AGROECOLOGICAL IMPLICATIONS OF THE SYSTEM OF RICE INTENSIFICATION (SRI) IN MADAGASCAR

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Abstract. A system of plant, soil, water and nutrient management for irrigated rice developed in Madagascar has been yielding 5, 10, even 15 t ha^{-1} on farmers' fields where previous yields averaged around 2 t ha^{-1}. This is achieved using whatever variety of rice the farmer is already using and without having to utilize chemical fertilizer or other purchased inputs. This system, known as SRI, shows that alternative management practices, creating optimal growing conditions for plants, can bring out previously untapped genetic potential. It also shows that the practices farmers have used for centuries may not always be the best in agronomic terms.

Key words: biological nitrogen fixation, phyllochrons, rice, roots, synergy, tillering

Abbreviations: BNF – biological nitrogen fixation; CIIFAD – Cornell International Institute for Food, Agriculture and Development; FAO – U. N. Food and Agriculture Organization; FIFABE – private agricultural company in Madagascar; FoFiFa – national agricultural and rural development agency for research and extension; IRRI – International Rice Research Institute; NGO – non-governmental organization; ORSTOM – French research institution; SOAMA – private agricultural company in Madagascar; SRI – system of rice intensification.

Introduction

The system of rice intensification (SRI) developed in Madagascar during the early 1980s by Fr. Henri de Laulaníe, S.J., who worked closely with farmers to understand how paddy production could be increased, has demonstrated some remarkable results. Yields on farmers' fields have been doubled, tripled, even quadrupled or more – without new varieties, chemical fertilizer, or other purchased inputs. What is required is different management practices for rice and farmer skills and investment of labor.

SRI challenges the way that rice is usually understood and the practices that farmers have used for many years to grow irrigated rice. As a strategy of rice production more than a specific technology or package of practices, SRI contributes to an enlarged agroecological understanding of opportunities for agricultural development.

It must be stated at the outset that the reasons why SRI increases yields so substantially, going against conventional wisdom, are not fully understood. The system raises more questions than it presently gives answers for. However, there are a number of contributions already in the scientific literature that are consistent with what is observed with SRI. These can help begin constructing an explanation of how 'yield ceilings' previously accepted as scientifically established may not be that real or constraining – if the environment above and below ground in which plants are grown is more suitably managed.

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The following discussion draws on sources in the literature but particularly from working with Association Tefy Saina, a non-governmental organization (NGO) in Madagascar that has been developing and popularizing SRI. My understanding owes much also to faculty and students from the Faculty of Agriculture at the University of Antananarivo; staff with FoFiFa, the government agricultural research agency; and Cornell colleagues.

Since all of the experimentation has been done on farmers' fields, the data have not always been as systematic or as controlled as scientists usually expect. However, the Tefy Saina field staff and university researchers have been as thorough and precise as conditions permit, and Cornell faculty have vetted the methods and measurement to be satisfied that these are as correct as possible. Moreover, their findings are consistent with those of a number of other researchers or evaluators that are reported here as well. So this gives me confidence that after five years of observation and evaluation, the results reported here are essentially correct and replicable. University, government or NGO colleagues in China, India, Indonesia, the Philippines and Sri Lanka have begun their own tests and evaluations, with results that suggest SRI can open new vistas for the production of rice.

1. Results to date

Tefy Saina and the Cornell International Institute for Food, Agriculture and Development (CIIFAD) began in 1994 to introduce SRI to farmers cultivating rice around Ranomafana National Park in the central part of the north–south rain forest corridor that runs along the eastern side of Madagascar. This work was supported by the U.S. Agency for International Development, which wanted to find and promote alternatives to slash-and-burn cultivation in the upland forest margins that endangers precious tropical ecosystems. Tefy Saina was already working on a small scale with farmers in other parts of the country and welcomed a chance to work on a larger scale.

Before our efforts began in the 1994–95 season, a team from North Carolina State University had tried to raise lowland (irrigated) rice yields, which averaged about 2 t ha^{-1}, so that there would be less need or incentive for farmers to grow upland, slash-and-burn rice. Working with a small number of farmers and using selected high-yielding varieties and chemical fertilizer, average yields of 3 t ha^{-1} had been obtained, with a maximum of 5 t ha^{-1} (del Castillo and Peters, 1994).

Our first year, only 38 farmers were willing to try the new system of production, described below, on a total area of 5.7 ha. Four years later, this number had expanded to 275 farmers, on 18.6 ha. During this four-year period, the average yields with SRI were 8.8 t ha^{-1}, which is more than four times the previous average. Some farmers harvested 12–14 t ha^{-1}. During this past year, 1998–99, when rice yields were generally lower in the Ranomafana area, 396 farmers used SRI, averaging 7.2 t ha^{-1}, with a few achieving yields of 16 t ha^{-1}.

This could be seen as a purely local phenomenon. However, SRI has produced similar results elsewhere in Madagascar. Thesis research by Randrianasolo (1995) in the Arivonimamo region found SRI methods on average tripling yields there. Field staff working around Zahamena National Park for the NGO, Conservation International, reported that farmers using SRI methods there were able to go from about 2 to 8–9 t ha^{-1} (personal communication, January 1999).

