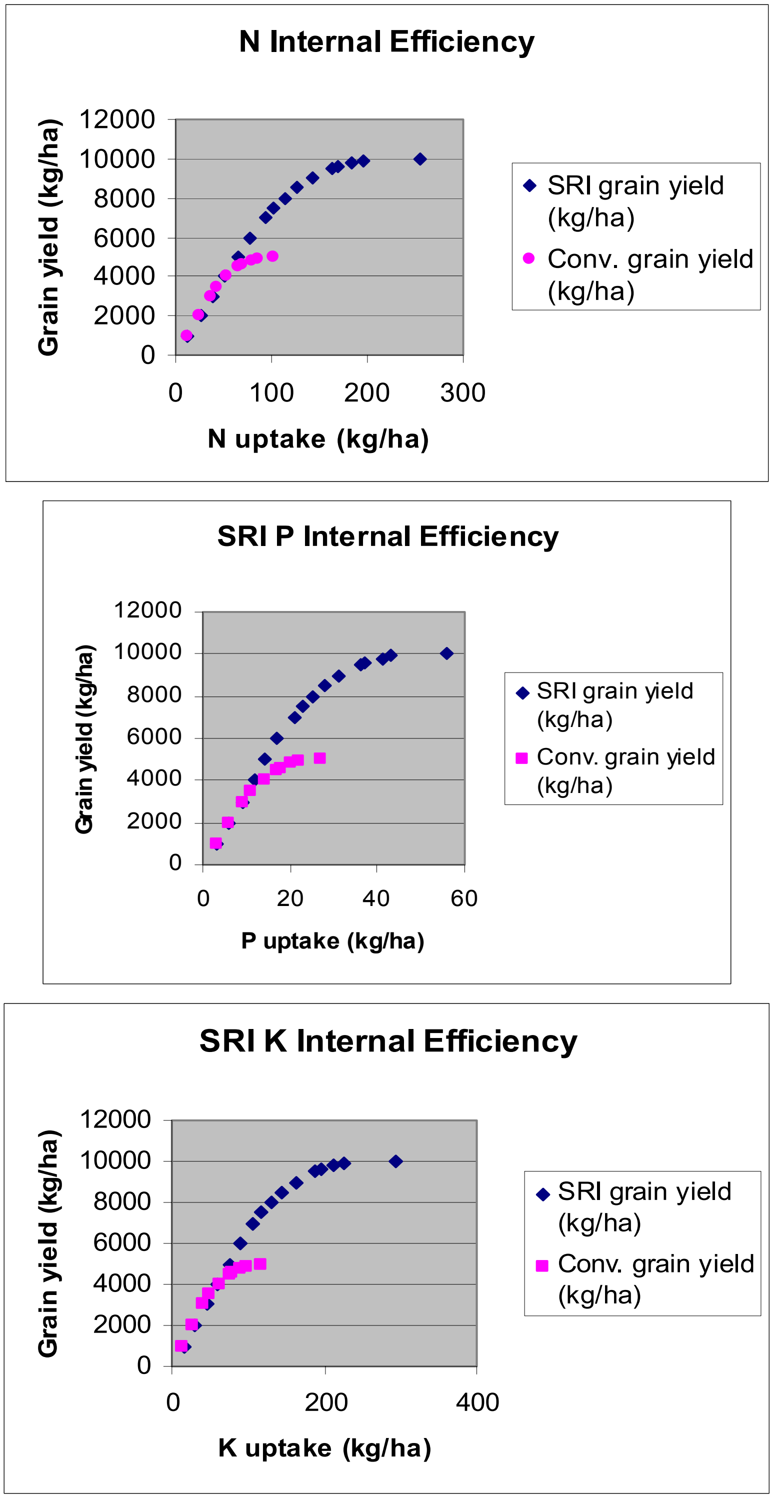

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Figure 9: Estimation of balanced N, P and K uptake for given grain yield for the SRI and conventional systems

Site variation for nutrient uptake and internal efficiency

Internal efficiency varied significantly along the regions of study. For instance, the average IE of SRI plants in Ambatondrazaka was 70.59 kg grain.kg^{-1} N, 345.1 kg grain.kg^{-1} P, and 82.14 kg grain.kg^{-1} K, while that of conventional plants was 78.98 kg grain.kg^{-1} N, 268.37 kg grain.kg^{-1} P, and 81.58 kg grain.kg^{-1} K. One can see that the P element was used more efficiently for grain production in SRI, as each unit kg of P taken up by the rice plant cultivated with SRI methods produced about 78 kg more grain.

Further consideration of the IE in Antsirabe region indicated an average IE of 66.07 kg grain.kg^{-1} N, 352.1 kg grain.kg^{-1} P, and 41.84 kg grain.kg^{-1} K for the SRI system, and 67.26 kg grain.kg^{-1} N, 343.4 kg grain.kg^{-1} P, and 45.16 kg grain.kg^{-1} K for the Conventional system. Soil analyses (0.21% N, 9.14 ppm P-Olsen, and 0.14 cmol(+).kg^{-1} K with SRI, and 0.20% N, 10.64 ppm P-Olsen, and 0.15 cmol(+).kg^{-1} K with conventional system) showed that despite the higher soil P content for the conventional rice plots, plants cultivated with SRI methods used the P element for grain production more efficiently.

