QUESTIONS AND ANSWERS ABOUT THE SYSTEM OF RICE INTENSIFICATION (SRI) FOR RAISING THE PRODUCTIVITY OF LAND, LABOR AND WATER

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The System of Rice Intensification (SRI), called the *Système de Riziculture Intensive* in French, was developed through the work of Fr. Henri de Laulanié, S.J., who lived in Madagascar from 1961 until his death in 1995. Having been trained in agriculture at the National School of Agriculture (ENA) in France before World War II, he brought a basic knowledge of agricultural science to the task of raising rice production, but most of what he learned about rice was learned from working closely with farmers and from observing rice plants very closely. He regarded the rice plant as his teacher, "*mon maitre*" (Laulanié 1993).

SRI has been written about elsewhere (Rabenandrasana 1999; Uphoff 1999; Uphoff 2002; Stoop et al. 2002). What is undertaken here is to link what has been learned about SRI from observations and measurements to what can be found in the scientific literature. Most of the answers remain to be validated by more systematic scientific investigation. Thus, the answers here should be regarded as provisional, presented with the hope that this account will prompt scientists who are in a better position than the author (a social scientist by training) to demonstrate agronomic relationships to the satisfaction of agricultural scientists. There are now enough reports of SRI methods raising yields significantly in many countries around the world, at least a dozen in Asia, Africa and Latin America, that the challenge is to understand how the set of changes in managing plants, soil, water and nutrients can achieve such great advances in factor productivity.

1. *What **yields** are obtainable with SRI methods?*

Association Tefy Saina (ATS), the Madagascar NGO most actively promoting them, has found that yields *of any rice variety* can be at least doubled, and often yields can be increased by considerably more than this with SRI methods. In the area around Ranomafana National Park on the edge of primary rain forest in the eastern part of the country, where average yields for irrigated rice using traditional methods are about 2 t/ha, farmer using SRI methods between 1993/94 and 1998/99 averaged over 8 t/ha. During this time, the number of farmers working with Tefy Saina to learn SRI, increased from just 38, using these methods on 5.7 hectares, to 396 using them on 50.6 hectares. In addition, many other farmers were informally or partially using the methods (data from Association Tefy Saina, Antananarivo).

During the same five-year period, hundreds of farmers on the high central plateau around Antsirabe and Ambositra (over 1,000 m) averaged 7.91 to 9.18 t/ha with SRI methods, compared to 3.95 to 4.23 t/ha with the more costly methods of production recommended by government agents, and 2.24 to 2.47 with peasant practices. The area cultivated with SRI methods increased during this time from 34 to 543 hectares (Hirsch 2000).

Similar yield increases have been recorded with SRI methods elsewhere in Madagascar. A comparative study in 1995/96 with 108 farmers on the high plateau, who were using these methods for the first time, found their average yields around the capital Antananarivo increased

from 3.2 to 6.3 t/ha, and from 3.9 to 8.0 t/ha around Antsirabe (MARD/ATS 1996). In the north near Andapa, a private company (SOAMA) reported that farmers using HYVs and "optimum" fertilizer applications had reached 6.2 t/ha, while 27 farmers in the same area who used SRI methods got 10.2 t/ha. (Four farmers who used IR-46 averaged 13.7 t/ha.) Around Marovoay in the northwest, another company (FIFABE) reported yields of 4.8 t/ha with "modern" practices including fertilizer, while farmers there who were practicing SRI it said got 7.1 t/ha. (These data are from the proceedings of a 1996 World Bank symposium on rice in Madagascar.)

Some farmers around Ranomafana who used SRI techniques most effectively have gotten yields around 14 to 16 t/ha. Some farmers in the Fianarantsoa region have attained even higher yields. In May 1999, the author together with Bruno Andrianaivo, an IRRI-trained rice agronomist who is a research staff member for FoFiFa, the agricultural research agency of the government, visited a farmer (Ralalason) who had just harvested 2,740 kg of rice from his small holding, 13 ares of land (1/8 hectare) near Soatanana. This represents a yield of 21 t/ha, ten times the national average. The farmer was in his sixth year using SRI techniques and had mastered them very well. His super-yield was made possible by the application of large amounts of well-made compost (we estimated a rate of about 40 t/ha), not to the rice crop but to the preceding inter-season crop of potatoes.

Increased yields with SRI have been attained at altitudes ranging from almost sea level to over 1,200 m, and on quite a range of soils, though the best yields require well-drained soils. They do not require particularly fertile soils, as most of the soils in Madagascar are very poor, and those around Ranomafana have been characterized, based on systematic soil analyses, as some of the poorest is the world (Johnson 1994).

There is increasing confirmation of higher yields now coming from other countries. The Agronomy Department at Nanjing Agricultural University in China did SRI trials with different spacing (20x20cm to 30x30cm) in 1999 and got 9.2 to 10.5 t/ha, the latter being with the wider spacing. The Agency for Agricultural Research and Development in Indonesia, at its Sukamandi rice research station, got 6.2-6.8 t/ha in its first trials (dry season 1999) and 9.5 t/ha in the second trial (wet season 1999-2000).

NGOs in the Philippines (CDSMC and BIND) and Cambodia (CEDAC) working with small farmers in these countries have recorded more than doubled yields, to 5 and 6 t/ha respectively, in their first year of using SRI methods. Farmers are very keen to continue with SRI because of the way the plants grow, with resistance to pests and diseases, so those evaluations are expanding. Farmers in Bangladesh working with CARE and the Department of Agricultural Extension have gotten 6.5-7.5 t/ha, and in Sri Lanka, farmer yields have averaged over 8 t/ha, reaching as high as 16 t/ha. The first two yields reported from Cuba using SRI methods were both over 9 t/ha, and trials in 2000 at the National Agricultural Research Center at Sapu in The Gambia in West Africa ranged from 5.4 to 8.4 t/ha. So the Madagascar experience is not a fluke.

