THE SYSTEM OF RICE INTENSIFICATION (SRI) AS A METHODOLOGY FOR REDUCING WATER REQUIREMENTS IN IRRIGATED RICE PRODUCTION

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I. INTRODUCTION

Worldwide, the agricultural sector makes the largest demands of any sector on our finite fresh water resources, and within this sector, irrigated rice production is the largest source of demand for fresh water. Given the following trends, making substantial, not just marginal, reductions in on-farm water consumption in rice farming will have far-reaching, even urgent significance:

- **As populations continue to grow** -- with supplies of fresh water at best remaining constant – ***water availability in per-capita terms*** declines each year, until population growth ceases.
- **As economic development proceeds**, competing demands for water will make it imperative for agriculture to ***become more water-economizing*** in its production methods. Both domestic consumption and industrial uses are already becoming stronger competitors with agriculture for available water. Rising incomes encourage expectations of better living standards that increase the demand for personal consumption of water, thereby augmenting total demand.
- **Reductions in water quality are occurring in many places** through various kinds of chemical and other pollution. The ***diminishing supplies of pure water*** affect the world's ecosystems as well as human health. Moreover, ***the cost of good water rises*** when water purification becomes more often necessary.
- Further, **impending climate changes are likely to adversely affect our present patterns and amounts of rainfall distribution** over time and space (even if they do not necessarily reduce total global amounts of precipitation, which could occur).

Such trends will make changes in agricultural practice and strategy unavoidable. It is easy to see how these trends put agriculture (and particularly irrigated rice production) on a collision course with the needs of natural environments, with deleterious effects on natural ecosystems and on biodiversity.

Making changes in irrigated rice production should not be expected to accomplish all of the reductions in consumption that will be needed to achieve long-term sustainability for human and other living communities in the face of impending water shortages around the world. Investment priorities, lifestyles, technology and many other factors affecting the supply of and demand for water will have to change dramatically if we are to avoid massive suffering and loss of life in this century from both direct and indirect effects of water shortage.

This being acknowledged, however, it should be clear that this seminar's focus on reducing water consumption in the irrigated production of rice is timely. (1) This sector is an obvious and relatively straightforward place to begin curbing water consumption, and (2) Much of our current water consumption for rice production is ***actually counterproductive***, as explained below. This latter consideration should make the introduction of water-saving more feasible and acceptable.

Experience with the System of Rice Production (SRI) tells us that farmers who grow irrigated rice with continuous flooding of their paddies have been wasting large volumes of water for centuries, even millennia. Fortunately, <u>more rice</u> can be produced by using <u>less water</u>, provided that concurrent changes are made in the way that plants, soil and nutrients are managed (Uphoff and Randriamiharisoa, 2002). While this claim may still be controversial in some circles, this conclusion is supported by experience from a large number of countries with documentation from credible sources (see section III). The claim is reinforced by extensive data from three years of on-farm evaluations in eastern Indonesia, presented in the accompanying case study paper by Shuichi Sato from the Japanese consulting firm of Nippon Koei.

Growing evidence indicates that the challenge of reducing water consumption in the rice sector can be met not with a compromise or some second-best solution, but ***in a positive-sum way*** with multiple benefits. Practices are available for growing rice with less water so that the productivity of the land, labor and capital used in rice production is raised all at the same time while making water more productive. This comes basically from nurturing roots rather than drowning them.

It has long been believed by farmers, and accepted by scientists, that rice grows better in standing water.[1] Lowland rice originated as an important cereal crop because its organs and physiology were better able to tolerate flooding; rice could grow successfully in inundated soil where other crops could not. Over time, farmers selected cultivars better adapted to anaerobic conditions (O'Toole, 2004). Lowland rice varieties have the advantage that they are not affected by the stress of water shortage, which was frequently a major constraint for rainfed upland rice.

Flooding, coincidentally, reduced competition from weeds. This made the practice popular with farmers because it reduced their labor requirements. Over time, what began as an adaptation to unfavorable growing conditions -- making the best of a bad situation -- became the norm. Lowland rice cultivation, able to perform satisfactorily under hypoxic soil conditions, became idealized in Asian cultures, mythology, folklore, and habits, and even in science. Its being 'semiaquatic' became something valued as desirable in itself, rather than being regarded as the adaptation to adverse circumstances that it is – something beneficial but suboptimizing.

The SRI methodology, developed by Fr. Henri de Laulanié over two decades of observation, experimentation and innovation in Madagascar, shows that keeping paddy soils moist but not continuously saturated gives better results, both agronomically and economically, than flooding rice throughout its crop cycle. Data on this are presented in Table 8. This benefit is enhanced by complementary agronomic practices that greatly increase the growth of roots and of soil biota (seen in Tables 1, 2 and 3. These practices make it possible to grow more productive ***phenotypes*** from any rice genotype. Figure 1 shows such difference between SRI and 'regular' rice plants.

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[1] This is a verbatim quote from the director-general of International Water Management Institute (IIMI), Dr. David Seckler, at a Centers' Week breakfast in Washington, DC (pers. comm., October 1998). Ironically, IWMI had just published a monograph providing evidence to the contrary (Guerra et al., 1998). The leading text in English on rice production states categorically that "rice thrives on land that is water saturated, or even submerged, during part or all of its growth cycle... most rice varieties maintain better growth and produce higher grain yields when grown in flooded soil than when grown in nonflooded soil" (DeDatta, 1981: 43, 297-298). This view reflects the conventional wisdom about rice that prevailed through the 1990s. However, by the end of the 1990s, SRI and other evidence such as Ramasamy et al. (1997) and Mao (2000) began to reverse this thinking.

Figure 1: Indonesian farmer holding two rice plants of same variety, i.e., same genotype. SRI plant on left has twice as many tillers (40) as 'regular' plant on right. (Picture by Shuichi Sato.)

II. THE SYSTEM OF RICE INTENSIFICATION

The practices utilized in SRI are not necessarily new. It is their *combination* that creates different growth dynamics for rice plants. Some of the SRI practices were practiced traditionally in China according to Prof. Yuan Longping (pers. comm.), or by Japanese farmers in the 1950s and 1960s before more 'modern' methods displaced them, e.g., heavy application of organic matter to the soil and no continuous flooding of fields (see Horie et al., 2005). Indeed, some SRI practices were used in the development of what is called the 'new plant type' (Khush, 1996), i.e., the use of 14-day-old seedlings, planted singly, and widely spaced, 25x25cm. SRI combines all of these practices, plus it proposes active soil aeration with a rotary weeder (Laulanié, 1993). This latter practice, besides eliminating weeds, stimulates the growth of roots and soil biota.

