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The Principles that Constitute System of Rice Intensification (SRI) and the Practices for Applying them at Field Level

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Abstract

Understanding the System of Rice Intensification (SRI) begins with a distinction between its *principles*, which are general, and the *practices* that give effect to these principles when applied, which are and adapted for particular situations. This makes SRI more like a menu than a recipe. It is not something to be promoted by rote learning, glossing over the reasons for its principles and practices of SRI, but rather something that emerges from an understanding of agronomic processes.

Put in simple straightforward terms, SRI management elicits the growth of more robust and more productive plants, *i.e., phenotypes*, from a given crop variety, *i.e., genotype*. Application of SRI's principles and practices evokes the fuller expression of plants' genetic potential than do most currently prevailing practices, such as high plant density, continuous flooding, and ignoring the contributions of the soil biota and the implications of profuse root growth. This paper enumerates and elucidates the agronomic principles and practices of SRI, considering how and why they achieve the effects that are widely and consistently observed.

Key words: System of Rice Intensification, SRI Management, Crop variety, Agronomy.

That the System of Rice Intensification (SRI) was developed inductively from observations and experimentation without hypotheses or *a priori* assumptions has been both a strength and a weakness for this agroecological innovation in rice crop management. On the plus side, Henri de Laulanié's empirical, thinking-outside-the-box construction of SRI in Madagascar some four decades ago is benefiting tens of millions of rice-producing households in over 60 countries, and it has produced important new knowledge for producing rice, some of which is rather counter-intuitive.[1]

For example, through observation and in-field experimentation with farmers, Laulanié established that: .

- ***Transplanting very young rice seedlings*** *enables the resulting plants to produce more tillers, panicles, and grains* than if they are transplanted at an older age.[2]
- ***Reducing plant density****, by as much as 80-90%, can increase grain yield per unit area,* if the remaining plants are managed with complementary practices designated by SRI.

[1] Laulanié referred to the rice plant as his teacher ('mon maître' -- my master), to suggest that he learned mostly from observation rather than from textbooks or journal articles (although he had earned a university degree in agriculture before he entered a Jesuit seminary in 1941). See the technical paper (Laulanié, 1992) from which he wrote his only published paper on SRI (Laulanié, 1993/2011).

[2] This effect can be explained morphologically by analyzing rice plant growth in terms of phyllochrons (Nemoto et al., 1995), as summarized on pages 154-160 of Uphoff (2016).

- ***Rice plants should not be kept continuously flooded*** because this widespread practice suffocates their root systems, and thereby constrains their yield.

These conclusions contradicted what was accepted scientific knowledge at the time (e.g., Sinclair, 2004). For example, recommendations from leading rice research institutions included transplanting seedlings more than 20 days old, not seedlings younger than 15 days; planting rice crops optimally densely rather than optimally sparsely; and keeping rice paddies always inundated so that the plants would never experience any water stress (De Datta, 1981). This 'common knowledge' is no longer tenable, however, because of SRI performance and research.

On the other hand, taking an inductive approach has meant that explanations have to be constructed *post hoc*, and theory has to catch up with practice rather than informing and leading practice. Persons who were skeptical about SRI, scientists as well as farmers, would probably have had less difficulty in accepting SRI's novel ideas and recommendations if these could have been better explained in scientific terms when SRI was introduced into the literature some 20 years ago (Stoop *et al.,* 2002).

There are now reasonably robust scientific explanations for SRI success, e.g., Toriyama and Ando (2010), Stoop *et al.,* (2011), Thakur *et al.,* (2016); and there is a large published literature on SRI.[3] However, it is clear in retrospect that it would have been beneficial to distinguish from the outset between the agronomic *principles* that account for the impact of SRI methodology and the respective agronomic *practices* that operationalize SRI in the field, indeed in millions of diverse fields.

Principles are formulated to be general, while practices are expected to be specific and varying. Keeping the soil in rice paddies in mostly aerobic condition rather than continuously flooded (hypoxic), for example, is a basic *principle* for SRI, that can be accomplished by a variety of *practices* which can provide active and/or passive soil aeration. Unfortunately, SRI was not understood well enough at the outset to make a clear delineation between principles and practices. After some introductory comments, this paper addresses this ambiguous area in SRI theory and undertakes to sort out this important distinction.

1. SRI as an Innovation

SRI was called a *system* rather than a technology by Fr. Laulanié because it depends more on knowledge and skill than on introducing a new variety or certain material inputs. It was not specified as a 'technology' because it was and is still evolving (Uphoff, 2023). We consider SRI to be rather a *methodology*, because it is something to be learned and adapted, not something to be 'transferred' like a technology. Basically, SRI represents a paradigm shift, a new and better way of thinking and proceeding. This differentiates SRI from what most people think of as a technology. The following statements characterize SRI simply and summarily:

- ***SRI crop management modifies the environment in which rice plants are grown,*** creating more favorable conditions for their health and growth above and below ground.
- ***SRI practices mobilize biological processes and potentials that already exist,*** within rice plants and within the soil systems in which they grow.
- ***SRI capitalizes on capacities and resources that are readily available to farmers,*** rather than requiring them to buy new inputs or to utilize new plant varieties.[4]

[3] *See SRI website for a listing of publications: http://sri.cals.cornell.edu/research/index.html.*

[4] *This statement needs to be qualified because having access to and using a mechanical weeder for weed control increases crop yield from SRI (see graphs shown below). Use of such a weeder, which aerates the soil, is highly recommended, but it is not required. A study done at ANGRAU concluded that using such mechanical weeders can cut the labor time that women spend in weeding SRI rice paddies by three-quarters (Mrunalini and Ganesh, 2008).*

All organisms, not just rice, begin with a certain genetic potential that is incorporated in their DNA. As they develop and interact with their environment, becoming actual, unique plants (or animals or micro-organisms), they achieve some or most but almost never all of this potential. Rather than creating and utilizing new genetic potentials, SRI crop management evokes the fuller expression of genetic potential that already exists.