2. *What **inputs** are needed to achieve these yield increases?*
No purchased inputs -- only additional labor, and particular skill and care in managing plants, soil, water and nutrients together. SRI does not require new seeds or high-yielding varieties, though some HYVs have responded very well to SRI management practices. FoFiFa in a 1989

extension bulletin announced that its variety 2067 (descended from Tainung 16) averages 5.6 t/ha, with a "maximum observed yield" of 7.7 t/ha. Yet farmers using 2067 with SRI practices around Ranomafana averaged about 11 t/ha in 1997-98, and one exceptional farmer in Soatanana reported above, who planted variety 2067, reached 21 t/ha in the 1998-99 season. We also noted above that four farmers who had used IR-46 in 1995-96 averaged 13.7 t/ha near Andapa.

So far, all rice varieties have responded positively to SRI practices. While chemical fertilizer can be used with good effect, the best results have been obtained with composted biomass. Factorial trials have showed compost giving higher yields ceteris paribus, though the difference is small with HYVs, which have been selected for their responsiveness to NKP fertilizer. Research should be done on differences in varietal response to SRI management, and on the relative merits of supplementing soil nutrients with organic vs. inorganic forms, using compost vs. applying fertilizer.

Many farmers have gotten these much-increased yields without any nutrient amendments to their soil, simply by using the other SRI practices. This is surprising. Rice plants with SRI appear better able to utilize available nutrients in the soil, as discussed below. Field research done for a NC State University doctoral thesis (Johnson 1994) evaluated the soils around Ranomafana as some of the poorest in the world, e.g., having only 3-4 ppm of phosphorus, and with low to very low cation exchange capacity in all horizons. With very high yields coming off such poor soils, some enhancement or replenishment of nutrients will probably become advisable with SRI at least in the future. However, the impressive response of rice to SRI practices suggests that some fairly basic research on plant nutrient requirements and dynamics should be undertaken to understand how these high yields are possible on such nutrient-deficient soils.

*3. What **practices** make these higher yields possible?*

SRI changes four practices that farmers planting irrigated rice have used for centuries, even millennia. They modify conventional plant-soil-water-nutrient management for rice in the following ways. With SRI:

1. Instead of planting *fairly mature seedlings*, 3-4 weeks old or older, with SRI one plants **very young seedlings**, just 8-12 days old, when the plant has put out just two small leaves, and the root is still very simple, with the seed still attached. If the transplanting is done carefully, as discussed below, there is *less trauma* to the plant and it recovers from the shock of transplanting more quickly than at a later stage in its development. This preserves the plant's potential for ***much greater tillering*** -- 30 to 80 tillers per plant, and possibly 100 or more -- as well as for more root growth and grain filling provided that the other SRI practices are used concurrently to help plants realize this potential.

2. Instead of planting seedlings in *clumps of 3-4 plants* and sometimes more, with SRI one plants **single seedlings**. This means that there will be no competition between and among the roots of multiple seedlings. Intra-species competition is not more beneficial for plant growth than inter-species competition, e.g., with weeds. The result is ***much greater root development,*** provided there is ***careful planting*** as discussed below.

3. Instead of planting seedlings fairly *densely*, seedlings are **widely spaced**. This leads to ***enhanced root development*** which supports more yield because tillering and grain filling are greatly increased with the wider spacing between plants. Clearly one needs to *optimize, rather than maximize* spacing, since the objective is yield per unit of land and other resources, not per plant. With SRI, however, "less produces more."

   With SRI, seedlings are planted **in a square pattern**, rather than *in rows*. This gives wider spacing and facilitates mechanical weeding. Optimum spacing depends on soil and other conditions, so it needs to be determined empirically for specific field conditions. But with SRI, it is reasonable to start with 25 x 25 cm spacing and to increase, or decrease, this spacing experimentally. Some of the highest yields have come with 50 x 50 cm spacing (just 4 plants per square meter), when soil quality has been built up.

   With SRI, the **seeding rate** is much lower. The 1995-96 study of SRI performance on the high plateau noted above showed doubled yields with an average seed rate of *only 7 kg/ha*, compared to the rate of 107 kg/ha with farmers' usual methods. Farmers gained 100 kg of rice per hectare just from the lower seeding rate with SRI.[1]

4. Instead of keeping rice fields *flooded throughout the growing season*, as has been considered necessary to get best yields, **fields are kept moist but never flooded** during the vegetative growth phase with SRI. The soil is "lightly irrigated," with intermittent applications of water, and *never saturated*. We observe that the plants grow better if the field is, from time to time, allowed to dry out for several days, to the point of surface cracking, to contribute to aeration of the root zone. During the ensuing reproductive phase, a thin layer of water (1-2 cm) is kept on the field. These recommendations are purely empirical.

   No systematic research has been done on what are the **optimal water management practices** in conjunction with other SRI practices. This will be very important knowledge to gain. We have observed some farmers in Madagascar changing the water management regime with SRI to an alternating pattern with paddies flooded for 3 days and then drained and dried for 3-4 days. The objective is to keep rice roots from being suffocated by continuous flooded conditions.

   Reducing water requirements for rice could be a major contribution to agriculture in the 21st century. SRI's water management regime is hard for people to accept because it has been believed for ages that "rice is an aquatic plant." But while rice can *survive* under flooded conditions, we observe that it does not *thrive* under such conditions. Flooding creates anaerobic soil conditions, which subject rice roots to hypoxia (oxygen starvation).

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[1] A recent CIMMYT publication reports on a somewhat similar technology developed for wheat by farmers in Sonoroa, Mexico (Sayre and Moreno 1997). Farmers who used wide spacing on raised beds and furrow irrigation, instead of flood irrigation, reported that wheat yields did not change as the seeding rate was reduced from 200 kg/ha to 25 kg/ha. Possibly with some other changes in management practices, the yield level could have been increased as seen with SRI methods.