Although SRI is best explained operationally in terms of making certain changes in conventional rice-growing practices, as listed below, it is not best defined in terms of practices. SRI is better understood by focusing on its objectives than on its means. *SRI is a strategy of irrigated rice production, adapted to local conditions, that alters plant, soil, water and nutrient management practices* (the means) with the purpose (the end) of: (a) inducing larger, better-functioning ***root systems***, and (b) more abundant, diverse and active communities of ***soil biota*** that live in association with those root systems. These organisms include both flora and fauna, from scales that are infinitesimally small to visible scales (Randriamiharisoa et al., 2006). They perform a range of important services for plants as they have done for over 400 million years, from the time when plant species first became terrestrial residents (Margulis and Sagan, 1997).

In the case of rice, we are learning that microorganisms are beneficial not only when living in association with plant roots (Döbereiner, 1987; Boddy et al., 1995) but also when they function

within plant roots, stems and leaves as endophytes (Yanni et al., 2001; Peng et al., 2002; Feng et al., 2005; Dazzo and Yanni, 2006). Rice plants should not be regarded as phenotypes that are determined directly by their genotype. Rather, like other organisms, they are more aptly understood as 'developmental systems' (Oyama, 2000). This perspective emphasizes the importance of multiple and contingent processes whereby the genetic potentials of developing organisms respond to and are guided by their environment, which includes other organisms. Laulanié's inductive methods were conducive to developing an integrated appreciation of the conditions that enable genetic potentials to become most fully realized in practice.

A. SRI Methods

The practices recommended as starting points for SRI are the following:

- When (if) transplanting, start with **young seedlings** (2-leaf stage), usually 8-12 days old, grown in an unflooded (upland) nursery, before the start of the fourth phyllochron of growth (Stoop et al., 2002). Using seedlings 3-4 weeks old is now the norm. [SRI farmers in several countries are now experimenting with direct-seeding, with good results; SRI does not require transplanting, only protection of plant roots from traumatic effects of late transplanting.]
- Seedlings are transplanted **singly**, not in clumps of 3-6 plants per hill, and **widely-spaced**, in a **square pattern** that facilitates weeding. Initial spacing recommended is 25x25 cm, but this can be even wider if the soil is fertile, or once it becomes more fertile with SRI practices.
- Transplanting should be done **quickly**, within 15-30 minutes of removal from the nursery, **shallow**, 1-2 cm, and **gently**, not inverting the root's tip when pushing the seedling into the soil. Careful handling is made more feasible when plant population is reduced by 80-90%.
- Rice paddies are **irrigated intermittently** rather than continuously flooded, so that soil is kept moist, with mostly aerobic conditions, rather than always saturated, i.e., anaerobic and hypoxic. After panicle initiation, current advice is to keep paddies a little flooded (1-2 cm). However, the logic of SRI suggests that intermittent irrigation be continued; this is being evaluated in several countries now, with thus far encouraging results.
- When paddies are not kept flooded, weed problems will become more severe and require **more weeding**. While hand weeding or herbicides can be used with SRI, best results come from multiple weedings with a 'rotating hoe' that **actively aerates the soil** at the same time it churns weeds back into the soil to decompose, thereby conserving their nutrients.
- Chemical fertilizer was originally used with SRI methods. But when it became too expensive for small farmers, SRI recommendation changed to **compost**, just any decomposed biomass. This has repeatedly given better results in factorial trials than does inorganic fertilizer. The other SRI methods have often added to (at least short-run) yield increases without compost.

Given this meeting's concern with **water saving**, this paper will focus on the effects of the fifth practice: **reduced application of irrigation water**. More information on this is provided from Indonesia in the complementary case study by Shuichi Sato, an irrigation management engineer.

B. The Effects of Changing Water and Other Management Practices

The benefits of keeping paddy soils aerated were first clearly documented in large-scale factorial trials done in Madagascar in 2000 and 2001. These were reported at a workshop at IRRI in 2002 on ***Water-wise Rice Production*** (Uphoff and Randriamiharisoa, 2002). The two sets of trials reported evaluated the respective and collective effects of six factors: age of seedling, number of seedlings per hill, spacing between plants, water management practices, kind of fertilization, and (a) variety: HYV vs. traditional, with soil held constant, or (b) soil quality: better clay vs. poorer loam, using the same variety. The trial plots were each 2.5x2.5 m, with six replications of the combinations of factors being evaluated. The trials were set up following Fisher bloc design methodology with randomization of treatments. The first set of trials (N=288) was done on the west coast of Madagascar, under tropical climatic conditions near sea level with poor sandy soils;

the second set of trials (N=240) was done in the central highlands, under temperate conditions at about 1200 m elevation on better clay or poorer loam soils.

Yield differences for the water management factor -- aerated soil (AS) vs. saturated soil (SS) -- are summarized in Table 1. The *ceteris paribus* average yield advantage of AS over SS (N=384) was 1.39 t ha^{-1}, i.e., with equal numbers of trials having seedling age either 8 days or 16-20 days, planted with either 1 plant or 3 plants per hill, and with compost or NPK fertilization. (Spacings were all 25x25cm or 30x30cm, with no significant difference observed between these two; as both are within the recommended SRI range, really only five factors, not six, were evaluated; this meant that there were 6 replications of each combinations, rather than the 3 that was planned.)

Table 1: Comparison of yield (t ha^{-1}) with 16 different combinations of practices, comparing the *ceteris paribus* effects of aerated soil (AS) vs. saturated soil (SS) (Averages are based on 6 replications; the numbers of comparison trials are shown in parentheses)

	Variety: on poor soils		**Soil Quality**: traditional variety	
	HYV	Traditional	Better (clay)	Poorer (loam)
Average advantage of AS > SS for 16 different treatments reported in source	+ 1.61 (96)	+ 0.50 (96)	+ 2.26 (96)	+ 1.19 (96)

Source: Uphoff and Randriamiharisoa (2002), Table 3.