Great variation was also observed in the nutrient uptake of SRI and conventional systems. Average nutrient uptake in Ambatondrazaka was about 99.93 kg N.ha^{-1}, 23.19 kg P.ha^{-1}, and 96.86 kg K.ha^{-1} for SRI, and 50.09 kg N.ha^{-1}, 13.73 kg P.ha^{-1}, and 47.32 kg K.ha^{-1} for the conventional system. Average nutrient uptake in the Antsirabe region, however, was about 85.55 kg N.ha^{-1}, 17.22 kg P.ha^{-1}, and 136.04 kg K.ha^{-1} for SRI, and 49.75 kg N.ha^{-1}, 10.27 kg P.ha^{-1}, and 78.83 kg K.ha^{-1} for the conventional system. Both numbers when seen on a region level reflected that N and P uptake varied very little in the conventional system (50.09 vs. 49.75 kg N.ha^{-1}, and 13.73 vs. 10.27 kg P.ha^{-1}) while greater variation was recorded with the SRI system (99.93 vs. 85.55 kg N.ha^{-1}, and 23.19 vs. 17.22 kg P.ha^{-1}).

SOCIO-ECONOMIC FACETS OF SRI

Rationale Behind the System

Madagascar as a country with rice as its staple food has been orienting its rural development policy to the improvement of rice-based farming systems since its independence in 1960. Several rice extension programs have been undertaken in order to improve rice yield. In-row transplantation, chemical fertilizer application, use of HYVs, direct seeding with pesticide application have all been recommended. However, the average national grain yield increased only by 15% from 1960 to 1989 (less than 0.5% per year) and thereafter it has stagnated at 2.1 $t.ha^{-1}$ (FAO, 1998).

Technical changes, commonly known as the “Green Revolution,” helped farmers to increase their grain yield during the time when subsidies on chemical fertilizers and pesticides were still supplied. Farmers were able to afford the use of fertilizers, and the adoption of new high-yielding varieties in conjunction with substantial application of chemical fertilizers led to definite increases in grain yield. Grain yield went from 1.5 to 2.9 $t.ha^{-1}$ on the high plateau and the east coast due to the action of a national agency for the extension of chemical fertilizer use. GOPR.

Subsidies were, however, removed when French assistance was withdrawn from Madagascar. When farmers were exposed to the real price of ‘modern’ inputs, they were unable to afford the use of chemical fertilizer. In addition, an absence of institutional credit led farmers to return to their conventional rice cultivation practices.

Thereafter, farmers were not able to keep pace with the rapid and dynamic changes of the agricultural systems anymore. They, instead, preferred to continue practicing their conventional methods of cultivation and only adoptrf and experimented with a few of the Ministry of Agriculture (MOA) recommendations.

Another important reason that constrained the Green Revolution in Madagascar was the relatively low performance of the HYVs on farmers fields, mainly because farmers were not able to purchase chemical fertilizer and pesticides. Poor peasant farmers, with very limited financial resources, were, thus, without means to get benefits from the Green Revolution.[11]

A search of technologies that could respond to such a situation of limited financial resources and thus rely less on external resources was thereafter urgent. When SRI first emerged in 1984, it was proposed as an alternative for increasing grain production.

While national grain yield was still averaging $2 t.ha^{-1}$, the System of Rice Intensification has been able to double or triple the grain production for its adopters. This great yield increase was not the effect of heavier application of inputs but instead the result of a different management approach. Explicitly, it relies less on the application of chemical fertilizer or pesticides but capitalizes on the internal potential of the rice plant (tillering and grain filling) in conjunction to the use of compost. The system, therefore, provides advantages for farmers who have very limited financial resources and want to increase their grain production in the short term. In the medium to long term, significantly higher yields will result in greater nutrient exports and will require nutrient inputs (organic and/or inorganic) to offset the increased nutrient exports.

Once farmers start adopting the system, they have to fine-tune it to their specific agroecological environments. This fine-tuning is possible since the system comprises a flexible set of principles rather than set package of technical practices to be used exactly as recommended. With SRI, farmers are asked and expected to do some

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[11] How well suited the HYVs themselves were to the mostly poor and highly varied soil conditions of Madagascar, not all easily remedied by application of inorganic fertilizer, could not be known since they were seldom used on farmers fields with all the recommended inputs and practices.

experimentation and modification varying the recommended practices so as to apply SRI principles to their own local conditions.

Grain Yield Production with SRI and Conventional Systems

Table 38 shows that the average yield on SRI plots were 6.36 $t.ha^{-1}$ whereas from conventional plots it was 3.37 $t.ha^{-1}$. It indicates that changes in management practices with the SRI cultivation system could lead to a doubling of the conventional grain yield.[12]

A breakdown of grain yield by regions (Antsirabe and Ambatondrazaka) indicates some regional differences in the rice yield for both SRI and conventional systems. The major difference occurred with SRI grain yield which averaged 5.47 $t.ha^{-1}$ in Antsirabe and 6.73 $t.ha^{-1}$ in Ambatondrazaka. The difference on the conventional grain yields remained fairly small, with 3.20 $t.ha^{-1}$ in Antsirabe and 3.43 $t.ha^{-1}$ in Ambatondrazaka.