It has long been known that rice roots when growing under flooded conditions "senesce," i.e.,

die back, by the time the plant reaches the flowering stage (panicle initiation). But this has been assumed to be "natural," with no questioning or evaluation of whether or not these conditions are beneficial for rice plants. An exception is research by Ramasamy et al. (1997).

When Indian scientists (Kar et al. 1974) grew the same HYV (Taichung native cv) in both saturated and unsaturated soils, they found that by the onset of panicle initiation, from which time, grain formation and filling begins, ***78% of rice plant roots growing under flooded conditions had degenerated***. There was no degeneration of roots in well-drained soils. It is hard to imagine that such a massive loss of root capacity by the time when grain production starts would have no adverse effects on yield, but we have found no research demonstrating that what has been *assumed* is in fact correct.

Our own research shows ***much greater root development*** with SRI methods, which are grow rice under mostly aerobic conditions. The amount of force required to pull up a clump of *three* plants grown with conventional methods was 28 kg. This reflects the surface tension which the root system had with its surrounding soil. The force needed to uproot a *single* plant grown with SRI techniques was 53 kg -- *almost six times more force per plant* (Joelibarison 1998; this method for evaluating root development was validated by IRRI in the 1980s). Understanding the causes and effects of greater root growth in rice is an area where much systematic research is warranted but has been lacking.[2]

5. When rice is not grown under flooded conditions, weeds are likely to become a problem. With SRI, it is necessary to do **several weedings** -- at least 2 and preferably as many as 4 before panicle initiation. This is best (most quickly and beneficially) done with a simple, inexpensive mechanical hand push-weeder (rotating hoe), that was developed at IRRI in the 1960s and that churns up the soil with small, toothed wheels. No nutrients are lost to weeds as they are returned to the soil to decompose.

   This weeding method has the advantage apparently of *aerating the soil* to encourage greater root and canopy growth. Analysis of data for 76 farmers using SRI methods around Ambatovaky near Ranomafana in the 1997-98 season found that *each weeding beyond two added 1 to 2.5 t/ha to yield*. Similar increases had been observed the previous year for 40 farmers. Whether this effect is limited to the soil and other conditions around Ambatovaky is not known, but it should be assessed. The hypothesis that active soil aeration can enhance rice plant growth and performance is one of the most interesting propositions to emerge from work with SRI thus far. This merits systematic evaluation, since the cost for an additional weeding in Ambatovaky was about $25, with an associated increase in yield worth about $300-750.[3]

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[2] There has been sadly little research done on rice roots. The most comprehensive and authoritative text on rice (DeDatta 1987) devoted only 8 lines out of 390 lines of text to any mention of roots in its chapter on the morphology, growth and development of the rice plant. Its index, with over 1,100 entries, has not a single entry on roots, and only one perfunctory reference to the rhizosphere. The author, who is a friend and colleague, explained this to me by saying that there was no research to report.

6. As discussed already, given the poor nutrient status of soils in most of Madagascar and the high yield levels resulting with SRI, some nutrient amendments should be normally part of the methodology. SRI was initially developed using chemical fertilizers, but drastic price increases in the late 1980s led to use of **compost**, which has contributed to the higher yields, sometimes to very substantially greater yields.

*4. Why were these practices **not discovered before**?*

Farmers have been growing paddy rice for thousands of years. One would expect that any practices which can exploit existing yield potentials of rice to the kind of levels reported here would have been discovered already. There are two main reasons why it took both diligence and serendipity to assemble the practices that constitute SRI. Both of these terms apply to Father de Laulanié, who developed the SRI methodology after and by working with Malagasy farmers for two decades.

1. Weeding and nutrient amendments are not controversial practices. It is the first four discussed above that are the core innovations of SRI. Each of these was unlikely to be discovered and adopted because **each seems to reduce the risk of crop failure**.

   Farmers in the past would have been reluctant to try these practices because they *look so risky*. (a) Planting large, mature seedlings seems like it should reduce the risk of plants dying after transplanting. (b) If several seedlings are planted together, at least some should survive. (c) Planting more plants is expected to give more yield, and (d) keeping an abundant supply of water in the field not only suppresses weeds (its main function), but also assures that the plants and soil will not dry out.

   SRI is *counterintuitive*, with "less" producing "more." Younger and fewer seedlings, grown in less water, produce more rice. Actually, we have not observed greater risk with SRI because its practices create a growing environment that is most suitable for rice plants. There is more labor and more management required; so the gains do not come free. But the returns to land and labor are increased enough to justify the greater effort.

2. If farmers tried any one of these SRI practices, the resulting yield improvement would be only a fraction of what can be produced with the full set of practices used together because of the **synergy** among them. There is an demonstrable ***positive feedback***

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[3] Yield levels associated with different numbers of mechanical weedings were as follow:

Weedings	N	Area (ha)	Harvest (kg)	Yield (t/ha)
None	2	.11	657	5.97
One	8	.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

Bonlieu (1999) found additional weedings to add about 0.5 t/ha to yield under the poorer conditions around Morondava on the west coast of Madagascar. Even this lower increment was a cost-effective investment. The possible beneficial effects of active soil aeration are something that deserves further evaluation.

relationship between (a) greater root development and (b) greater tillering, and vice versa, and then when both contribute to (c) greater grain filling.

Transplanting young plants when other practices remain the same would not reveal the potential for more tillering. Spacing mature seedlings widely would give more root growth, but probably no increase in yield. Closely-spaced plants would not do well in well-drained fields because of their limited root growth. So, the whole *ensemble* of practices should be practiced together to get the remarkable results we see with SRI. If it is quite unlikely that the separate, apparently-risky practices would be experimented with, it is even less likely that the set of practices the constitute SRI would be tried out by farmers whose livelihoods depend on their rice production.