These substantial differences are attributable directly to the effects that growing plants in aerobic rather than anaerobic soil had on ***plant roots*** as well as to the effects that different water regimes had on the ***soil biota*** that can contribute significantly to plants' health and growth, favoring aerobic over anaerobic organisms. One should note, however, that the effects of **combining** aerated soil with the other recommended SRI practices were even greater. This is seen from Table 2 which compares the results of standard rice-growing practices (mature seedlings, close spacing, flooding, etc.) with the results of SRI-recommended practices. **Active soil aeration** was not evaluated in these trials because including alternative weeding methods as an additional factor would have doubled the number of trial plots needed. Other data have shown that the difference between SRI and non-SRI results would likely have been even greater if the use of a 'rotary hoe' vs. hand weeding or chemical herbicides had been included in the design.

Table 2: Analysis of factorial trial results at Morondava, 2000, and Anjomakely, 2001, comparing the effects of varietal and soil-quality differences with SRI vs. non-SRI practices (Average yields in t ha^{-1}; the numbers of trials are shown in parentheses)

	Variety (planted on poor soils)			**Soil Quality** (growing a traditional variety, *riz rouge*)		
Alternative treatments	HYV	Traditional	Average	Better	Poorer	Average
Standard practice: SS, 16 or 20 day seedlings, 3 $hill^{-1}$, NPK fertilization	2.84 (6)	2.11 (6)	2.48 (12)	3.00 (6)	2.04 (6)	2.52 (12)
SRI practice: AS, 8 day seedling, 1 $hill^{-1}$, compost fertilization	6.83 (6)	5.96 (6)	6.40 (12)	10.35 (6)	6.39 (6)	8.37 (12)

Source: Uphoff and Randriamiharisoa (2002), Table 2.

The average yield for all the trials that employed **standard practices**, i.e., saturated soil, older seedlings, 3 per hill, and NPK fertilization (N=24), was **2.5 t ha^{-1}**. In contrast, **SRI** trials with aerated soil, young seedlings, 1 per hill, and compost (N=24) averaged about 3 times more yield -- **7.4 t ha^{-1}**. Thus, ty themselves, SRI water management practices raised rice yield by 1.4 t ha^{-1}, other things being equal. On the other hand, when all the other SRI practices were used together with the reduced application of water, another **6 tons ha^{-1}** were added to output.

These results have been considered too good to be true. But various studies and evaluations done since the 2002 workshop, reported in Section III from other countries beyond Madagascar, have confirmed repeatedly the results reported to that workshop on 'water-wise rice production.' The absolute numbers vary from place to place, and from year to year, but the pattern is repeated. Specifically the accompanying case study from Indonesia, based on 414 comparison trials conducted over a three-year period, gives empirical, on-farm confirmation of these relationships.

C. SRI Water Management Practices

These practices were developed empirically by Fr. de Laulanié from his observing some farmers in Madagascar not keeping their rice paddies flooded during the period of vegetative growth. He tried this on his own trial plots and found that plants thrived better this way. But no systematic evaluations were done to establish whether it is in fact ***optimal*** to apply just a minimum of water (*un minimum de l'eau*) prior to panicle initiation (PI) and then to maintain a thin layer of water, 1-2 cm, on the field after PI in conjunction with the other recommended SRI practices.

Association Tefy Saina, the NGO that was established in 1990 by Fr. de Laulanié with some of his Malagasy friends to promote SRI as part of a comprehensive strategy for rural development (Laulanié, 2003) advises farmers to apply water to the rice paddy in the afternoon or evening, letting the water soak into the soil over night, and then to drain any standing water from the field in the morning. This way, during the day the soil is exposed directly to the sunlight, not losing any solar energy by reflection from a covering layer of water, and the soil is also open to the air. At night, the thin layer of water insulates the field and conserves soil warmth for plant growth. (This effect would not be as important in more tropical climates with less diurnal variation in ambient temperature compared with the temperate climate on Madagascar's central plateau.)

Continuous water management can be quite time-consuming, and in Madagascar this kind of careful application is not necessarily practiced by most SRI farmers. Another paper presented at the 2002 *Water-Wise Rice Production* workshop gave data on a study of 108 Malagasy farmers in four locations in Madagascar. These farmers were chosen for study because they were using both SRI and conventional methods (McHugh et al., 2002). This way, the effects of inter-farm and inter-farmer differences could be minimized. As seen in Table 3 below, almost twice as many farmers were using alternate wetting and drying (AWD) methods on their SRI plots as were doing non-flooding (NF), which is the standard SRI recommendation.

From the bottom row of Table 3, one can see a consistent yield advantage from using the other SRI methods regardless of the method of water management. We note that in this data set, NF was the *least* productive water management method when it was used with conventional practices (mature seedlings, close spacing, etc.). However, since only one farmer was using this combination of practices, his yield may not be representative. In this data set, we note further that AWD showed up as a more productive method of water management than non-flooding.

Table 3: Summary of rice yields with different irrigation management practices on the same farms and with the same farmers in Madagascar (N=108) (CF=Continuous flooding; NF=Non-flooding; AWD=Alternate wetting and drying)

	Conventional plots			SRI plots		
	CF	NF	AWD	CF	NF	AWD
No. of farmers using practice	90	1	17	18	32	58
Overall mean (t ha^{-1})	3.34	2.38	3.52	5.89	5.91	6.74
% Increase with SRI practices	--	--	--	76.3%	147.9%	91.5%

Source: McHugh et al. (2002) Table 4.

Data included in McHugh's M.S. thesis (but not in the workshop paper) reported on the length of time that farmers who were practicing AWD kept their paddy fields first wet and then dry, e.g., 3 days flooding, then 4 days drying; or 2 days flooding, then 8 days drying. The range was from 1 to 10 days for both wetting and drying. Of the 100 hypothetical possibilities (combinations of 1 to 10 days wet and 1 to 10 days dry), there were over 30 combinations, and no patterns were discernable as to why farmers chose one regime or another, or in the associated water-yield relationships. Possibly differences in soil, e.g., water retention, or labor availability, need to economize on time devoted to water management because of high opportunity costs of labor, could account for the different choices. But neither McHugh nor this author could find any consistent explanations.