An evaluation in 1995–96 of 108 farmers cultivating rice on the high plateau, where methods are more modernized and average yields are higher than in rain forest areas, found that yields could be doubled with SRI methods; from 3.2 t ha^{-1} around the capital of Antananarivo to 6.3 t ha^{-1}, and from 3.9 t ha^{-1} around Antsirabe to 8.0 t ha^{-1} (MADR/ATS, 1996).

In 1996, the World Bank held a symposium on rice production in Madagascar. Two farmers reporting on their experience with SRI showed a doubling of their yield, from 1.95 to 4 t in the hot low-lying coastal area and from 1.8 to 8.2 t on the high plateau east of Antananarivo (CAM, 1996). Two commercial companies reporting on the yields that they had attained using full packages of modern practices (high-yielding varieties and optimal applications of chemical fertilizer). They noted that some farmers in their region had achieved yields 50–60% higher using SRI with whatever varieties they were already using.[1]

In May 1999, I visited one of the farmers who has become most proficient with SRI methods, 30 km from the regional capital of Fianarantsoa. A FoFiFa researcher who had been trained on rice production at the International Rice Research Institute (IRRI) in the Philippines, Bruno Andrianaivo, took me to see the field of Ralalason, who had just harvested 2,740 kg of paddy from his 13 ares (one-eighth of a hectare), which amounts to 21 t ha^{-1}. This was his sixth year using SRI with Tefy Saina advice, and it was 30% more than the 16 t ha^{-1} he produced the previous year. Now that he was well acquainted with the methods, his labor inputs were no longer much higher than when using traditional methods, but his yield was ten times higher than the national average.[2]

2. Methods

These production figures have surely whetted readers' interest in knowing how such increases in production are possible. The conjunction of different practices that came together to constitute SRI under the insightful leadership of Fr. de Laulaníe was partly serendipitous, but it followed many years of careful study and experimentation with farmers (de Laulaníe, 1993a).

SRI changes several practices that most irrigated rice farmers around the world have utilized from time immemorial, and it is supported by two other practices that are somewhat novel but that are not controversial in terms of their being beneficial for increased production. There is disagreement over how willing farmers will be to accept such labor-intensive practices. The method is probably not practical on a large scale, though there are millions of land-constrained farm households for which such practices would be very remunerative with yield increases such as SRI can provide. One farmer in Ranomafana is now cultivating 6 ha with SRI, so it is not limited to fractional landholdings.

The practices that are changed dramatically with SRI all have a persuasive logic, that of avoiding or minimizing risk. This is something that small farmers cannot easily bear. However, we have not found that these practices, if combined skillfully, put rice crops at any more risk than in conventionally planted and managed fields. So this may be a case where farmer perceptions and practices are not necessarily wise and optimal for production. Scientists have accepted these farmer practices as the norm, however, and have developed their knowledge of rice according to these practices (constraints). Consequently, we have found scientists even more reluctant than farmers have been to agree to experiment with SRI and to evaluate it. See how SRI contrasts with the rice-growing practices in China, where irrigated rice has been grown for millennia.

2.1. AGE OF SEEDLINGS AT TRANSPLANTING

Rice seedlings are usually transplanted when they are about 30 days old. As one of the leading textbooks on rice, written by a former head of the agronomy department at IRRI, states: “It is fairly common to transplant seedlings that are 40–50 days old. However, the best age for transplanting wet-bed seedlings is 20–30 days” (de Datta, 1987: 230).

Farmers believe that larger, more mature plants will survive and grow better. With SRI, however, seedlings are taken carefully from nurseries when they are still quite young, preferably only 8–12 days old and certainly not older than 15 days. As explained physiologically below, this increases their tillering potential, which is affected also by other SRI practices. While conventionally grown rice plants will have 5–20 tillers, with SRI the number per plant can be 50–80, and possibly over 100. Tillers are the grain-bearing stalks that emerge as the plant grows. Not all tillers will flower and become fertile; those that do are called panicles.

2.2. PLANTING AND SPACING OF SEEDLINGS

In China and elsewhere, seedlings are usually planted in clumps of 3 or 4, or even more (de Datta, 1987: 230). This appears to increase the chances that at least some will survive the transplanting, though with careful transplanting, we find very little mortality; and any plants that die can be replaced within the first 10 days. When any plants are planted close together, whether of different species or the same, there will be competition for space and nutrients that inhibits root growth. As a rule, farmers like to plant rice quite densely, e.g., in clumps 10–20 cm apart. The conventional view is that: “Close spacing is essential to minimize weed infestation and to obtain high yields” (de Datta, 1987: 478).

With SRI, single plants are planted quite far apart, usually at least 25 cm by 25 cm, and with possibly even wider spacing when all the techniques have been mastered. They are placed in a square (grid) pattern, rather than in rows. This facilitates mechanical hand weeding, in two directions rather than just one. Ralalason, whose success with SRI was cited above, used 50 cm by 50 cm spacing, having only 4 plants per square meter yet with spectacular results. In the 1996 evaluation of SRI cited above, the rate of seed application for SRI was only 7 kg/ha, compared with the traditional rate of 107 kg/ha, saving farmers 100 kg of rice per hectare (MADR/ATS, 1996).[3] Planting fewer plants per square meter to raise production seems counterintuitive, but the architecture of plants that are given more room for roots and tillers to grow is quite different, supporting much greater grain filling and ultimate yield. With better root development, there is little or no lodging, which is a cause of considerable crop loss.