We would note that IRRI, in a communication responding to the papers and data on SRI that we submitted to it in early 1998, acknowledged that each of the SRI practices can enhance yield (it had no data on use of single seedlings, however). But it did not address the possibility of *multiplicative rather than additive* effects, which was supported by our data and suggested explanations.

*5. Has this hypothesized explanation of **synergy** been demonstrated?*

Yes. Students in the Faculty of Agriculture at the University of Antananarivo have conducted **factorial trials** that would assess the *respective and joint contributions* to yield that are made by the different practices that together constitute SRI. This is very complicated and demanding work, but Jean de Dieu Rajaonarison carried out factorial trials during the 2000 minor season on the west coast of Madagascar near Morondava. Andry Andriankaja then conducted trials in 2001 at Anjomakely, 18 km south of Antananarivo on the high plateau. Both studies were supervised by Prof. Robert Randriamiharisoa, director of research for the Faculty of Agriculture.

Both sets of trials tested six factors: age of seedling (16 or 20 days vs. 8 days), number of seedlings per hill (3 vs. 1), spacing (25x25 cm vs. 30x30 cm), water management regime (continuous flooding vs. controlled applications), fertilization (no fertilization as a control vs. NPK applications vs. compost), and either variety (HYV vs. local variety) or soil (good quality clay soil vs. poor quality loamy soil). This design required 96 trials (2x2x2x2x3x2), which with three replications required 288 plots, each 2.5 x 2.5 m (or 240 in the Anjomakely trials, since there were no trials with no fertilization on the poor soil in that split plot design). Because the values for the spacing factor in both sets of trials were both within the SRI range and yielded essentially no difference, 0 t/ha or 0.08 t/ha (N = 288 and N = 240), in our analysis we combined the spacing trials which means there are *six replications*, not just three, for each of the factor combinations reported.

Results have been reported in their theses (Rajaonarison 2001; Andriankaja 2001) and are being reported in more detail elsewhere. The findings are summarized in the following table. The number of plots included for the respective averages is shown in parentheses.

	Morondava (same soil)			Anjomakely (same variety)		
	HYV	Tradl.	Ave.	Clay	Loam	Ave.
Conventional Practices:						
mature seedlings, 3 per hil	2.84	2.11	2.48	3.00	2.04	2.52
saturated soil, NPK fertilizer	(6)	(6)	(12)	(6)	(6)	(12)
Average with 1 SRI practice:	3.39	2.67	3.03	4.25	2.83	3.54
young seedling, or 1 per hill,	+0.55	+0.56	+0.55	+1.25	+0.79	+1.02
or aerated soil, or compost	(24)	(24)	(48)	(24)	(24)	(48)
Average with 2 SRI Practices	4.10	3.27	3.69	6.74	3.57	5.16
	+0.71	+0.60	+0.66	+2.49	+0.74	+1.62
	(36)	(36)	(36)	(36)	(36)	(36)
Average with 3 SRI Practices	4.68	4.28	4.48	8.31	4.59	6.45
	+0.58	+1.01	+0.79	+1.82	+1.02	+1.39
	(24)	(24)	(48)	(24)	(24)	(48)
All SRI practices:	6.83	5.96	6.40	10.35	6.39	8.37
young seedling, 1 per hill	+2.15	+1.68	+1.92	+2.04	+1.80	+1.92
aerated soil, compost	(6)	(6)	(12)	(6)	(6)	(12)

*6. How can such high yields be obtained on such **nutrient-deficient soils**?*
This is a challenging question. We think that the increased tillering and root growth can be explained based on existing knowledge, discussed below. But it is a puzzle as to how such high yields can be obtained on soils that are deficient in all nutrients (and with high levels of Fe and Al -- in many areas around Ranomafana there is serious iron and aluminum toxicity). pH levels range usually between 3.8 and 4.6. In most locations, phosphorus (3.5 ppm) is less than half of what is thought to be the minimum for any respectable crop growth (10 ppm). We have a number of hypotheses that deserve examination. These are based on leads that we have gotten from the literature.

1. **Root development:** The simplest explanation, and surely a crucial part of SRI, is the much greater development of root systems with SRI methods. When rice is grown under flooded conditions, the roots, especially with plants placed in clumps and planted close together, do not develop much depth. Most of the fine roots are in a mat close to the surface, reflecting the root system's demand for oxygen, which it can get at the water-soil interface from oxygen dissolved in irrigation water than more deeply in the soil. In general, under irrigated conditions about 75% of rice roots are concentrated in the upper 6 cm of soil (Kirk and Solivas 1997: 619). This, however, is not necessarily the way that rice roots grow "naturally," i.e., when there is a good supply of oxygen in the soil.

If chemical fertilizer is provided abundantly at the same time as water, the roots can be "lazy," since they do not need to grow in search for water and nutrients.

With SRI practices, the root system is several times larger and considerably deeper, enabling them to access more nutrients even in nutrient-poor soil. A large root system is more likely to capture some of the essential trace minerals like Zn, Mg, B and other elements that are important for plant growth and health. This will give the plant *more balanced nutrition*. Possibly the mechanical hand weeder used with SRI by pruning some of the upper roots encourages deeper root growth, though this is at present conjecture.

This first possible explanation is essentially structural or mechanical. It focuses on plants' *increased access to nutrients* that can result from having a larger root system which itself results from the way that an SRI rice plant is managed. Early transplanting is essential for this effect; it not only preserves plants' greater tillering potential but an accompanying potential for greater root growth.