This suggests that research on the ***optimization*** of water applications when used with the other SRI practices could lead to still greater water saving/water productivity from SRI methods. Fr. de Laulanié may have concluded that getting farmers to greatly reduce their water applications throughout the whole crop cycle would be too radical a departure from past practices and current beliefs to gain acceptance. If so, he might have been satisfied just to get farmers to no longer flood their fields throughout the vegetative growth phase of rice, when CF certainly reduces tillering. Having fewer tillers diminishes not only plants' *sink* capacity, but also their *source* capacity -- since the growth of rice plant roots is directly linked to their rate of tillering. This physiological fact is important to keep in mind.[2] Some SRI practitioners in India such as the Timbuktoo Collective in Andhra Pradesh, are experimenting with AWD throughout the entire growth cycle and are reporting good results. So the SRI water management practices currently recommended may still be *suboptimal* for many conditions, with more water reduction possible.

Any evaluation of water schedule that uses conventional agronomic practices (older seedlings, closer spacing, etc.) is likely to give little guidance for deciding what water management regime will give best results with SRI practices. As seen from Tables 1, 2 and 3, SRI practices have a demonstrable synergistic effect when used together, making the water-saving techniques of SRI more beneficial than when these techniques are used by themselves with conventional practice.

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[2] In rice, as in other gramineae species, tillers and roots emerge concurrently from the apical meristem, in units known as phytomers (Nemoto et al., 1995).This could be one reason why the New Plant Type (NPT) has yet to live up to expectations. After presenting a paper at an international rice conference comparing NPT performance with that of the best non-NPT varieties (IR64 was used as an example of the latter), Dr. Markarim from the Indonesian Agency for Agricultural Research and Development lamented that "NPT is good in sink, but poor in source. The sink doesn't fill." IR64 outyielded the NPT variety by 7.4 t ha^{-1} to 5.8 t ha^{-1}, he reported, and the main reason appeared to be that IR64 had 82% grain filling and the NPT had only 59% (Makarim and Suhartatik, 2005). This researcher had overlooked the way that the NPT had been developed, since the NPT was bred to have fewer tillers but ones that would all be fertile. This means that the number of NPT roots will be correspondingly reduced, thereby reducing the plants' source capacity.

Professor Mao Zhi of Wuhan University in China has been evaluating 'water-efficient irrigation' (WEI) for some years (Mao, 1993, 2000, 2001). He has shown that by reducing flooding, e.g., with no water layer on the fields throughout 75-85% of the rice-growing season, the water requirements for irrigated rice can be lowered with no loss of yield, and indeed with some enhancement. Compared to traditional rice irrigation (continuous flooding), irrigating with only shallow water depth (SWD) reduces water requirements by 3-18%, while alternate wetting and drying (AWD) reduces them by 7-25%; what Mao calls semi-dry cultivation (SDC) which is close to SRI methods cuts water use by 20-50%. Compared to traditional irrigation, SWD gave yield improvements of 1.6-5.3%; AWD enhanced yield by 2.9-6.4%; and SDC raised yield by 8.5% (Mao 2000). These results are close to those reported by Ramasamy et al. (1997) for similar modifications in irrigation practice.

Unfortunately, yield increments in the range of 5-10% may not give farmers sufficient incentive to modify their present practices, since there are certain costs required for learning new methods and then possibly additional labor to implement them. SRI, on the other hand, by combining different and more productive agronomic practices with appropriately altered, water-reducing irrigation schedules, can offer farmers significant economic inducements to reduce their use of irrigation water because of the increased income benefits reported in Table 8 below.

D. Apparent Reasons for SRI Effects

The large increases in yield that result from the greater productivity of the land, labor, water and capital employed in irrigated rice production when SRI practices are used together cannot be attributed to any single mechanism because a large number of concurrent and apparently synergistic effects are evoked by the changed plant, soil, water and nutrient management practices. There has been little scientific investigation done so far on these mechanisms, so their status is more that of hypotheses than explanations. However, many reasonable and tenable explanations can be derived from the scientific literature (Randriamiharisoa et al., 2006).

Many of the possible reasons for SRI results pertain to the way that the rice plants are handled differently. Wider spacing, for example, has the effect of achieving 'the edge effect' throughout the whole field. When plants are more exposed to solar radiation and to circulating air, it is known that this contributes to greater growth and productivity seen in plants growing on the edges of fields. While the edge (or border) effect should be avoided when trying to measure, i.e., estimate, yield, it should be something sought-after through agronomic practice.

The transplanting of young seedlings before they begin their fourth phyllochron of growth also has demonstrable, beneficial and replicable effects on rice plants' tillering and root growth (see Nemoto et al., 1995; Stoop et al., 2002). This effect of transplanting young plants is independent of, but synergistically enhanced by, growing them in well-drained soils with root zones that are kept aerobic for most of the time (Randriamiharisoa and Uphoff, 2002). Here we focus on the effects of managing rice paddy soil under aerobic, i.e., non-hypoxic conditions

Soil Chemistry**:** When rice plants are provided a given supply of nitrogen in the soil in ***both*** ammonium (NH_4^+) and nitrate (NO_3^-) forms, their yield response can be 40-60% higher than if the N available is entirely in one form or the other (Kronzucker et al., 1999). When soils are kept completely flooded, N will be available almost entirely as ammonium, whereas with alternate wetting and drying of soil, as with SRI practices, there is a mix of NH_4^+ and NO_3^- forms.

Further, in saturated soils, plant roots' uptake of silicon is diminished. Rice growing in well-drained soils should have stronger roots and shoots, something we see with SRI. While there have been no detailed analyses, it has often been seen that SRI rice plants can withstand the effects of strong winds and rain. For example, Figure 2 shows two adjoining fields in Vietnam after a typhoon had hit farmers' rice crop.[3] Larger and stronger root systems also make plants more resistant also to adverse effects of drought or cold spells, not just of storms and heavy rain.

***Plant Physiology*:** When rice plants are grown in continuously saturated paddy soils, their growth is diminished and their functioning is compromised by disintegration of the roots.[4] In saturated soil, about 75% of rice roots remain in the top 6 cm of the soil, where oxygen is more available (Kirk and Solivas, 1997). Moreover, when the soil in which rice plants are grown is kept continuously flooded, >75% of their roots degenerate by the beginning of the plants' reproductive stage, according to an evaluation done by Kar et al. (1974).