Table 38: Regional distribution of SRI and conventional grain yields

	Grain yield ($t.ha^{-1}$)	
	Conventional	SRI
Both areas: Antsirabe and Ambatondrazaka	3.36	6.36
	Regional variation	
Antsirabe	3.20	5.47
Ambatondrazaka	3.43	6.73

Possible Limits and Constraints for Farmers

One of the objectives of the present study was to identify any possible bottlenecks that hinder the extension of the system and its spread among farmers. An often mentioned

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[12] As noted above, few of the farmers were putting compost on their SRI plots and were still getting nearly as high a yield from just the other methods. The regression analysis reported below shows in fact a doubling of yield with SRI methods when used under these farmers' field conditions.

constraint is the greater labor requirements of the SRI system. Some studies have suggested that SRI requires about 72% more labor than the conventional system and this constrains farmers who have limited labor availability (Razafimahery, 1996).

Our findings indicated that one of the obstacles for the adoption of the system was the lack of efficient irrigation and drainage facilities. One-third of the farmers surveyed in our study mentioned that water control was the main constraint in their system of cultivation. These farmers asserted that they either were not able to irrigate or to drain their rice field at a desired time.

In fact, almost all of the lowland rice fields in Madagascar have been constructed to capture and hold water. They are surrounded by elevated bunds and irrigation water moves from field to field. Farmers possessing rice fields located farther from the source have to wait until their neighbors closer to the water source are fully satisfied with the amount of water in their rice fields. This situation renders the possibility of alternate irrigation and drainage at specific times very difficult, and most farmers are not able to keep their soil wet but unsaturated during the vegetative growth period. There are even worse cases where farmers have to rely upon rainfall in order to start their rice calendar. In such cases, farmers are totally exposed to the irregular distribution of the rainfall, and their rice fields are prone to either waterlogging or severe drought. In either case, SRI success is endangered by irregular plant growth through the vegetative period. Furthermore, very young transplanted seedlings are also more susceptible to damage from submergence than are older seedlings.

Another obstacle facing farmers is the availability of adequate labor at the right time. This high seasonality of labor input has been often mentioned as one of the main obstacles in technological change in African agriculture (Delgado and Ranade, 1987). The most labor-requiring period for rice cultivation, and especially for SRI, occurs at the beginning of the growing season, when farmers normally face a major rice deficit (this time of hunger is known as the *soudure* period). During this period, family decision-makers prefer allocating household labor to activities with an immediate cash return (income) such as working as hired labor. This labor allocation preference constitutes an obstacle for some farmers, particularly the poorest, to adopt the SRI.

A third obstacle that might keep farmers from practicing the system is the perception of risk. Most farmers are risk-averse and prefer keeping their current farming systems instead of adopting any new, untried technology (Hardacker et al., 1997). In Madagascar, farmers are used to planting many rice seedlings together per clump, up to half a dozen, with a close spacing between clumps. This seems to assure them that if some seedlings die, at least a few will survive in each clump. When transplantation of single seedling per clump with much wider spacing is advised, farmers conceive of such recommendations as a waste of space and believe that it is when to transplant only one seedling per clump. This conception becomes an even greater concern when farmers see the appearance of a still almost bare field during the first weeks after transplantation.

SRI Labor Requirements and Productivity of Labor

Labor requirements have often been mentioned as the main hindrance in the extension of the SRI system. Data from Razafimahery (1996), Association Tefy Saina (1992) and Rakotomalala (1998) indicated that conventional system requires about 213 persondays/ha while SRI requires about 366 persondays/ha. These numbers suggest a 72% increase in labor requirements with the SRI system.[13]

An analysis of SRI labor requirements shows that the most demanding activities are field leveling, transplanting, and weeding. First, leveling is crucial for the system since an uneven rice field may lead to an accumulation of water and subsequently risks

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[13] These data also indicate that labor requirements are higher in the first and second years of SRI practice, and that labor expended per hectare comes down once greater skill and confidence have been gained in using the methods. The 72% figure appears rather too high as an average, though it could apply with the first use of SRI techniques. Some farmers in Madagascar assert that their labor requirements per hectare are actually reduced over time to less than conventional methods, and this is reported by some farmers in Sri Lanka too. But we do not have enough longitudinal data to confirm this conclusion which, if correct, will eventually be an additional reason for farmers to accept SRI..

washing away the rice seedlings right after transplanting. Regarding transplantation, this has been cited as the main labor constraint for farmers. Many mentioned that while transplantation for the conventional system only requires one laborer, SRI requires up to three laborers with two holding the strings need to space seedling evenly and precisely while the third plants the seedlings. While most farmers are using this transplanting technique, some farmers already have made a technical advance on the system and are now using less labor for the planting. This is possible use of a "*rayonneur* (wooden rake) to trace evenly spaced lines in perpendicular directions on the muddy surface of a prepared field. This enables transplanters to put seedlings into the soil quickly at the intersection of the lines.