2. **Biological nitrogen fixation (BNF):** Rice plants producing 8, 10, 15 or even 20 tons per hectare require large amounts of nitrogen, which is quite evidently not present in the soil. The amount of nutrients added through compost cannot explain the observed yields. There is a small body of literature on BNF in rice that is not yet very encouraging. As much as 70 kg/ha of N can be provided by diazotrophic microorganisms in, on and around the roots of rice plants (Ladha et al. 1998: 56). This would, however, not be sufficient for the kinds of yields achieved with best SRI practices.

Most of the BNF research has considered rice grown under flooded, i.e., *anaerobic* soil conditions. The work of Johanna Döbereiner and associates in Brazil has shown that sugar cane, also a gramineaceous species, can get 150-200 kg/ha of N through BNF, which is more in the range that would be required for high rice yields. While most people think that BNF is associated only with leguminous species, practically all gramineae (grass) species can benefit from BNF accomplished by associated microbes in, on and around the plants' roots. The research by Döbereiner, summarized in (1987), found that BNF is not a fixed capacity, but rather more a contingent one. More BNF has been observed in soil that has not had N fertilizer applied, and with cultivars that have not have N fertilizer applications through several generations.[4]

There is a symbiotic relationship seen between plants and the complex associations of microorganisms that live in the rhizosphere and on and in the roots. Microorganisms are able to transfer capabilities *within generations and even among species* through exchange of plasmids that contain genetic material, as shown by the work of Lynn Margulis and others (Margulis and Sagan 1986). Döbereiner (1987) postulates that BNF is a capability that can increase or decrease within *populations* of microorganisms according to plant requirements, not being the result of just a single species. About 80% of the bacteria found in rice roots are N-fixing (Ladha et al. 1998: 57, citing Watanabe et al. 1981).

[4] This could explain, at least in part, why researchers outside Brazil have had difficulty replicating some of Döbereiner's results, if they treat BNF as an inherent quality rather than as one that has responsive or evolutionary qualities.

The only literature we have been able to find assessing differences in BNF between aerobic and anaerobic soil conditions indicates that BNF is greater when aerobic and anaerobic soils were continuously mixed compared to anaerobic or aerobic soils alone (Magdoff and Bouldin 1970). The increased yields observed around Ambatovaky and also on the west coast around Morondava (Bonlieu 1999) were associated with additional weedings with the "rotating hoe" which churns up the soil might be explained, at least in past, by such a dynamic, where layers of more and less aerobic soil are mixed together.

The water management regime with SRI which involves alternatively wetting and drying the fields could also contribute to the BNF dynamic that Magdoff and Bouldin observed. Recent research in the U.K. found that alternatively wetting and drying soils increases greatly, by 185-1900%, the amount of water-soluble P in soil. The researchers suggest that this dynamic could also increase nitrogen mineralization in tropical soils. Under aerobic, unflooded conditions, populations of aerobic microbes can flourish which are then killed by osmotic pressure when the soil is wetted, making their contents available (Haygarth and Turner 2001). Research on such dynamics and effects is overdue. Most soil analyses focus on inorganic rather than organic forms of nutrients. There has been no interest in the effects of alternating aerobic and anaerobic soil conditions because it was presumed that rice should be grown in a continuously flooded, anaerobic environment.

3. **Demand-Constrained N Uptake**: It is widely recognized that rice uptake of N is very "inefficient," with sharply diminishing returns as more N is supplied through fertilizer (Kirk and Bouldin 1991; Ladha et al. 1998). Only 30-40% of the N applied to fields is taken up by rice plants. Kirk and Bouldin (1991: 199) report that the uptake rate of N is "independent of the concentration (of N) at the root surface." Rice plants have very sophisticated (and poorly understood) mechanisms for *down-regulating* uptake when their internal N status is satisfactory. They up-regulate their capacity for uptake when their need is greater.

A model of N acquisition in rice plants that is driven more by demand than by supply would explain the low efficiency of N applications and the observed diminishing returns. Quite possibly we have been overestimating plants' N requirements by focusing so much on supply. We do not know how much N rice plants can get from their rhizosphere when and as they need it. Possibly rice plant growth is not as constrained by N supply as has been thought but rather by the conditions under which rice plants are grown.

With SRI practices, when seedlings are transplanted very early and very carefully -- with no trauma to the root and no malpositioning thereof, and with favorable soil conditions -- the plants can go through a very rapid, *indeed exponential*, growth of tillers and roots, as discussed below. This pattern of growth would create very considerable demand for N, causing the roots to up-regulate their uptake of N to meet plant needs.

One possible reason for the down-regulation of N uptake even when N is abundantly available in the root zone could be that plants need a "balanced diet" of nutrients. With a stunted root system, they do not get the trace elements that are needed to utilize properly the N available for plant

growth. The plant protects itself when it lacks enough of other nutrients for "balanced growth" by shutting out N, or by efflux of ammonia that offsets influx.

Thus, the SRI plant-soil-water-nutrient management practices that result in accelerated tillering and root growth during the vegetative growth phase could be creating the necessary demand to drive N uptake, provided that the plant has sufficient intake of other nutrients needed for healthy growth.

The twist that this model gives is that the plant is seen not as a biological machine, which we can force to grow by putting more inputs into it, but more as a biological organism, which has its own needs and capabilities that we would be well advised to understand and work with, rather than try to warp for our purposes. Possibly there has been a huge waste of expenditure on N fertilizer, with environmental as well as economic costs, which could be averted with a different tack.

4. **Overestimation of Plant Nutrient Requirements:** An even more radical explanation, consistent with the above, derives from the work of Ana Primavesi, a Brazilian agronomist whose work is widely known and respected in Latin America within sustainable agriculture circles. She reported in her 1980 book on ecological management of tropical soils (translated from Portuguese into Spanish in 1984, but never into English) the following results of an experiment with maize grown hydroponically in nutrient solutions of different concentrations.