Figure 2: Rice fields in Dông Trù commune, Hanoi province, after typhoon in September 2005. Conventional rice-growing methods were used in field on right, while SRI methods were used in field on left, with center trip having closer plant spacing to evaluate the effect of this factor. (Picture courtesy of Elske van de Fliert, FAO advisor on vegetable IPM, Hanoi.)

In his research on the effects of reduced water application for irrigated rice, Mao (2000) reported that under alternate wetting and drying, the average number of roots per plant was 58 compared with 51 for traditional flooding; and with AWD, the average diameter of roots was larger, 0.78 cm vs. 0.57 cm. Since surface area increases exponentially with diameter, the amount of contact with the soil that root systems grown under AWD have would be much greater. Also important, Mao reported that the number of *white*, i.e., healthy, well-functioning, roots was 76% more for

[3] A senior researcher with the China National Rice Research Institute reports that the SRI crop of the leading SRI farmer in Zhejiang Province (Nie Fu-Qiu, Bu Tou village, Tian Tai township) was hit by three typhoons during August-September 2005. While most of the neighboring fields were knocked down by the storms, Nie was able to harvest a yield of 11.38 t/ha. While other farmers had low seed-set rates, Nie's rate was 93.8% (Dr. Lin Qianxing, CNRRI, pers. comm., Oct. 8, 2005).

[4] Kirk and Bouldin (1991: 197-198) describe this disintegration as "often almost total" and say that it "must surely impair the ability of the older part of the plant to take up nutrients and convey them to the stele." They note that after panicle initiation, "The main body of the root system is largely degraded and seems unlikely to be very active in nutrient uptake."

AWD rice plants; plants grown with continuous flooding had 57% more roots that were *black*, i.e., decaying and non-functional.

In our evaluations of SRI, we have used the root-pulling resistance (RPR) method developed at IRRI in the 1980s to assess root systems (Ekanayake et al., 1986). In his evaluation of SRI plants in Madagascar, Barison (2002) compared, with replicated trials, the amount of force (in kg) required to pull up rice plants grown by different methods: SRI with compost, SRI with no fertilization, the government's recommended best practices (SRA) with NPK and urea fertilizer, and SRA without fertilization, as well as the traditional system (transplanting mature seedlings closely and under flooded conditions). In Table 4, we see per-plant differences in root-pulling resistance as much as 4 to 10 times, considering that the SRI hills are single plants and there were 2-3 plants per hill with SRA, and 4-6 plants in traditionally-cultivated rice hills.

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

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

Source: Barison (2000), Table 14.

Soil Biology**:** In addition to the effects that SRI practices like wide spacing, transplanting young seedlings, and maintaining aerobic soil conditions would have on soil chemistry and on rice plants' physiology, there are many contributions to plant growth, health and performance that can result from having larger, more diverse and more active communities of soil organisms in, on and around the roots. The beneficial effects that having more aerobic soil conditions can have on biological populations and processes in soil are discussed in Randriamiharisoa et al. (2006). They are only listed here with some references that provide more discussion and information:

- **Biological nitrogen fixation** (e.g., Magdoff and Bouldin, 1970; Watanabe et al., 1981; Boddy et al., 2006).
- **Nitrogen cycling** by protozoa and nematodes (e.g., Bonkowski, 2004).
- **Phosphorus cycling** by microorganisms (Turner and Haygarth, 2001; Gyaneshwar et al., 2002; Turner et al., 2003; Turner and Newman, 2005; Turner et al., 2006).
- **Mycorrhizal fungi** benefits: greater uptake of nutrients and water and resistance to various stresses (Solaiman and Hirata, 1997; Ellis, 1998; Martin et al., 2001; Habte, 2006)
- **Plant growth promotion**, including production of *phytohormones* (Frankenberger and Arshad, 1995; Emery and Atkins, 2002; Khalid et al., 2006), *induced systemic resistance* and protection against pathogens (Dobbelaere et al., 2003).

Research on soil biological aspects of SRI is only beginning, but the net effects of its water management practices are clearly beneficial for the life in the soil, and this in turn is beneficial for rice plant performance. Positive and negative effects of aerobic and anaerobic conditions operate concurrently, which makes sorting them out more difficult empirically than if there were only one set of effects to assess. This is the same problem that faces researchers investigating the effects of phytohormones. We suspect that phytohormone effects were at work which made the root system of the SRI plant on the right in Figure 3 so much larger than the roots of the 'regular' rice plant on the left, which was same age and same genotype.

Figure 3: Rice plants (same variety, VN 2084) both planted in the same nursery 52 days before this picture was taken. The SRI plant on right was transplanted into an SRI growing environment when just 9 days old. (Picture courtesy of Dr. Rena Perez, Ministry of Sugar, Havana, Cuba.)

The research by Mao (2000) cited above on the effects of reduced water applications for irrigated rice has shown some remarkable effects that changing water management practices has on the populations of soil organisms. Table 5 below reports differences in the size of several categories of microorganisms under alternative irrigation methods. The biggest effect is seen with ammonifiers, but there are also very large effects, several orders of magnitude, for nitrifying, denitrifying, P-solubilizing, and S-reducing bacteria in the rice soils at Changsha Irrigation Experiment Station in Hunan Province where Mao compared soils managed under alternate wetting and drying (AWD) with those under flooded rice irrigation (TRI).

Table 5: Number of microorganisms in early rice fields (10^6 g^{-1} dry soil) with different water management techniques, Changsha, 1992

Irrigation Technique	AWD		TRI		% increase (+) or decrease (-) with AWD, or multiples (x) with AWD (+ or -)	
Date of sampling	*13 June*	*16 July*	*13 June*	*16 July*	*13 June*	*16 July*
Aerobic bacteria	0.277	1.624	0.657	1.025	+ 137%	+ 58%
Anaerobic bacteria	0.021	0.015	0.035	0.017	- 40%	- 13%
Actinomycetes	0.422	0.288	0.161	0.094	+ 1.5x	+ 2x
Ammonifiers	11.550	112.000	0.355	4.200	+ 31x	+ 25x
Nitrifying bacteria	0.100	0.011	0.009	0.010	+ 10x	+10%
Denitrifying bacteria	0.390	0.400	0.085	0.042	+358%	+852%
Phosphobacteria	4.025	0.960	0.710	0.420	+460%	+ 128%
Cellose decomposers	0.040	0.040	0	0.004	∞	+ 900%
Sulphoficators	0.116	0.400	0.004	0.001	+ 28x	+ 39x
Desulphoficators	0.413	0.008	3.570	1.176	- 88%	- 146x

Source: Mao (2000), Table 14. The authors added the calculations in the last two columns.