Besides transplanting, our study showed that weeding is also a time-requiring activity (Table 41). This does not, however, constitute as much of a constraint for peasant farmers, except where access to the hoe is lacking, since the weeding period does not coincide with the peak period of demand for labor.

Overall, our survey in Ambatondrazaka, Antsirabe and Fianarantsoa showed the average total labor requirement of SRI management practice is about 246.8 persondays/ha while that of the conventional system is 192.7 persondays/ha. These numbers indicated that the SRI system requires on average only about 28% more labor, which is well compensated by a doubling of grain production, and sometimes more.

An important way to compare the performance of two methods of cultivation is their respective returns to labor over the growing season. For SRI, the return to labor is about 23.64 kg of rice/man-day. This was much more than to labor used with the conventional system, which yielded only 14.98 kg of rice/man-day, 37% less.

Assessing the Constraint of Labor Use on SRI Adoption

Labor requirements are highly seasonal, and the most labor is required at the beginning of the growing season (Tully, 1990). When the labor use was evaluated throughout the growing season, the period of peak labor occurs in October and November for Antsirabe and December and January for Ambatondrazaka (Tables 39 and 40).

Table 41 indicates that transplanting activity with SRI sysem requires up to 23% of the overall labor input, while with the conventional system, transplanting takes only 15% of the labor. Most of this work occurs in October in Antsirabe and in December in Ambatondrazaka, creating higher labor use during these periods (Tables 39 and 40).

When labor distribution is assessed along with the rainfall distribution, a strong positive correlation is noticed. It appears that most farmers rely upon the onset of rain to be able to cultivate their rice fields. Once the rain comes, they start the soil preparation (plowing, puddling and so forth) and then transplanting the seedlings. The result is an accumulation of labor needs during the first two months after the onset of rain.

Table 39: Distribution of SRI labor input and rainfall in Ansirabe, 1990-99

Month	Distribution of labor (in percent of labor/ha)	Distribution of rainfall (in mm)
July	0	8.70
August	0	4.78
September	5	20.24
October	38	74.02
November	31	116.18
December	13	194.60
January	1	345.22
February	1	225.38
March	1	163.57
April	3	102.54
May	6	23.74
June	0	5.24

Table 40: Distribution of conventional labor input and rainfall in Ambatondrazaka, 1990-99) in Ambatondrazaka

Month	Distribution of labor (in percent of labor/ha)	Distribution of rainfall (in mm)
July	0	16.96
August	0	4.99

September	0	13.64
October	4	35.28
November	6	28.13
December	36	198.29
January	30	319.98
February	16	227.04
March	2	126.60
April	2	33.75
May	4	13.33
June	0	7.30

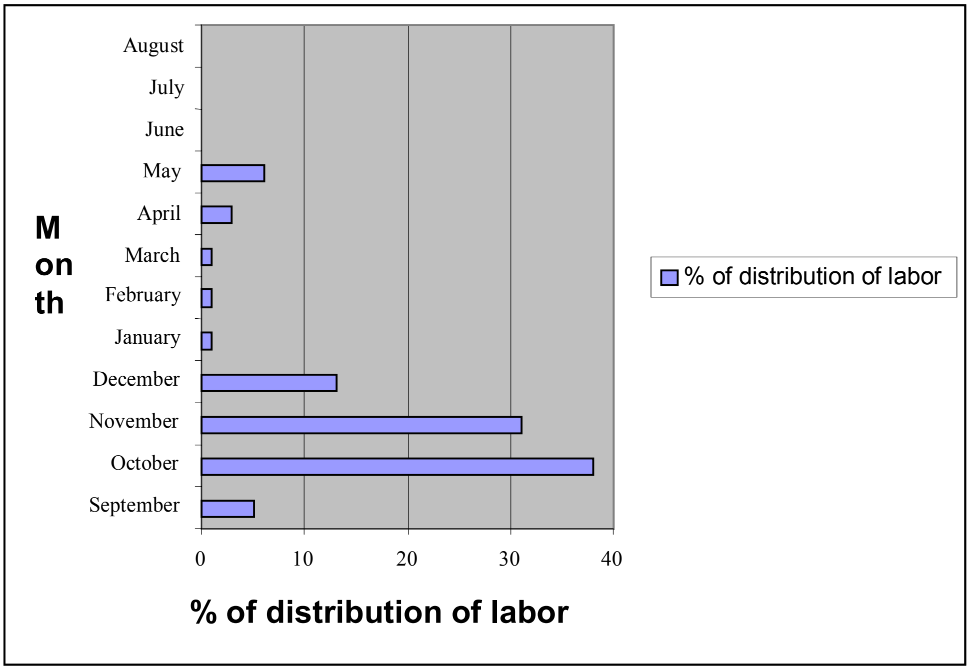

Figure 10: Distribution of the labor engaged with SRI (in percent of labor/ha)