	Plant (g)	Roots (g)
Normal solution (100% concentration)	0.43	0.07
Concentrated solution (200% concentration)	0.33	0.07
Diluted solution (2% concentration)	0.31	0.23
Diluted solution, Frequently changed (2% concentration)	0.44	0.56

Unfortunately, as far as we know, this experiment has not been followed up with further study, but this is a research result that begs examination. It suggests that plants can have normal growth with **very low concentrations of nutrients** provided that there is **constant supply** to the root system. There will be compensating growth of roots, such as seen with SRI in the very poor soils of Ranomafana and elsewhere in Madagascar, so that small amounts are continuously accessed to support growth of the canopy and further roots. The beneficial effects of using compost would be consistent with this understanding, as it releases its nutrients very slowly even if they are not provided in large amounts.

Primavesi's results are so far outside our present understanding of plant nutrient requirements that they have been ignored. But if they are correct, or even partly correct, the implications for agricultural theory and practice are immense. Scientists who have been fixated on "harvest index" may be appalled by the "waste" implied by massive root growth. But if the nutrients that go into root structures remain in the soil, they are not lost to the biological system.

The yields obtained with SRI are similarly "far outside our present understanding" of plant potentials. So we are forced to consider explanations that depart from the presently accepted ones, though they should be contiguous and continuous with the body of scientific knowledge that has been accumulated thus far.

The four strands possible explanation sketched above are consistent with things known about rice plant physiology, though not necessarily widely known or yet accepted. They could be mutually reinforcing, in that none is sufficient by itself to account for the large increases in rice production with SRI practices, but collectively they could explain how yields can be achieved that are up to 10 times the national average.

Such dynamics could explain why with SRI, the correlation between number of tillers per plant and number of grains per panicle is **positive rather than negative**. That a negative correlation has been observed in the past is probably due to the conditions under which rice has been grown, e.g., saturated soil, rather than to any inherent characteristic of rice. The shallow rooting and root senescence that have been observed with irrigated rice and have been taken as natural characteristics of rice likewise are probably an artifact of plant, soil, water and nutrient management practices.

*7. What explains the **greater tillering** with SRI?*

"Normal" rice plants will have 5-10 tillers, maybe up to 15 or 20 under best conditions. With SRI, the average number of tillers can easily be 30 per plant, often 50 per plant, and with best management even more. Individual plants can have 80 or even 100 tillers, with huge bases, all coming from a single tiny seedling transplanted when less than 2 weeks old. The record number of tillers with is currently 140, but possibly this will be exceeded with further improvements in understanding and practice.

It is known that when plants are more widely spaced, they will produce more tillers. But farmers do not want to maximize tillers per plant; they want the most grains of rice per unit of land (and per hour of labor and per investment of other inputs). So tillering per se is not an advantage. Farmers and scientists have tended to seek an optimum through higher rather than reduced plant density. This, however, according to Fr. de Laulanié's work is a mistaken strategy. Rather, one should seek an optimum within a strategy of wide spacing rather than dense planting.

What Kirk and Bouldin (1991: 199) say that "the mutual regulation of root and shoot activities is poorly understood. One should not talk about either root or tiller growth as independent activities, since both are interdependent, and anything that inhibits either inhibits both. However, I will write here just of tillering, presenting what Fr. de Laulanié discovered empirically in 1983 and could then explain in physiological terms after he became acquainted with the work of the

Japanese researcher, T. Katayama, who discovered the basic patterns of plant growth for rice and other graminaeceous species that can be mapped in terms of *phyllochrons*.

Katayama's work, done mostly in the 1920s and 1930s, was published in Japanese in 1951. Unfortunately, it has never been translated into English, so English-speaking researchers have little knowledge of phyllochrons. These were reported in French in a book on rice by Didier Moreau (1987). This was how Fr. de Laulanié learned about phyllochrons, which helped explain the superb results he had begun obtaining with SRI methods. Even a three-volume encyclopaedia of Japanese scientific knowledge on rice (Matsuo et al. 1997) contains only a few pages on phyllochrons, with no consideration of their possible implications for raising rice production. A recent dictionary of plant science terms and concepts published by Oxford University Press does not even have an entry on 'phyllochron' in its 500 pages (Allaby 1998).

Little attention has been devoted to phyllochrons, at least with regard to rice. However, in 1995 there was a whole issue of *Crop Science* (35:1), the journal of the Crop Science Society of America, devoted to phyllochrons, considering mostly how they can help to explain the growth and performance of wheat. The only article on phyllochrons in rice was contributed by Japanese scientists who were familiar with Katayama's work (Nemoto et al. 1995).

Phyllochrons are recurrent period or interval of plant growth during which the plant, from its meristem, puts out one or more units (called phytomers) of a tiller, a root and a leaf. The length of time for a phyllochron is determined by a complex of factors, noted below, rather than by a fixed period of calendar time. In Madagascar, the length of a phyllochron can be as little as 5 days, though it can be even as few as 4 days at low altitudes where temperatures are high, and as much as 7 or 8 days at high altitudes with cold temperatures.

This statement already does some injustice to the complexity of phyllochrons, because they can become longer as a result of other factors than altitude and temperature, the most obvious and measurable factors. If the soil is too dry, or too wet and lacks oxygen, or is deficient in nutrients, or is too hard and impermeable, the length of these intervals of growth will become longer. If plants are closely spaced, for example, so that their roots have less space for growth and their canopies are too dense for light and air to be abundant, the intervals will also become longer.

For maximum tillering (and root growth), one wants to complete as many phyllochrons as possible during the vegetative growth phase, before the plant begins its reproductive phase with the onset of flowering and panicle initiation. Rice scientists talk about periods of early tillering, active tillering, and active tillering without appreciating the relationship among the tillers that are being produced, instead referring to them in aggregate, quantitative terms, rather than structural or relational terms.