These differences are attributable just to the reduction in soil moisture and accompanying increase in soil oxygen with AWD vs. TRI. Given the effects on populations of soil organisms that would be elicited by (a) increased addition of organic matter to the soil, and (b) increased root exudation from larger root systems, further augmented by (c) active soil aeration, these effects could be even larger with SRI practices. But we have no data on this. Some research has been done at Tamil Nadu Agricultural University under Dr. T. M. Thiyagarajan, analyzing the rhizospheres of rice plants grown with different water management regimes (Table 6). Because these trials were not yet using all of the SRI practices as recommended, they should be regarded only as indicative, not conclusive. Some physiological concomitants measured in the rice plants grown under these alternative conditions of aerobic soil vs. saturated soil are shown in Table 7.

Table 6: Microbial populations in rice rhizosphere with different cultural methods, on-station trials, Tamil Nadu Agricultural University, India, 2001-2002

Microorganisms	Conventional	SRI
Total bacteria	$88x10^6$	$105x10^6$
Azospirillum	$8x10^5$	$31x10^5$
Azotobacter	$39x10^3$	$66x10^3$
Phosphobacteria	$33x10^3$	$59x10^3$

Source: Gayathry (2002).

Table 7: Comparisons between conventional flooded rice and SRI AWD rice, 2001-2002 (means of values at active tillering, panicle initiation, flowering, and grain-filling stages)

Season	Wet 2001-02		Dry 2002	
Variable	Conv.	SRI	Conv.	SRI
Total chlorophyll (mg g^{-1})	2.76	3.20	2.60	3.13
Soluble protein (mg g^{-1})	8.35	12.62	10.25	11.95
Nitrate reductase (mg NO_2 g^{-1} h^{-1})	12.42	18.11	11.74	16.70
Root CEC			8.40	11.23
Root cytokinins (pmol g^{-1})			56.77	72.47

Source: Nisha (2002).

There are no systematic studies that establish causal connections between the differences reported in Table 6 and Table 7. However, the contrasts seen in Table 6 are directly related to changes in water management, i.e., to ***reduced*** water applications. The kinds of differences shown in Table 7 are surely contributing to the differences in plant phenotype that are seen in Figures 1, 2 and 3, and to the yield and profitability results reviewed in the next section.

III. COMPARATIVE DATA ON SRI WATER SAVING, TOGETHER WITH YIELD AND PROFITABILITY

Table 8 on the next two pages summarizes the results of ten evaluations of SRI that compared the effects of these practices in terms of farmers' yields, cost reduction, and profitability, noting also how much reduction was made in their use of irrigation water with SRI management. Actually, in most of the evaluations, the criteria for what constituted 'SRI' were fairly relaxed, so many of the farmers were not using the full set of recommended practices, or were not using them all as recommended. So this means that there is scope for further improvements in outcomes.

Some of the reported differences in water use were measured by evaluators, while others were reported by farmers. In fact, the water-saving differences are so substantial and consistent -- nearly 50% on average, with a range of 24-62% -- that greater precision is unlikely to alter the conclusion previously reported, that **SRI methods enable farmers to reduce their irrigation draws by 25-50% while getting higher and more profitable production at the same time.**

Whether that level of water saving is actually achieved at the level of whole irrigation systems depends on whether the new methods are used throughout a command area, of course. Farmers in the middle of a system that is designed to operate with field-to-field, i.e., cascade, irrigation cannot make this kind of water saving. Moreoever, their SRI results will be diminished by the undesired saturation of their own fields from water seeping in from neighboring flooded fields. The data in Table 8 should thus be regarded as *indicative* of the water savings that SRI makes possible.

The average yield increases reported from SRI methods are about 60%, bearing in mind that these results do not always reflect full or proper use of those methods. Given that farmers' costs of production were reduced by an average of >20%, net income per hectare would be increased more than the rice in yield. In these evaluations, profitability rose by ~82% since farmers were able to produce rice at considerably less cost per kg. This was calculated precisely for Nepali farmers as shown in Table 9, with cost per kg of rice produced reduced by >53%.

Table 9. Production cost of one-kilogram rice by SRI and farmers' methods in Morang (2005)

SN.	Method	Average (Rs./ka)	Minimum (Rs./kg)	Maximum (Rs./kg)
1	SRI methods	2.8	1.39	6.2
2	Farmers' methods	6.0	3.5	8.5

Source: Uprety (2006).

Such calculations of profitability do not yet take into account any premiums for the higher quality of SRI production. The outturn of milled rice from SRI paddy (unmilled rice) is often ~15% greater compared with paddy that is grown with conventional methods. SRI paddy usually has less chaff because there are fewer unfilled grains, and fewer broken grains, with less shattering during the milling process. In Sri Lanka and India, millers have begun offering a higher price for SRI paddy. An evaluation done at Sichuan Agricultural University in China has found SRI giving 16-17% higher outturn of milled rice, i.e., kg per bushel of paddy (Jun, 2004).