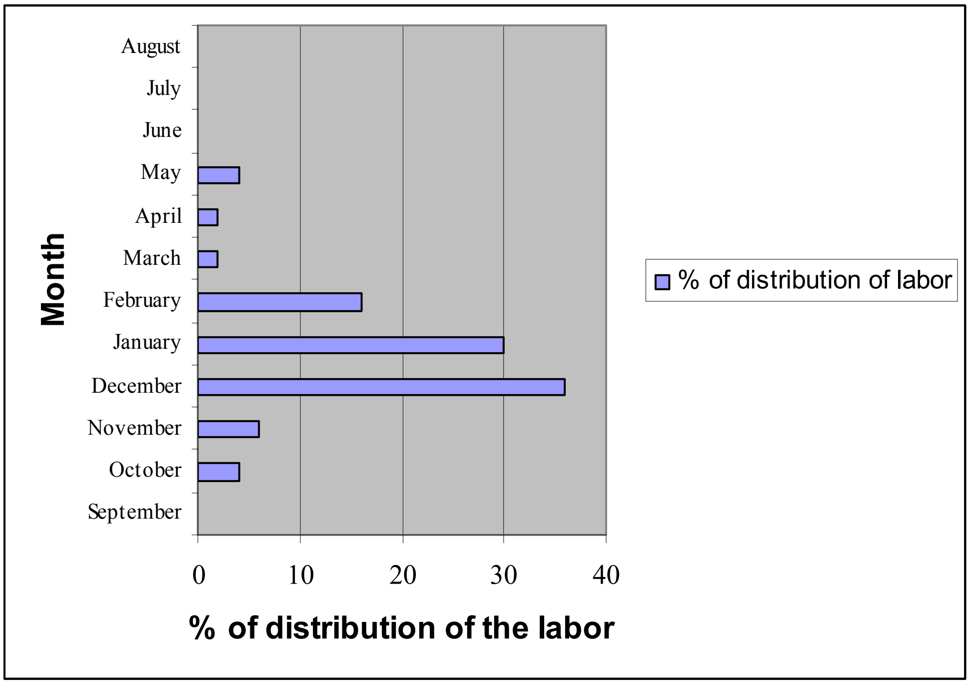

Figure 11: Distribution of labor engaged with conventional system (in percent of labor/ha)

Since our main concern is to identify possible barriers that farmers might encounter for adopting the system, the above figure needs to be complemented by the allocation of labor at the household level and the period of rice shortage (*soudure*). About 85 over the 109 sampled farmers relied on hired labor for their transplantation activity. This number showed that there was higher dependence on hired labor at the period of transplantation. This relatively high dependence on hired labor is likely due to the displacement of the labor of some farmers.

This reflects also the eagerness of some farmers to work as hired laborers during the period of peak labor. In fact, this eagerness was mainly due to the fast cash preference of farmers during that period. Most of the farmers were already going through a period of rice shortage, starting generally from October, and they would therefore allocate their labor to an income-generating activity that gives quicker if not necessarily larger returns, e.g., hired labor, rather than to working on their their own rice field. This allocation preference to some extent constitutes a hindrance for the wider adoption of the system.[14]

Table 41: Labor requirement and allocation of labor throughout the rice-growing season with conventional and SRI systems

Activity	Period	CONVENTIONAL		SRI	
	Based on a normal season, October through April	Labor requirement (manday/ha)	% of labor allocated for each activity throughout the season	Labor requirement (manday/ha)	% of labor allocated for each activity throughout the season
Compost/fertilizer application	October	16.91	9	17.43	7
Plowing	November	26.36	14	26.07	11
Irrigation before puddling	November	4.13	2	2.95	1
Puddling	November	17.47	9	21.72	9
Leveling	November	13.92	7	18.51	8
Nursery	November	13.74	7	8.81	4
Transplantation	November	29.41	15	56.96	23
Water control	November-January	6.68	3	7.68	3
Weeding	November-January	40.13	21	62.13	25
Guarding	March	9.00	5	9.91	4
Harvest	March-April	14.95	8	14.63	6
Total labor use		**192.7**	**100**	**246.8**	**100**

Multivariate Analysis of SRI and Conventional Grain Yields

Empirical Settings

Comparison of the performance of one system compared to others has often been done by only considering one single factor involved in the production function. The

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[14] However, an analysis of how to optimize household returns and well-being from available resources would recommend that farmers who have a labor constraint -- not enough labor to cultivate their whole rice area at the appropriate time with SRI methods -- use such methods even on just part of their field, becauwe this will give higher returns to their land, labor, water and capital. As discussed here, possibly they are too cash-short to make such an investment. In such a case, government or other provision of consumption loans at a non-usurious interest rate, enabling poor farm households to benefit from SRI methods, would help to move them out of poverty through their capitalizing on their own productivity gains.

commonly used variables are the unit of area cultivated and amount of labor, and performance is based upon the productivity per unit are and/or per unit of labor.

There are, however, several other variables included in the production function that might likewise influence the grain production of a system of rice cultivation. Soil fertility, climatic conditions and level of education of the farmers are, for instance. variables that can alter or promote crop production.