Katayama discovered the qualitative, structural relationships among tillers, most importantly, that -- provided conditions are conducive -- *each tiller (except for the main tiller) produces another tiller two phyllochrons later*. (The main tiller takes three phyllochrons to begin producing tillers from its base.) This dynamic pattern of plant growth leads to *accelerating increases* in the number of tillers (and roots) if the plant can prolong its vegetative growth period, before it starts its reproductive growth.

Toward the end of the potential vegetative growth period, there can be really rapid tiller and root growth before panicle initiation begins, as shown below. Rather than a logistic (S-shaped) curve of tiller growth that is observed with rice grown under the constrained conditions of flooded soils and degenerating roots leading to severe senescence by the time of panicle initiation, the curve can be instead exponential.

The pattern of tiller/root production in a plant having favorable conditions is as follows:

Phyllochron	New Phytomers	Cumulative No. of Phytomers
1st	1	1
2nd	0	0
3rd	0	0
4th	1	2
5th	1	3
6th	2	5
7th	3	8
8th	5	13
9th	8	21
10th	12	33
11th	20	53
12th	31	84

Note that these numbers follow what is known in biology as the Fibonacci series, a pattern of exponential growth often observed with plant or animal life, where each period produces a number of "offspring" equal to the total of the two preceding periods. (Note that after the 9th phyllochron, the numbers produced in each successive period are reduced by 1 or then by 2, etc., because of physical limitations of space at the base of a tiller for adding more tillers in the respective rings. Rice plants do not achieve the full potential of a Fibonacci series.) The exponential pattern is seen by grouping phyllochrons by threes through 12 phyllochrons of growth:

1-3	1	(4^0)
4-6	4	(4^1)
7-9	16	(4^2)
10-12	63	$(4^3 - 1)$

If phyllochrons are grouped into sets of four, we see a truly exponential path of growth:

1-4	2
5-8	11
9-12	71

There can be many reasons why a rice plant might not be able to complete 12 phyllochrons of growth before it switches into its reproductive mode, shutting down vegetative growth and concentrating its growth energies on flowering, grain formation and grain filling.

The first and most critical reason is that rice seedlings transplanted after the third phyllochron experience trauma or shock that slows their growth (lengthens phyllochrons) so that the plant cannot complete as many phyllochrons before switching from vegetative growth to begin reproduction. When seedlings are transplanted in their initial growth stage, before the fourth phyllochron, and if they are transplanted carefully, the trauma and shock can be minimized. The plant proceeds to grow rapidly (with short phyllochrons). When transplanted seedlings are 3 or 4 weeks old, or even older, their biological clock is slowed, and plants complete only 6, 7 or 8 phyllochrons of growth before flowering begins.

Other factors can also slow the biological clock, such as the soil being too dry or too wet or nutrient-deficient. We have seen that plants been transplanted later than the third phyllochron (once they get more than just two tiny initial leaves) lose much of their potential for tillering (and rooting). This is a matter of physiology, following the analysis done by Katayama many decades ago. Unfortunately, the productive implications of his analysis could not be seen until it was linked with different plant-soil-water-nutrient management practices (spacing, water application, etc.) that could bring out the potential for rice plant growth.

Root growth is explained along with greater tillering by the insights one can get from understanding phyllochrons. The master farmer reported above, Ralalason, said that he had one rice plant in 1998-99 with 140 tillers. This means that the plant got into a 14^{th} phyllochron of growth before panicle initiation. Many farmers with SRI have reached 100 tillers, which means that these plants reached into their 13^{th} phyllochron. If a 13^{th} phyllochron of growth can be completed, this will add 50 tillers (134 total), while a 14^{th} phyllochron could add 80 tillers (for a total of 234). This latter number is for now purely hypothetical.

Fr. de Laulanié thought that when sufficient knowledge had been gained about phyllochron dynamics and the conditions under which rice plants could perform maximally, yields as high as 20-30 tons per hectare would be possible with rice. This suggestion will astound rice specialists who have concluded that there is presently a "yield ceiling" for rice between 12 and15 t/ha. Laulanié was persuaded from his decades of work with rice that super-yields could be attained with existing genetic potential, by varying management practices to better accommodate plant requirements.

*8. Do SRI principles apply only for **transplanted lowland rice**?*
No. We have done some experiments adapting SRI concepts to **upland rice**, not involving any transplanting or water management, but using spacing, compost and soil aeration, and have gotten a yield of 4 t/ha. Our purpose was to find some alternative to slash-and-burn cultivation of rice in upland areas. This compared very favorably with traditional upland yields of 0.8-1.5 t/ha and was achieved with compost and a small amount of fertilizer, no burning. It did require, however, more labor input. The main constraint is the labor time required for cutting up (shredding) leguminous shrub branches (tephrosia and/or crotalaria) to produce the mulch needed to suppress weeds, provide nutrients, and retain soil moisture.

We have also tried **direct seeding** while evaluating the effects of varying SRI practices, with good results. Some of the plants had more than 100 tillers, but we could not get any yield data

because locusts devastated this profuse test plot. The principles of SRI should not require transplanting, which is probably more of a detriment than benefit. A Malagasy woman farmer reported to us in January 2000 that she had divided her small farm (just 13 ares) into two parts, half transplanted and half direct-seeded, with no real difference in yield, but some saving in labor time. She was persuaded that direct seeding could be more advantageous than transplanting. This is another area for evaluation.

*9. What are the best **transplanting practices** for SRI?*
We see the transplanting step in rice production as crucial, because so much of the success of SRI depends on vigorous and extensive root growth, to support the increased tillering and then the greater grain production. Much of the loss of potential yield with conventional practices we see as due to inappropriate, even harmful transplanting practices, quite apart from the over-maturity of the seedlings.