Table 8: Summary comparison of water-saving and yield, cost-reduction and profitability effects of using SRI methods

COUNTRY	Water-Saving Achieved	Increased Yield/ha	Cost Reduction	Increase in Profitability	Data Base for Calculations, and Comments
CAMBODIA					
Evaluation commissioned by GTZ (Anthofer et al. 2004)	% of farmers who flood fields at TP reduced from 96.3% to 2.5%; during vegetative growth, from 64.3% to 22.4%	41% (excluding all holdings < 0.3 ha)	56%	74%	Data from an evaluation of in 2004 400 SRI and 100 non-SRI farmers, randomly chosen in 20 villages in 5 provinces
CEDAC evaluation (Tech 2004)	50.2% (reduction in expenditures on water)	105%	44%	89% (per household with use of SRI on 35% of land)	Data from 120 farmers who had used SRI methods for three years, average for 3 years (2001-2003), compared with pre-SRI production (2000)
CHINA					
China Agric. University evaluation (Li et al. 2005)	44.6%	29.9%	7.4%	64.4%	Results from a village study in Sichuan province; average figures for 2003 and 2004 when number of SRI users went from 7 to 398; farmers identified water-saving as the most attractive feature of SRI
INDIA					
TNAU evaluation (Thiyagarajan 2004)	40-50%	27.8%	11% (8% less labor)	112%	Data from 100 on-farm comparison trials in Tamiraparani river basin, Tamil Nadu, in 2004, each plot 0.1 ha, with detailed record-keeping
IWMI evaluation (Sinha and Talati 2005)	Rainfed adaptation of SRI methods	32%	35 (8% less labor)	67%	Data from 110 farmers in two villages in West Bengal in kharif season 2004, one of them suffering drought; incomplete use of SRI methods adapted to rainfed conditions; use went from 4 to 150 farmers within three seasons

INDONESIA					
NK evaluation (Sato 2004, 2006)	40%	84%	24%	412%	Calculated from data from 1,849 on-farm trials on 1,363.6 ha during 2003, 2004 and 2005 in South Sulawesi and West Nusa Tenggara provinces; profitability calculated from WNT data: SRI net benefit 6.2 million rupiahs/ha; non-SRI 1.2 million
NEPAL					
District Agric. Dev. Office, Morang (Uprety, 2005, 2006)	43% (reduction in cost of irrigation)	82%	2.2% (greater where mechanical weeders are available)	163% (including net income from by-products)	Agronomic data from 413 farmers in 2005 main season; economic data from random sample of 50 farmers from this number; profitability affects also by increased straw production, which has value
SRI LANKA					
IWMI evaluation (Namara et al., 2004	24% fewer irrigations; 23% fewer hours of irrig.	44% average	11.9-13.3% at prevailing farm wage rates	90-117% at prevailing farm wage rates	Data from 60 SRI farmers and 60 non-SRI farmers randomly selected in two districts in 2003 survey (Namara et al., 2004)
VIETNAM					
Thai Nguyen University (Nguyen and Hoàng, 2005)	62%	25.7%	NA	NA	Results of factorial-trial evaluations in 2004; complete set of SRI practices gave yield of 8.8 t/ha
Dông Trù village (Uphoff, 2006)	60%	21%	24%	65%	2005 season; data from records kept by local IPM farmer field school participants

There is also reason to think that SRI rice may have higher nutritional value because of the larger root system which gives the plant access to a much larger volume of soil and to a larger supply of micronutrients, in contrast to rice that has a truncated and dying root system under continuously flooded soil conditions and one that relies mostly on inorganic NPK for its growth. But these things remain to be evaluated systematically.

In addition, evaluations done for GTZ and IWMI (Anthofer et al., 2004; Namara et al., 2004) have calculated that farmers' risks of financial loss are reduced with SRI. While yields are higher and costs of production are reduced, the money farmer need to invest in purchased inputs is reduced, so there is less risk. Moreover, SRI rice crops are more resistant to biotic and abiotic stresses. It is also being seen that SRI methods shorten the growing cycle of rice by 1-3 weeks at the same time they double the crop output (Uprety, 2005). This further reduces farmers' water requirements, although earlier harvesting also has some other advantages.

The data reported in Figure 8 summarize evaluations done by a variety of researchers and professionals in different countries. More information on the evaluation done in Indonesia is presented in the accompanying paper by Shuichi Sato of Nippon Koei Co. Ltd.

IV. DISCUSSION

If SRI methods only enabled farmers and irrigation managers to **reduce the water requirements** of irrigated rice by 25-50%, this alone would be sufficient reason for governments, international agencies and environmental organizations to promote the adoption of SRI, since water is becoming more and more limited to meet agricultural production needs. That these methods **also raise production and lower costs**, thereby making rice production more profitable, should make their spread attractive and a high priority. However, some constraints or requirements need to be considered.

Mental Dispositions

It seems that many people -- farmers, extensionists, administrators, policy-makers, but especially researchers – have difficulty accepting that so many benefits can be obtained so simply. SRI only requires changing the management of plants, soil, water and nutrients, rather than investing in improving crop genetic potentials or buying and using new seeds or manufactured inputs. This requires considerable **reorientation of thinking and ensuing practice**. Fortunately, though, this is essentially a subjective constraint and not a matter of material requirements. As the results of SRI practice become more widespread and better known and documented, this barrier to acceptance should become negligible. While seeing is not always believing, the kinds of phenotypical difference evident in Figures 1, 2 and 3 should make most people willing at least to try out SRI rather than present a priori reasons why they would not expect it to succeed.

Facilities and Organization for Water Management

The main objective constraint for getting best results from SRI practices is **water control**. SRI recommends applying just a minimum of water, just enough to meet crop water needs, never keeping the soil flooded and saturated. Many irrigation systems are not currently constructed and/or operated so that small amounts of water can be supplied to fields reliably. The problems impeding such management can be technical and/or social (Uphoff, 1986; Uphoff et al., 1991). If there are no properly functioning irrigation structures and/or no effective bureaucracy managing water in large irrigation systems and/or no effective organization among water users in smaller ones, water management becomes a limiting factor for the utilization of SRI.

Whether the limitations in water control are due to deficiencies in 'hardware' or 'software,' these should be remediable by government and/or development agency and/or water user activity.

Given the profitability that SRI makes possible in the rice sector, investment in control structures and/or systems of administration and/or farmer organization should be justifiable economically.

Where farmers' fields lack field channels that give them access to and control over water supply, or lack proper drainage structures and channels, the increased productivity of paddy land is great enough that giving up some small portion of land (~5%?) to install the physical infrastructure needed for control should be profitable. Also, farmers will have more incentive than before to cooperate in ensuring reliable though small water applications for everyone. The increased productivity of rice production attainable with SRI is likely over time to lower the market price of rice, and thus calculations of rates of return. But donors should find such investment attractive for SRI's contributions also to food security, to eliminating hunger, to poverty reduction, and to enhancing environmental quality. Investments in making greater agricultural production feasible (and more profitable) while reducing agricultural demands water supplies should themselves be worth investing in as a general proposition.