2.3. WATER MANAGEMENT AND SAVING

Around the world, farmers, like most scientists, believe that rice is an aquatic plant and that it grows best in standing water with the soil saturated.[4] However, with SRI, rice paddies are kept unflooded during the period of vegetative growth. Water is applied only as necessary to keep the soil moist, and it is even allowed to dry out for periods of 3–6 days. This is done to keep the soil well aerated, so that root growth is better. Only after flowering begins are paddies flooded, with 1–3 cm of water during the reproductive period. About 25 days before harvest, they are drained, a practice agreed upon for all methods of growing irrigated rice.

Research going back 30 years, e.g., Hatta (1967), has shown that rice does not necessarily produce more when grown under flooded conditions. A recent study on this question states: "Numerous studies conducted on the manipulation of depth and interval of irrigation, to save on water use without any yield loss, have demonstrated that continuous submergence is not essential for obtaining high yields" (Guerra et al., 1998: 11).

But this has been largely ignored, even by the institutes publishing this conclusion, because of incorrect preconceptions that rice is an aquatic plant. While rice can survive under flooded conditions, it does not thrive under them. We find that rice yields can be considerably *higher* when paddies are not flooded and when rice is grown with the mutually reinforcing practices of SRI. Of course, not growing rice plants under water is quite a radical departure from standard practice. However, unflooded soil conditions encourage roots to grow and seek out water, whereas in saturated soils, they can afford to be 'lazy' and grow very little, especially if nitrogen fertilizer is being supplied to the root zone.

More important perhaps is the research done by Kar et al. (1974) showing that when rice plant roots are kept continuously submerged, most of them degenerate (78%). This surely reduces rice plants' access to nutrients as well as to water during the period when their grains are being formed. Yet this consequence of flooding has hardly been considered in the literature.

It must be conceded that SRI looks terrible for the first month after transplanting. One can hardly see the tiny plants that are spread out thinly over the field, with no standing water reflecting the sky. The second month, one sees some growth, but still the field looks unpromising. In the third month, however, when an exponential increase in tillering begins, the field practically explodes with growth, followed by unusually profuse flowering and grain filling.

2.4. WEEDING

Flooding of paddies has been done for generations mostly as a means of weed control, saving labor that would otherwise have to be spent in weeding. While rice yields are satisfactory to good with this method, SRI shows that they can be greatly increased. To control weeds with SRI, farmers need to do some weedings, and preferably as many as four, either manually or mechanically. This is less onerous if done with a simple and inexpensive (under $10) hand weeder developed by IRRI that has toothed wheels on it. This churns up the soil as it is pushed between rows of plants in both directions, thanks to the grid pattern of planting.

While such weeding requires more work than with flooded fields, any rice crop that is not weeded is at risk of yield reduction. The combination of SRI practices that go together with such weeding greatly increases output so that the investment of greater labor returns at least twice as much output per day.

During the 1997–98 season, 76 farmers in the Ambatovaky area west of Ranomafana National Park used SRI practices under the supervision of Tefy Saina. The two who did no mechanical weedings got a respectable yield, 2–3 times the average with conventional practices. But as seen in Table I, those who did several weedings, and especially those who did four, got very high returns for their additional labor. We think that this shows further the advantage of soil aeration since there would not have been so much difference in yield simply because of weed reduction.

2.5. NUTRIENT SUPPLY

The soils around Ranomafana are some of the poorest in the world according to studies done for North Carolina State University.[5] The standard view is that where soils are inherently so low in fertility, the only solution is to add inorganic nutrients. "The two principal soil fertility constraints [around Ranomafana] are low nutrient levels and soil acidity. These constraints cannot be realistically managed by low-input technologies such as composting or even manuring. The nutrient-poor soils give rise to nutrient-poor plant residues and manure. . . The only viable strategies for producing sufficient agricultural yields are to use man-made fertilizers or to continue slash-and-burn practices [in upland areas]" (Johnson, 1994: 7).

We have found, however, that with SRI practices and no external inputs, using only compost, farmers are producing about three times the average yield levels that NC State achieved with inorganic fertilizers plus high-yielding varieties.

The amount and quality of compost applied varies considerably. Those who get the best yields with SRI either have somewhat better soil or apply more compost. Ralalason, whose success was reported above, applied about 5 t of compost to his 13 ares, a high rate of about 40 t ha^{-1}, which was rewarded with a yield of 21 t ha^{-1}. Ralalason has learned to make very high quality compost, using cuttings of leguminous shrubs like tephrosia and crotalaria, and incorporating rice straw and hulls and all kinds of biomass such as banana leaves.

Tefy Saina does not consider the use of compost as a necessary element of SRI, though it recognizes that with such high production levels, sooner or later there will need to be

TABLE I. Impact of additional soil-aerating weedings on yield with SRI practices, Ambatovaky, Madagascar, 1997–98 season ($N = 76$).