Since we only limited size, we will limit our analysis of the production function to consideration of regional variation, the type of system of cultivation, soil fertility, the level of farmers' education, and labor requirements. Grain yield as the dependent variable was plotted against these five independent variables.

The following model was used in our production function:

$$Y_i= \beta_0+ \beta_1X_{1i}+ \beta_2X_{2i}+ \beta_3X_{1i}X_{2i}+ \beta_4X_{3i}+ \beta_5X_{4i}+ \beta_6X_{5i}+ \beta_7X_{6i}+ \beta_8X_{7i}+ \beta_9X_{8i}+ \beta_{10}X_{9i}+ \varepsilon_i$$

Where β_0, β_1,..., β_8 and β_9 are the regression coefficients,

and ε_i is the error term

X_{1i} represents the region delimitation dummy variable, with

- X_1=1 for the region of Antsirabe, and
- X_1=0 for the region of Ambatondrazaka.

X_{2i} represents the system of cultivation dummy variable, with

- X_2=1 for conventional system, and
- X_2=0 for SRI system

X_{3i} and X_{4i} represent the soil fertility dummy variable, with

- X_3=1 for poor soil,
- X_4=1 for medium soil, and
- X_3=X_4=0 for rich soil

X_{5i}, X_{6i}, X_{7i} and X_{8i} represent the level of farmers' education dummy variable, with:

- X_5=1 for illiterate farmers,
- X_6=1 for farmers having education up to elementary school,

- X_7=1 for farmers having education up to secondary school,
- X_8=1 for farmers having education up to high school, and
- X_5=X_6=X_7=X_8=0 for farmers having an education beyond high school

X_{9i} represents the labor requirement.

Production Function

MINITAB was used in order to estimate the production function using the five mentioned explanatory variables.

Table 42: Regression estimates of production function in kg.ha^{-1}

Variables	Equation coefficient	P-value
Constant	6,096	0.000
Region delimitation: Antsirabe	-1,728	0.000
System of cultivation: Conventional system	-3,127	0.000
Interaction between region and system (cross-region comparison)	1,055	0.023
Soil fertility: poor soil	-443	0.078
Soil fertility: medium soil	-327	0.161
Level of education: illiterate	678	0.253
Level of education: elementary school	80	0.814
Level of education: secondary school	58	0.861
Level of education: high school	-118	0.732
Labor	4.76	0.022

Grain yield, rice cultivation and soil fertility

Many would assume that SRI performance is perhaps related to practicing SRI on more fertile soils. Our results, however, failed to support this assumption. Variation of the grain yield was not significantly associated with differences in soil fertility (based on available soil P). This implies that the high yield obtained with SRI was not the effect of better soil fertility.

The negative sign of the fertility coefficients, despite the non-significance of the fertility factor, reflects, however, the expected tendency of overall grain yield to decrease in parallel with a decrease of soil fertility.

When the grain yield was considered with respect to the system of cultivation, a significant difference was noticed between SRI and conventional practices. The regression equation indicated that SRI was far more beneficial in terms of grain yield than was the conventional system, giving a 3,127 kg.ha^{-1} additional grain production. The 95 percent confidence interval for this grain yield increase was comprised between 2,662 kg.ha^{-1} and 3,592 kg.ha^{-1}.

With all other factors remaining equal, given the circumstances and practices of the farmers in this sample, SRI methods produce 6,096 kg.ha^{-1} while those of the conventional system would yield 2,969 kg.ha^{-1}. These numbers clearly showed that a change of management practices by using SRI methods led to a doubling of the grain yield on average, even for farmers already getting more from conventional methods than do most of their countrymen, and without using the full recommended set of SRI practices.

Grain yield and regional variation

When broken down by regions, our results indicated that when SRI and conventional systems are used on plots with the same soil fertility, SRI grain yield was about 3,127 kg.ha^{-1} higher in Ambatondrazaka, and 2,072 kg.ha^{-1} in Antsirabe, in comparison to conventional methods. These additional grain yield increases, once the soil fertility effect was controlled, reflected the pure effect of different management strategies with the SRI system.

Regional variation of grain production was also observed. SRI grain yield was higher in Ambatondrazaka with an additional 1,728kg of rice/ha there compared to Antsirabe. Such a yield difference is altered to 673 kg of rice/ha when a cross-region comparison of the conventional system was made, between Ambatondrazaka and Antsirabe. The relatively higher grain yield around Ambatondrazaka indicates that farmers in this area already have a better mastery of the conventional techniques. In fact, farmers around Ambatondrazaka have already gone through several programs of rice intensification, and they are more attuned to making changes in agricultural systems.

Grain yield and level of education

Schultz (1964) showed the importance of farmer's education in the increase of the crop productivity. He suggested that there is a significant positive relationship between education and crop productivity. While several studies have confirmed this finding, there are also some studies which did not find any direct relationship between education and crop productivity.

Our results found no significant direct relationship between the level of education of farmers (illiterate, elementary school, secondary school, high school, or beyond high school) and their grain yield. Interestingly, the marginal increase of grain yield declines as the level of a farmer's education increases. Such observation might suggest that farmers with a higher level of education pay less attention to their rice cropping systems because they rely more on off-farm income to meet food and other household needs.