Labor Requirements
Initially, the main constraint for SRI was seen as its **labor-intensity**, as reported by Moser and Barrett (2003). This has been regarded as an intrinsic characteristic of SRI by skeptics such as Dobermann (2004) and Sheehy et al. (2004). However, that view was static and not informed by any real experience with SRI. Since it is expected that any innovation must have some drawbacks ('no free lunches'), proponents of SRI at first accepted that its methods would require more time to manage seedlings more carefully and in particular to control weeds when rice paddies were not kept flooded. So the attribution of great labor-intensity to SRI was agreed on.

Systematic evaluations of SRI since the Moser-Barrett article appeared have been showing, however, that once farmers have learned the new methods and become comfortable with them, SRI labor requirements are in fact ***less*** than with conventional irrigated rice production. Here are the results of different evaluations.

- When analyzing the data from 108 Malagasy farmers who using *both* SRI and conventional methods, Barrett and Moser together with Barison and McHugh (who had gathered the data) found that by the fourth year of SRI use, labor inputs were **reduced by 4%** per hectare, and in the fifth year, these requirements were **10% less** (Barrett et al., 2004).
- An evaluation of SRI in Sri Lanka done by an IWMI team wrote repeatedly about the higher labor demand of SRI, even though this stereotypical view was not supported by any total data on labor inputs. While 75% of the 60 SRI farmers interviewed agreed that SRI required more effort, **even higher percentages** of them said that **SRI reduces their labor time** for land preparation, transplanting, water management, and harvesting. The study calculated that even incomplete use of SRI methods more than doubled profitability per hectare, so at a minimum, the *productivity* of labor (kg of rice produced per hour of work) was greatly increased (Namara et al., 2004). If farmers had to invest more labor with SRI, this was well repaid.
- A study done for GTZ in Cambodia, covering 400 SRI farmers and 100 non-SRI farmers randomly selected in 5 provinces, found that overall, SRI was **'labor-neutral.'** SRI did not require more labor on average. Since *newer* SRI users needed more labor ha^{-1} than did conventional rice farmers, this meant that experienced SRI users required *less* labor ha^{-1} (Anthofer et al., 2004).
- Most SRI farmers surveyed by Anthofer et al. (2004) said that they preferred its pattern of labor demand. Labor during transplanting, a time of peak labor demand, was reduced by 10 days of labor ha^{-1}. Although the labor required for weeding went up by a comparable amount, this was done when demand was more slack and timing was somewhat flexible. A majority (55%) of 120 farmers who had practiced SRI for three years reported that **SRI is 'easier to practice'** while only 18% said it is 'more difficult'; 27% said 'no difference' (Tech, 2004).

- In Tamil Nadu state of India, an evaluation of SRI on comparison plots, side-by-side with conventional practices, on 100 farms in Tamiraparani river basin found that total labor inputs were **8% less** with SRI. There was a marked disparity in gender effects, however. Men's labor went up by 59% while women's work decreased by 25%. (Because SRI weeding was now 'mechanical,' with SRI this was done by men rather than women.) Men were well compensated for the additional work, however, since net income ha^{-1} went up from $242 with conventional practice to $519 ha^{-1} with SRI methods (Thiyagarajan, 2004).
- An IWMI-India evaluation of SRI in two communities in West Bengal state, where SRI use had gone from 4 farmers to 150 within three seasons reported an **8% reduction** in the hours of labor required ha^{-1} with SRI, while profitability went up 67% (Sinha and Talati, 2005).
- An evaluation of a village in Sichuan province of China, where SRI adoption increased from 7 farmers in 2003 to 398 in 2004, found that the most attractive aspect of SRI to these users, expressed in both questionnaires and focus groups, was **labor-saving** (Li et al., 2005).
- Farmer Field School participants in Dông Trù village of Vietnam kept detailed records of all their inputs for practicing SRI in 2005, including labor. They found that the additional work needed for weeding (554 hrs ha^{-1}) was exactly offset by reduced time for transplanting (554 hrs ha^{-1}). They reported a small increase in time for land preparation, but this extra time was a one-time investment, so they expected SRI to take less labor in the future (Uphoff, 2006).

Even if SRI were labor-intensive, its other advantages could justify adoption of its methods. However, it no longer appears that this is a general problem with SRI. There can be initial higher requirements, which Moser and Barrett (2003) correctly identified. But labor-intensity is not an inherent problem with SRI that need limit its attractiveness and spread. Indeed, once farmers see that they can reduce their seed requirements, their water requirements, their costs of production, and even their labor requirements, with higher production, SRI should become widely popular.

It is too early to try to draw any bottom-line conclusions about SRI because it is still 'a work in progress.' It is changing and evolving year by year, as more farmers and researchers become involved with it and apply their intelligence and experience to making its practices even more efficient and productive. There have been a number of labor-saving innovations to speed up transplanting, e.g., a roller-marker that marks a symmetical grid on the muddy paddy, and weeding, e.g., a four-row weeder that greatly cuts labor time for this operation, and a motorized weeder that reduces time even more. Farmers are experimenting with no-till crop establishment and with raised beds, as well as intercropping systems that save labor, conserve nutrients and enhance income. Nobody can know now the net results of these methods a few years hence.

What can be said with some confidence is that SRI has debunked the myth that 'rice is an aquatic plant,' needing or preferring inundation. Within the next 5-10 years, depending on how well and quickly governments, NGOs, farmer organizations and others spread knowledge about SRI methods and experience, it is likely that the flooding of rice paddies can become 'archaic.' This radical shift in practice will be driven by the enhanced incomes that become possible from reducing water applications when rice is sparingly irrigated. SRI concepts and methods are now being extended to upland, i.e., rainfed rice, with average yields >7 t ha^{-1} in Negros Occidental, Philippines (Gasparillo, 2003). SRI thinking and practices are also being extrapolated by farmers to other crops, such as finger millet, sugar cane and cotton, with good results.

These transitions in agriculture are based upon a growing appreciation of agroecological principles that re-embed agricultural crops within the ecosystems in which they have emerged, interdependent with the myriad of flora and fauna that have co-evolved with plants over hundreds of millions of years (Uphoff, 2002; Uphoff et al., 2006). SRI could have the effect of not just making agricultural practice more compatible with conservation of natural resources and biodiversity, but of helping agriculturalists to understand how their practices are intimately and intrinsically part of what we refer to broadly as 'nature.'

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