Weedings	(N)	Area (ha)	Harvest (kg)	Yield (t ha^{-1})
None	2	0.11	657	5.97
One	8	0.62	3,741	7.72
Two	27	3.54	26,102	7.37
Three	24	5.21	47,516	9.12
Four	15	5.92	69,693	11.77
	76	15.40	147,709	9.59

Source: Individual farmer records, maintained by Tefy Saina.

some replacement of nutrients exported from the fields. For the present, it is a fact that few farmers in Madagascar can afford inorganic fertilizer, and because there is so little demand, there is little supply available in rural areas. So a strategy of incorporating organic nutrients in the soil is the only way that most farmers can augment their production. With the combination of SRI practices, they can get a higher return for the labor of making and applying compost than when conventional methods are used together with inorganic nutrient inputs. In the future, after incomes have been raised, we would anticipate some need to add inorganic nutrients to the soil, especially phosphorus, which is particularly deficient.

3. Implications for agroecological approaches

As can be seen, SRI presents many puzzles – just as it opens various opportunities – for agricultural scientists as well as practitioners. The yields reported from many different parts of Madagascar, with varying soil and climatic conditions though none of them really good, raise questions, for example, regarding standard expectations of soil nutrient requirements for growing a good crop. There is no question that plants need nutrients to grow and that these must come from somewhere. But perhaps there are biological processes encouraged by the management practices of SRI that either enable plant root systems to extract more nutrients from the soil accessed, or to acquire a more complete and balanced set of nutrients that includes many minerals besides N, P and K. Below I consider the SRI performance and suggest explanations that can be found in the literature or that seem worthy of specific research.

The underlying issue is that we probably need to deal with is the manifestation of *synergy*, a central principle of agroecology. In December 1997, after we had a reasonable understanding and documentation of SRI performance, we sent a paper on this methodology to the International Rice Research Institute in the Philippines. We anticipated a response from IRRI scientists that would help resolve the questions that SRI presented.

The reply which came after eight months acknowledged that five of the six practices combined in SRI had been evaluated by IRRI or other scientists, and each could contribute positively to rice growth (Fischer, 1998). Planting single seedlings vs. planting them in clumps had not been evaluated in the literature, to our surprise. Unfortunately, the response never addressed the central issue raised by our paper and highlighted in its subtitle: “A Study in Synergy?” It seems that the scientific method which evaluates changes in management or genetic characteristics one at a time under carefully controlled circumstances – *ceteris paribus*, other things being equal – is disinclined, though not unable, to examine the question of how various changes may *interact*, in either positively or negatively reinforcing ways.

Here I will lay out what we understand to be the synergistic elements of SRI. Some are well documented in the literature and others are only speculative, but based on some research that can be found there. This is still a puzzle-solving work in progress, where scientists and field workers have been sharing observations and surmises, trying to explain what has been seen over the past 15 years. SRI is not considered as a specific technology or as a fixed ‘package’ of practices. Rather, it is understood as a strategy, even philosophy, for growing rice according to a set of principles that have been derived from practice and also elaborated by researchers. Fr. de Laulaníe himself was trained in agriculture in France before going through a Jesuit seminary. He read widely and avidly about rice, though his methods were unconventional and highly inductive.

3.1. INCREASED TILLERING

SRI is best described as a congruent set of plant/soil/water/nutrient management practices. There is solid physiological research to explain why early transplanting of rice seedlings, before the fourth *phyllochron*, i.e., usually before 15 days, will evoke existing genetic potentials for increased tillering.[6] The phyllochron is an interval of plant growth in grass family (*Gramineae*) species which include rice, wheat, barley and other grains. It is observed as the time between successive emergence of sets of tillers and leaves from the main tiller. This interval of growth is determined by various environmental factors that impinge on the growing plant (temperature, moisture, nutrient availability, soil structure, etc.) rather than being set according to a predetermined number of calendar days (Nemoto et al., 1995).

During each phyllochron of growth, which in rice is usually about 5 days but can range between 4 and 8 days depending on altitude, soil and other conditions, one or more *phytomers* – each a unit of tiller, leaf and root – will emerge. An increasing number of phytomers emerge as the plant grows because after the fourth phyllochron, each tiller produces – two phyllochrons later – another tiller. This biological process was studied in detail by a Japanese plant scientist during the 1920s and 1930s, but only published after World War II (Katayama, 1951). Unfortunately, this work has not been translated into English, though it was reported in French many years later. When Fr. de Laulaníe read about phyllochrons in Moreau (1987), he immediately understood why the practice of early transplanting that he had fortuitously discovered with his farmer-students in 1983 led to radically increased tillering.[6]

The rice plant follows a very predictable pattern of tillering, though the *pace* of tillering is quite variable. How many panicles (fertile tillers) there will be, depends on the number of phyllochrons of growth that can be completed before the plant switches from its vegetative stage into its reproductive stage, redirecting energy from growth to flowering and grain filling. Figure 1 shows the pattern of tillering in qualitative (configurational) as well as quantitative terms.

The first (main) tiller emerges during the first phyllochron, but then the plant produces no more until the fourth phyllochron, between 12 and 18 days later. During the fourth phyllochron, a second tiller, the first one off the main stem, emerges, and in the fifth phyllochron there is a third tiller, another off the main stem. Then in the sixth phyllochron there are two new tillers – one from the main tiller and another from the base of the second; the seventh phyllochron produces three tillers, the eighth produces 5, and subsequent phyllochrons of growth produce 8, 13, 20 tillers. The twelfth phyllochron, if it can be reached before flowering begins, produces 31 tillers!