System of cultivation and cost of production

An evaluation of the cost of production showed that SRI requires about 24% more investment than the conventional system. The increase of investment is mostly the result of the higher labor use at the beginning of the growing season (transplanting) and at the weeding time. The increase of the labor cost with the SRI system was about 28%, and this was similar to the increase of the overall cost of production. Interestingly, there was a significant decrease of the seed cost, by 728%, due to the lower use of seed with the SRI system.

The cost of production itself was about 1,326,150 Fmg/ha for SRI and 1,066,438 Fmg/ha for the conventional system. Despite this higher cost, the higher yield increase with SRI more than compensated for the additional cost. The additional investment of 259,712 Fmg/ha was easily much less than the 2,947,000Fmg/ha increase in revenue. An increase of 142% of the revenue was observed with the SRI system. On the other hand, an analysis of grain yield produced per Fmg invested showed that SRI provided great advantages to peasant farmers. The earned 4.40 kg of rice grain/1000Fmg invested with SRI compared with 2.71 kg/1000Fmg when investing in conventional cultivation. This represents a 63% increase in returns to capital.

Table 43: Cost of production, total revenue, net revenue, return to labor and grain yield return to investment of conventional and SRI systems

	Conventional system	SRI system	% difference
Fertilization cost (Fmg/ha)	24,819	82,762	+233%
Seeds cost (Fmg/ha)	78,119	9,438	-728%
Labor cost (Fmg /ha)	963,500	1,233,950	+28%
Total cost of production (Fmg/ha)	1,066,438	1,326,150	+24%
Revenue in Fmg/ha (at a market price of 1,000 Fmg/kg)	2,887,000	5,834,000	+102%
Net revenue (Fmg/ha)	1,820,562	4,507,850	+148%
Returns to labor (Kg rice/labor)	14.98	23.64	
Returns to labor (Fmg/labor)	14,980	23,640	
Grain yield return to investment (Kg grain/1000Fmg)	2.71	4.40	

Chapter 8

CONCLUSIONS

Results from both our on-station experiment and on-farm survey have shown a significantly better performance of the SRI relative to the conventional rice system 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.[15]

Two important conclusions are supported by this study. Despite higher 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.

An estimation of N, P and K uptake using the QUEFTS model showed that grain yield increased linearly with the nutrient uptake until a grain yield level of about 7,500

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[15] 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.

$kg.ha^{-1}$ under SRI, while the linear relationship between grain yield and nutrient uptake occurred only up to a grain yield level of about 3,500 $kg.ha^{-1}$ with the conventional system. This rapid decline of grain yield in relation to nutrient uptake for plants cultivated under the conventional rice growing method suggested that limitations on one or more nutrients in the plant cells constrained the efficient use of other nutrients.

In any case, the attainment of higher yield with the SRI cultivation method 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, probably 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 method suggests greater activity of nitrogen-fixing bacteria such as N2-fixing endophytes within the root cells and in the SRI rhizospheres.[16]

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.[17]

In our evaluation of the socio-economic aspect of SRI and conventional methods, a multivariate analysis of the production function in relation to the region of production, type of cultivation system, soil fertility, level of education of the head of the household, and labor use, showed that the *ceteris paribus* SRI grain yield of 6,096

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[16] 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.

[17] 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).

$kg.ha^{-1}$ was significantly higher than the conventional grain yield, which was only about 2,969 $kg.ha^{-1}$. Furthermore, regional differences in grain yield were observed in our survey.

Despite the high SRI grain yields observed and calculated, the extension and adoption of SRI cultivation methods has been relatively slow in Madagascar Our socio-economic evaluation of the SRI and conventional systems suggests that three main constraints to the adoption of the SRI cultivation method: (1) the field-to field irrigation system is a major constraint for farmers who need to irrigate and drain their fields at frequent specific stages of crop growth; (2) the seasonality of labor demand resulting in certain peaks in demand during the first part of the growing season when the supply of labor is relatively inelastic; and (3) perceptions of risk in planting very small, young rice seedlings, given the risk-averse character of most farmers when it comes to adopting new technologies.[18]

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[18] Some farmers are finding that the SRI methods when properly used give rice plants more resistance to drought and to pest and disease damage. So this latter consideration is likely to recede as farmers gain more experience with SRI. Investment in irrigation infrastructure, credit schemes to enable poor farmers to tide over the hunger season, and fostering social organization and cooperation could mitigate the first two constraints, enabling farmer households and the country as a whole to benefit from the opportunities presented by SRI that have been documented here in agronomic terms.