With SRI, the young seedlings are removed very carefully from the nursery with a trowel or other implement so that the seed is not separated from the tiny root. (The nursery has been managed like a garden and not flooded, just watered as needed with a watering can.) The seedlings are transported quickly to the field and kept covered and moist, so that the roots do not become desiccated. Because there are so few seedlings required, transport is easy. They should be transplanted with 15-30 minutes.

Most important, the plants are **not plunged down vertically into the soil**, as this is likely to invert their root tips, giving the transplanted seedling a *J shape* with the root tip oriented upwards. When situated in soil this way, the plant requires time and energy to reorient its root tip downward so it can resume growth. SRI plants are laid into the soil with a **sideways motion**, so that the root lies horizontally, and the seedling has more of an *L shape*. Actually, an *I shape* would ideal, but this is very difficult to achieve.

Seedlings that have been taken roughly from the nursery will lose many of their fine roots. To the extent its roots are allowed to dry out, the plant's growth will be set back, and fewer phyllochrons of growth will be achieved. If plunged into standing water, which is a hypoxic environment, the plant will experience even more trauma, especially if its root tips have not been properly oriented for quick resumption of growth.

Transplanting shock can last 1-2 weeks (Kirk and Solivas 1997: 618). This is time taken out of the vegetative growth phase, reducing rapid tiller and root growth at the end of that period. When farmers are planting hundreds of plants per square meter, they cannot give each of them the care that SRI recommends. But when spacing is only 25 by 25 cm (16 plants per m^2), or 50 by 50 cm (4 plants per m^2), farmers can afford to give what we call 'TLC' (tender, loving care) to each seedling. The effort will be repaid if water management and weeding practices support the accelerated growth of the plant.

*10. What about the **sustainability** of this system?*
Can these high yields be maintained on poor soils? In general we find that farmers' yields go up over time rather than decline, reflecting greater confidence and skill in using the methods. Possibly skill factors are masking soil nutrient depletion, but our observation is that the methods

of soil, water, plant and nutrient management enrich the soil, by supporting greater microbial biodiversity, which is makes unavailable nutrients available through such processes as phosphorus solubilization. But answers to this question need to be empirical, and we do not have enough evidence to provide a confident answer. Probably at some point, there will need to be inorganic amendments of nutrients such as P, but our hope is that with higher production and profits, farmers can afford to make such soil amendments.

*11. Can a **labor-intensive strategy** of agricultural production succeed in today's world?*
This is a very important question. Once one has gotten over the problem of incredulity -- how can cutting the seeding rate drastically and having so few plants give double or more the yield? -- and the physical constraint where farmers have field-to-field irrigation and thus little control over their supply, the labor-intensity of SRI is the main barrier to adoption of SRI. We recognize that this is a problem for many farmers, particularly the very poor who have little land and must invest their labor in immediate returns to feed their families on a day-to-day basis. They cannot afford to wait three months for a high return on their labor.

What we do know and can say is that the returns to labor should be at least 50% higher with SRI compared to conventional methods. (This calculation is based on a detailed analysis of the practices and returns for 108 farmers in Madagascar who are practicing both SRI and conventional rice production on their farmers, which controlled for soil quality and for farmer skill differences.) Since the returns to land and water as well as labor are higher with SRI, it is advantageous -- if labor supply is a constraint -- to practice SRI on just a part of the household's rice land, and to use the rest of the land for some other productive purpose at a time and in a way that does not compete with the rice management cycle. If a household does not have enough labor to use SRI for its entire rice land, it will be better off using the methods on part of its holdings. This seems counterintuitive, but so is much about SRI.

In fact, there may be reason to question whether SRI is or needs to be labor-intensive. During a recent visit to Sri Lanka when some farmers using SRI practices were asked how additional labor was required per hectare to use these methods, several farmers who have been using them for several years now and have gained skill and confidence replied that they are finding that SRI requires ***less labor per hectare*** than the conventional modern methods they had been using, e.g., applying four sprayings of pesticides per crop -- if this labor is saved, this can be better used in the weeding operations, and they now find that they require less labor for transplanting with SRI. So possibly we may find that SRI is not even more labor-intensive on average, though when the methods are first used, they definitely will require more time to be invested in acquiring skills to manage rice more carefully and effectively.

Further Issues
These are not the only questions that could be asked, but the answers give a good understanding of this methodology for raising rice yields. Association Tefy Saina and CIIFAD to not refer to it as a 'technology' because it is not a set of practices to be adopted as a package. There are some core principles, with which certain practices like use of young seedlings or early and frequent weeding (soil aeration) are associated. But farmers are encouraged to approach SRI experimentally, at least varying the spacing and water management to learn what will give the best results under their particular soil and other conditions.

Association Tefy Saina, CIIFAD and our colleagues in FoFiFa and the University of Antananarivo have been trying to construct plausible explanations for the remarkable increases in production that we have seen SRI make possible. These are still hypotheses that need to be examined and confirmed, or disproved, by plant and soil scientists who have the appropriate training, methodologies and means.

To test these hypotheses thoroughly and fairly, it will be important for scientists to understand the principles behind SRI and to consider it in a holistic manner, within which particular mechanisms or relationships are measured and tested -- rather than approach SRI piecemeal, examining it in *ceteris paribus* terms, component by component.

We do not ask anyone to accept SRI or to "believe" in it without empirical validation, but rather to approach it with a willingness to explore the possibilities and potentials of synergy. We should at least entertain the possibility that from this examination of SRI, we will emerge with a somewhat different paradigm for understanding rice plants' growth and performance. Possibly this understanding can extend to other crops as we come to appreciate more fully the contributions that soil microbiology can make to more productive and more sustainable agriculture, tapping genetic potentials that already exist.

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