In mathematical terms, as Fr. de Laulaníe discovered, the first three phyllochrons produce only 1 tiller (4^0), the second three phyllochrons produce 4 tillers (4^1), the third set of three

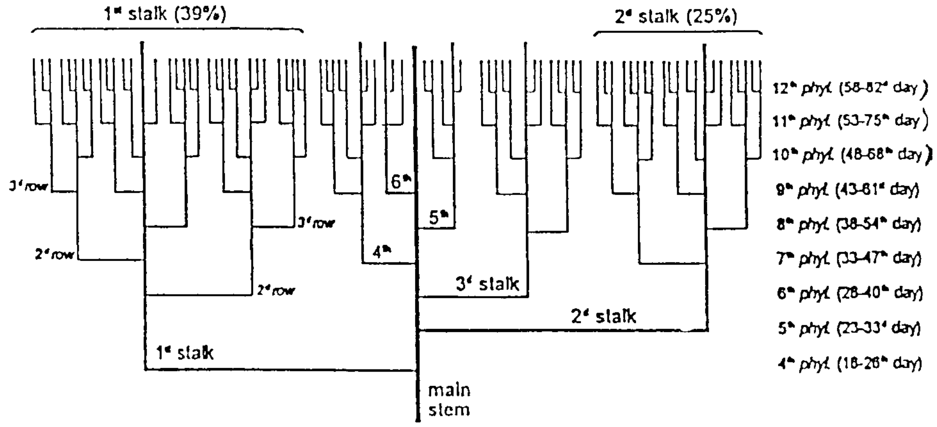

Figure 1. Diagram of possible increase in tillers (stalks) from a rice plant through 12 phyllochrons of growth. Source: Vallois (1997: 11), adapted from de Laulanie (1993a).

produces 16 (4^2), and the fourth set, 63 ($4^3 - 1$), for a possible total of 84. With extremely favorable conditions for growth, a rice plant can enter a thirteenth phyllochron of growth and produce 100 or more tillers. Ralalason last season had one plant with 140 tillers, which means that it reached the fourteenth phyllochron.

The reason for offering this detail is that it shows how the benefits of early transplanting have a physiological basis, as seedlings transplanted after the third phyllochron, when their tillering is starting to accelerate, have this growth process retarded. Even with other conditions being good they are less able or likely to produce as many tillers as with SRI management. Most rice plants only complete 7 or 8 phyllochrons of growth before the onset of flowering because of late transplanting and other influences inhibiting their growth.

The dynamic of synergy arises because plants will not tiller unless they have adequate root growth to support the enlarged canopy, and rooting will not advance unless the soil, water, nutrient, temperature and space conditions are conducive for root growth. But for the plant's roots to growth, they need the nutrition that comes from photosynthesis in the canopy as well as from the soil. Having more tillering depends on more rooting, and vice versa.[7]

3.2. ROOT DEVELOPMENT

One of the first explanations we considered was increased growth of roots when seedlings are transplanted singly and with wide spacing. Roots are challenged by occasional water stress to grow more deeply and by the use of compost instead of directly applied fertilizer so that they need to explore a larger volume of soil. The thesis research by Joelibarison (1998) assessed root development using a simple measure developed at IRRI (Ekanayake et al., 1986). The amount for force, measured in kilograms, required to pull up a plant under reasonably standardized soil moisture conditions is a proxy for total root mass, reflecting the amount of friction and surface tension the roots have with their surrounding soil.

This is a rough measure, not likely to reflect small differences. But the differences that Joelibarison found were so large that there was no question the SRI practices produced a radically different root structure. It took on average 28 kg to uproot a clump of *three* rice plants conventionally grown under close and flooded conditions; it required on average, 53 kg to pull up *single* plants grown with SRI methods – roughly six times more force per plant.[8]

Several pieces of published research that have examined root growth and function could help to explain this difference. French scientists working at ORSTOM in the 1980s studied the internal structure of rice roots under flooded and unflooded conditions (Puard et al., 1986; 1989). They found that when an 'upland' variety of rice (IRAT-13) was grown under unflooded conditions, a cross-section of its root showed a symmetrical ('normal') formation of the vascular system, with xylem conducting water and nutrients upward and phloem carrying the products of photosynthesis downward from the leaves. When this variety was grown under flooded conditions, the formation of air pockets (*arenchyma*) displaced much of the vascular system to permit oxygen from above ground to reach root tissues.

Similarly, when an 'irrigated' variety of rice (IRAT-173) was grown under submerged conditions it exhibited the development of *arenchyma*, taking up even more of the cross-section of root. When it was grown under unirrigated conditions, this variety's root cross-section looked as 'normal' as did IRAT-13 grown under similar circumstances, with no displacement of xylem and phloem channels.[9]

There has been little research on rice roots' functioning under flooded vs. unflooded conditions. The one study we have found was noted above. Kar et al. (1974) grew a Taichung-native rice variety under both flooded and well-drained soil conditions in pots, so that root growth could be examined at different stages of development. They found that although there was more root growth under flooded conditions, by the time that the plant reached flowering stage, 78% of its roots had degenerated, whereas there was no significant degeneration in unflooded soil.