APPENDIX A

Regression Analysis: Grain yield versus region, system of cultivation, soil fertility, level of education of the farmers, and labor inputs

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The regression equation is
Rdt = 6096 - 1782 X1 - 3127 X2 + 1055 X1*X2 - 443 X3 - 327 X4 + 678 X5 + 80 X6
          + 58 X7 - 118 X8 + 4.76 Lab Req

179 cases used 17 cases contain missing values

Predictor        Coef     SE Coef          T        P
Constant       6095.6       515.9      11.81    0.000
X1            -1781.6       389.8      -4.57    0.000
X2            -3127.1       234.7     -13.32    0.000
X1*X2          1054.7       459.8       2.29    0.023
X3             -442.8       249.6      -1.77    0.078
X4             -326.9       232.3      -1.41    0.161
X5              678.4       591.4       1.15    0.253
X6               80.1       338.9       0.24    0.814
X7               57.7       328.0       0.18    0.861
X8             -118.4       344.6      -0.34    0.732
Lab Req         4.763       2.054       2.32    0.022

S = 1265        R-Sq = 63.3%     R-Sq(adj) = 61.2%

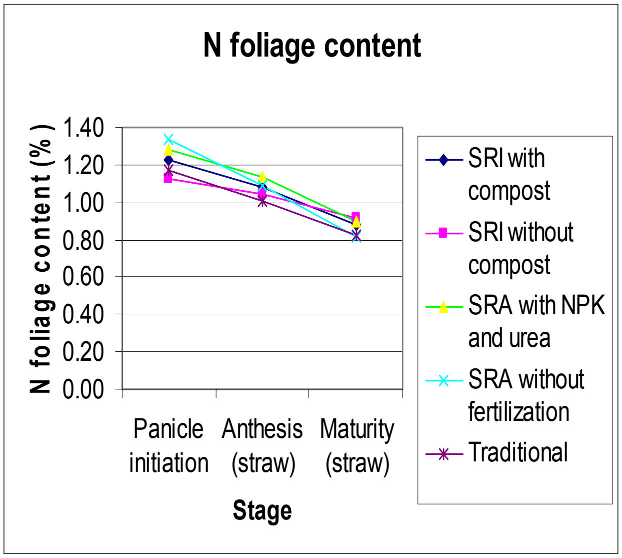
Analysis of Variance

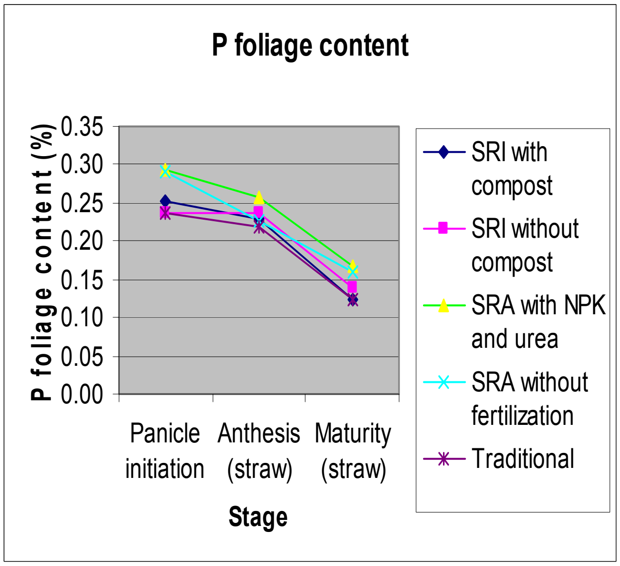
Source           DF          SS          MS         F        P
Regression       10   464794776    46479478     29.03    0.000
Residual Error  168   269014374     1601276
Total           178   733809150

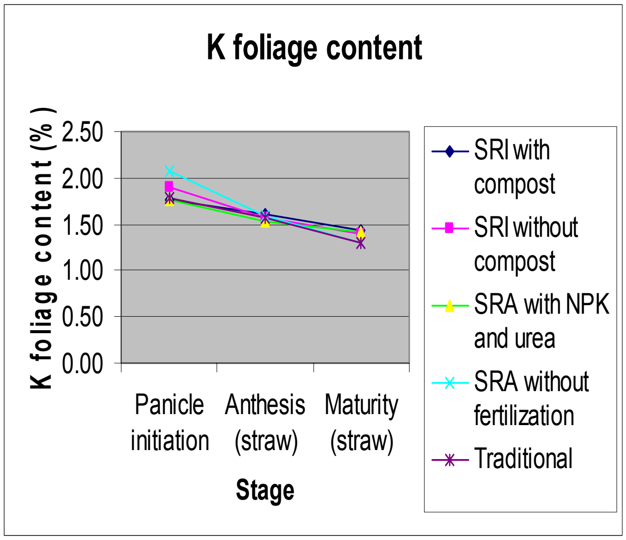
Source       DF      Seq SS
X1            1    14061658
X2            1   427399470
X1*X2         1     7264148
X3            1     2954592
X4            1     1757876
X5            1     1920613
X6            1      508327
X7            1      142632
X8            1      177712
Lab Req       1     8607749
```

APPENDIX B

Nutrient foliage content in the on-station trial at Beforona






K foliage content
K foliage content (%)
2.50
2.00
1.50
1.00
0.50
0.00
Panicle initiation
Anthesis (straw)
Maturity (straw)
Stage
SRI with compost
SRI without compost
SRA with NPK and urea
SRA without fertilization
Traditional

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