This, together with the observations of Puard and associations, could account for the much greater root development of rice grown in soil that is only kept moist, not flooded, and periodically let to dry. Frequent weeding with a 'rotating hoe' would assist in aeration of the soil. Greater root development would support greater tillering as well as more grain filling during the reproductive stage.

3.3. GRAIN FILLING

The standard view among rice breeders has been that there is a 'yield ceiling' constraining even the high-yielding varieties developed for the Green Revolution, requiring the development of a 'super-rice' variety with a different architecture. This variety will have only a few tillers (10–12) but they will all become fertile and full of rice (200–250 grains per panicle) as described by Khush and Peng (1996) and by Conway (1997). When I first discussed SRI with colleagues at Cornell, there was no interest in the kind of high tillering that SRI was achieving because it was thought that there are diminishing returns when plants have more tillers. If the number of tillers is increased, it was believed that a declining proportion of them would be fertile, and those that were fertile will have fewer grains; see Ying et al. (1998), for example.

Our experience with SRI, however, is that the relationship among tillering, panicle formation and grain filling can be definitely positive-sum, given that the plants have dramatically greater root development below ground to support these dynamics above ground. Such root growth makes rice plants into ‘open systems,’ though they cannot expand output indefinitely. This relationship is seen in Figure 2 showing the positive association between having more tillers per plant and more grains per panicle (fertile tiller). With SRI methods, we have seen panicles with as many as 400 grains; indeed, one was presented to the Minister of Agriculture by a pleased SRI farmer, Edline Rakotovao, at the end of the 1997–98 season.

If rice plants can produce 200–250 or more grains per panicle on 50, 60, 70 or more panicles per plant, the logic of the super-rice is called into question. The issue for optimizing production is how many of these high-yielding plants can be grown per square meter, recognizing that at some point wider spacing will not continue to give the highest production. The research by Joelibarison (1998) suggested that 25 cm by 25 cm spacing was more productive per unit area than 30 cm by 30 cm, but the performance of experienced farmers like Ralalason suggests that even wider spacing can produce the highest yields, when soil, water and nutrients are being concomitantly managed to best effect.

When rice plants are grown under flooded conditions, in saturated and anaerobic soil, this tends to create a ‘closed system.’ Nutrients, particularly N, need to be pumped into this system to obtain further increases in production, but diminishing returns set in, eventually sharply, as has been observed in the later stages of the Green Revolution. SRI by creating

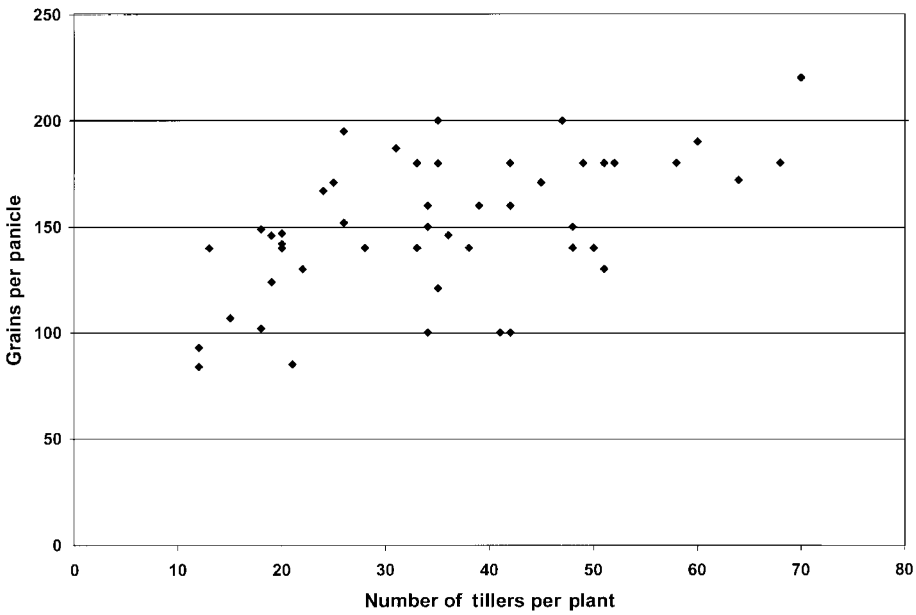

Figure 2. Number of grains per panicle associated with number of tillers per rice plant using SRI methods, Ambatovaky, 1997–98 season ($N = 74$)

a positive growth environment for the plant capitalizes on synergy from the interaction of soil nutrients across a wide range, adequate but not excessive water, photosynthesis, plant self-protection, and other elements contributing to plant vigor.

3.4. SOIL AND NUTRIENT MANAGEMENT

As noted already, the farmers with whom we have been working are tilling some of the poorest soils in the world. How are such high yields possible? We have no fully satisfactory explanation, though some have been suggested already. SRI was initially developed using chemical fertilizer in the 1980s, but its price shot up at the end of the decade, Fr. de Laulaníe began working with compost, as something that farmers could produce with their own resources. In Madagascar, although soils are poor and only a small portion of the land is arable, there is a lot of biomass growth, and some of it (especially leguminous trees and shrubs) can be quite valuable for compost. The IRRI scientists with whom I have spoken about SRI consider the application of compost to be one of the most likely explanations for high SRI yields. Certainly the success of Ralalason reported above is due in large part to his provision of supplementary nutrients to his fields. Two lines of investigation that have been initiated by Brazilian researchers possibly could account, at least in part, for the impressive increase in production with SRI.

3.4.1. Biological nitrogen fixation?

While compost, especially if enriched by leguminous species biomass, can account for yields up to 10 t ha^{-1}, it is hard to imagine how yields in the 10–20 t range are possible without a lot of nitrogen fixation in the rhizosphere. This could be done by associations of diazotrophic bacteria and other microbes living in, on and around the roots, as documented by Döbereiner (1987).

Döbereiner and her colleagues have been studying processes of biological nitrogen fixation (BNF) since the late 1950s, with most attention to sugar cane, a plant in the grass family like rice. They have found that there can be rather substantial associative N-fixation, 150–200 t ha^{-1}, with sugar cane cultivars that have not had inorganic N applications for many generations. When they worked with cultivars (or in soils) that have had chemical fertilizer recently applied, however, this effect was not very strong. Measurements of N-fixation in the root zone of rice have been more difficult, with varying estimates ranging from under 10 t ha^{-1} to over 50 t ha^{-1} (see also Boddy et al., 1995; Baldani et al., 1997). Other researchers have had difficulty reproducing these results, so they have not been taken very seriously outside Brazil. The basic proposition that *associations* of microbes rather than particular species produce the result makes this work inherently difficult to replicate – but this does not invalidate it. We think this is worth exploring.

Economic conditions around Ranomafana and in much of Madagascar are such that farmers have used little if any chemical fertilizer over the past decade or two. Possibly the soil and water management techniques used with SRI create more favorable conditions for microbial associations to fix nitrogen that benefits the rice plants grown this way. The alternation of aerobic and anaerobic conditions that comes from intermittent wetting and drying of the soil, increased by the method used for mechanical hand weeding which inverts soil layers, could contribute to this biological dynamic of nitrogen fixation. This is only a hypothesis at present, but it could be evaluated scientifically.[10]

3.4.2. Fewer nutrients required with continuous supply?

There is some research, also from Brazil, which suggests that plants can have satisfactory growth with much lower concentrations of nutrients than previously thought necessary, provided the supply is constant over time rather than given at just a few intervals. Plants appear able to get significant benefit from quite small amounts of nutrients if these are available continuously. Compost, used with SRI, furnishes nutrients in a steady flow, even if lower than that provided by applying chemical fertilizers. Continuous release of nutrients allows the plant to use them when and as needed.

Primavesi (1984) reports that maize plants grown hydroponically in a nutrient solution with only 2% of normal concentration could achieve as much growth in terms of plant weight as did plants grown in normal solutions, i.e., with nutrient concentration 50 times higher – if the diluted solution was changed frequently, i.e., every other day. The plants grown in the much-diluted solution had average root mass that was *eight times* greater (56 g vs. 7 g) than in normal solution. This increased growth of roots is similar to what we have seen with SRI. It would give plants much greater access to whatever small amounts of nutrients are available in the soil (see Table 3.5 on page 81 of Primavesi's book).

3.5. CROP SELF-PROTECTION?

We have not had opportunity to do any systematic research on what farmers report to be fewer pest and disease problems with SRI –grown rice – except in the case of locust attacks, which tend to focus on SRI plots because they are more full of grains. Most farmers using SRI cannot afford agrochemicals of any sort. Although one might expect more pests and diseases with a larger crop, SRI experience appears to confirm the principle of FAO's crop protection strategy: to reduce losses due to pests and diseases, grow healthy plants.

This sounds tautological, but the FAO program has shown that crops that are vigorous can resist pest and disease attacks, either repelling them or being only marginally affected. Plants that are grown under crowded conditions, with growth 'forced' by applications of fertilizer, are more vulnerable to predation and illness. Moreover, when there is 'forced growth' the strength of plant tissues is reduced, and lodging can become a more serious problem. Even though the panicles with SRI are larger than with most rice crops, there has been little problem with lodging, which would be another benefit from the synergy of dynamic plant growth.[11]

4. Conclusion

Even though SRI was developed in the early 1980s, there is still very little systematic evaluation by plant or soil scientists. The methods that constitute SRI were developed very inductively and even fortuitously, so this may be a case where science needs to catch up with practice. Creating a very conducive growing environment is more important than any specific input, as the paradigm within which SRI operates is more biological than mechanistic.

We think that the methodology will make clearer to scientists the value of studying and understanding agricultural processes in terms of more holistic, synergistic relationships rather than through piecemeal, *ceteris paribus* kinds of investigation. It is our hope that SRI will prove to be instructive not only for the growing of irrigated lowland rice but will encourage rethinking and innovation for other crops and cropping systems as well.

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Notes

[1]SOAMA conducting trials at Andapa in the north of the country achieved average yields of 6.2 t ha^{-1}, while 27 farmers using SRI methods in the same area averaged 10.2 t ha^{-1} (Tang-Po, 1996). Good news for plant breeders was that the four SRI farmers using a variety developed by the IRRI averaged 13.7 t (one reached 16.7 t). FIFABE growing rice in the northwest around Marovoay reported average yields of 4.8 t ha with modern methods, while farmers using SRI methods got 7.1 t (Rakotonirina, 1996). Researchers at Nanjing Agricultural University in China in 1999 got 10.5 t yield with SRI methods using wide spacing (30 $\times$ 30 cm), while the Agency for Agricultural Research and Development in Indonesia got 9.5 t in the 1999–2000 wet season. So we know that SRI methods can produce similar results outside Madagascar.

[2]When he started, the transplanting time for SRI was about double the traditional method (12 days compared to 6 days for his size field), but now that he was using very wide spacing with very few plants per square meter, his transplanting time was only 5 days. Careful water management requires more labor, as does producing copious amounts of excellent quality compost to add to the field, but large increases in yield repay this work well.

[3]Evaluation of a farmer-developed, raised-bed technology for growing wheat in Mexico that is similar to SRI in some respects, e.g., much reduced irrigation and wide spacing of plants, has found seeding rates of 15–25 kg/ha giving yields as good as or better than rates of 200 kg/ha (Sayre and Moreno, 1997: 6).

[4]"[Rice] thrives on land that is water saturated, or even submerged, during part or all of its growth cycle. . . A main reason for flooding a rice field is that most rice varieties maintain better growth and produce higher grain yields when grown in flooded soil than when grown in a nonflooded soil" (de Datta, 1987: 43, 297–298). A few varieties that are long-stemmed are well adapted to growing in deep water, but that does not

prove that they will yield best under submerged conditions. Some varieties are known as 'irrigated' varieties because they perform better under flooded conditions than do 'upland' varieties; but this does not mean that submergence is ideal for them, as shown below in a discussion of the formation of air pockets (*aerenchyma*) in rice plant roots.

[5]Given the parent rock from which the soils were formed, "there are no significant areas of naturally fertile soils within tens of kilometers of the park boundary. The pH values in water range from 3.9 and 5.0, with most values between 4.2 and 4.6. . . The levels of exchangeable bases (Ca, Mg and K) are low to extremely low in all horizons. The subsoil horizons contain virtually no exchangeable bases. Phosphorus levels for all horizons are below 3.5 parts per million (ppm), far below the 10 ppm level, which is generally considered to be the threshold at which large crop-yield reductions begin to occur" (Johnson, 1994: 6–7).

[6]In emphasizing possibilities for exploiting better existing genetic potentials, we are not arguing against the value of continuing work on genetics to increase such potentials. The research and proposals of our colleagues Tanksley and McCouch (1997) can open up important avenues for raising production. We point to potentials that can be capitalized on by different and better management practices to say that research investments should not go all in the genetics 'basket'.

[7]There is now work being done on phyllochrons in the U.S. by wheat scientists, but not rice scientists. See Rickman and Klepper (1995) and other contributions to a symposium on phyllochrons published in *Crop Science* (Vol. 35, No. 1). Although Katayama's method of analyzing plant growth is known and taught in Japan, the exposition of phyllochrons in the encyclopedia on rice published by Japanese scientists and translated into English (Matsuo et al., 1997) is much less detailed and explanatory than that by de Laulaníe (1993a,b). This tillering pattern corresponds to what is known in biology as a Fibonacci series.

[8]Curiously, this finding was not even commented on in the IRRI response (Fischer, 1998). Perhaps this reflects the general neglect of roots and their performance by plant scientists. Nobody has taken me up on a proposed bet that less than 5% of all the research done by plant scientists over the past 50 years has been below ground.

[9]When I reported Puard's findings at a seminar at IRRI headquarters on February 12, 1999, my inference that the formation of *arenchyma* would impede nutrient transport in submerged roots was challenged. Research on maize (not rice) was pointed to as showing no loss in function due to *aerenchyma*. However, the researcher whose studies were cited (Malcolm Drew, Texas A&M) clarified subsequently by e-mail that his findings only showed no loss of nutrients *horizontally* from xylem or phloem into the air pockets (Drew, 1997); his research did not rule out reductions in nutrient transport vertically, and he suggested that under flooded conditions, it is possible that less oxygen reaches the root *tip*, thereby inhibiting root growth (personal communication, March 3, 1999).

[10]Research done many years ago by Magdoff and Bouldin (1970) found that BNF fixation was greater in plastic columns that had aerobic (unsaturated) soil at the top and anaerobic (saturated) soil at the bottom when they were periodically rotated, mixing up aerobic and anaerobic layers. This suggests that the weeding process used with SRI could contribute to BNF. This is a subject amenable to precise research.

[11]Even in the case of locust attacks, we have a number of reports of situations where newly-planted fields of SRI rice were attacked by swarms of locusts and eaten down to the ground. But because the roots of the tiny but vigorous plants survived, they regenerated a normal rice crop after the locusts left. SRI plant management prescribes getting seedlings quickly from the nursery into the field within 15–30 min, and laying their roots into the soil gently. The seedling root is laid in horizontally so that the tip can easily orient itself to grow downward; jamming the seedling straight down into the soil, as is usually done, turns the root tip upward.

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