In some ways, this puts SRI at odds with scientists and commercial interests that have promoted a 'Green Revolution' strategy for agricultural development. This approach makes improvements in crops' genetic resources and then utilizes more inputs - synthetic (inorganic) fertilizers, agrochemical protectants, and more water to benefit from the increment in potential. It is often forgotten that increased irrigation has been a major part of Green Revolution successes, and this is an increasingly scarce, costly, or unreliable resource.

SRI methods enable farmers who want to use hybrid or improved varieties to get even greater yields from these HYVs or hybrids (e.g., Diwakar *et al.,* (2013), with less expenditure for new and costly seeds, so this further raises farming income. On the other hand, SRI management can also improve the performance and profitability of so-called 'traditional' varieties (Dwiningsih 2023), which makes these unimproved varieties competitive economically with modern varieties. So, SRI can help conserve rice biodiversity as well as benefit farmers.

2. Pictures Each Worth More Than a Thousand Words

An understanding of SRI is best communicated by two pictures that shaped my own comprehension of this agronomic innovation methodology. The first was sent to me in 2004 by a colleague in Cuba, Dr. Rena Perez; the other I took myself during a visit to Indonesia in 2009. These are, admittedly, not average or typical rice plants grown with SRI methods; they are, indeed, some of the best. But they show how much *potential for growth* there is in rice (and other) plants if their genetic potential is capitalized upon more fully by creating favorable conditions for them to grow in, not just improving their physical circumstances but also enriching biological elements and concomitants in their environment.

The two rice plants in the picture below are held by Luis Romero, one of the first farmers in Cuba to try out SRI methods. While it may be hard to believe, these plants are both *the same age* (52 days after seeding) and *the same variety* (VN2084), so they are the same genotype, like twins starting life with the same genetic resources. The SRI-grown plant on the right was removed from its nursery when only 13 days old and transplanted into a rice field with wide spacing between single plants in a square grid pattern; with intermittent irrigation rather than flooding; and with organic matter added to the soil, not relying mainly on chemical fertilizer.

This picture was taken just after the smaller plant on the left had been removed from its nursery to be transplanted into a typically-managed rice field. at 52 days after sowing. This was a typical age for transplanting rice seedlings in that part of Cuba. Dr. Perez happened to have her camera with her on that day when she visited Romero's farm to observe his transplanting. The SRI-grown plant seen on the right was pulled up from its field at random for comparison. The SRI rice plant has 43 tillers, while the conventionally-grown rice plant on the left has just five.

Both plants started with the same genetic potential, the same DNA, but their conditions for growth were quite different. In addition to comparing the difference in plant canopy size, note also that the root system of the SRI plant was both much larger and also lighter-colored, because its roots had not suffocated and degenerated from being in flooded (hypoxic) soil. Its tillers are more numerous and wide-spread because the plant was not being crowded by other plants. This picture shows how much difference in plant growth can be elicited by giving rice plants in more favorable conditions: no crowding, no continuous flooding, and starting with young seedlings transplanted carefully so that their potential for growth is not diminished.[5]

Below, on the left, is the picture of another rice plant, this one presented to me by Indonesian farmers during a visit to their SRI training school in East Java. This plant grown with SRI methods had *223 tillers emerging from a single seed* (*Ciherang* MV). The farmers acknowledged that this was their best SRI plant from the previous season, but it showed them and others the potential for growth and productivity that SRI methods can elicit. The plant's large canopy of tillers and leaves was supported by a massive root system.

How is such rice plant performance possible? Not just in Cuba and Indonesia, but also in dozens of other countries, including India? The picture above on the right was sent to me from Punjab by Dr. Amrik Singh, ATMA/Gurdaspur. The rice plant on the left with the larger roots and canopy is easily identified as having been grown with SRI practices. The agronomic principles that account for such effects are broadly relevant, across countries and also across numerous crops (Adhikari *et al.,* 2018; Berhe *et al.,* 2017; Dhar *et al.,* 2016; Gujja *et al.,* 2018).

3. The Agronomic Principles that Constitute SRI

SRI has usually been described and presented in terms of certain practices, but it is better understood in terms of certain *principles* that are then implemented by particular practices. It is the practices that can make rice plants more vigorous and more productive, better able to fulfill their genetic potential and capitalize on the potentials of coexisting life in the soil. However, the principles that comprise SRI that should be understood and should guide farmers' practices. The principles remain steady, while the practices can and do vary.

Synergies among the recommended SRI practices contribute to the effectiveness of the system overall, as discussed in section 7. But two factors stand out as the foundations for SRI effects.

- The *increased growth and performance of* ***plant root systems*****,** evident in the pictures above, and
- The *abundance, diversity, and activity of the* ***soil biota*****,** informally referred to as 'the life in the soil.' This encompasses the many millions of organisms, ranging from miniscule microbes to good-sized earthworms, that live (and die) in the soil.

[5]*Anticipating that some people would be skeptical about this picture because it is so easy to alter digital files, I sent a video camera to Dr. Perez so that during the next season she could document in real time the respective plants' growth, also interviewing Romero about his practices and his results. Anyone with access to the internet can see for themselves how SRI plants' express their genetic potential during a growing season: http://sri.cals.cornell.edu/countries/cuba/SICAenglish.wmv (Spanish with English subtitles, 36 min). In Latin America, 'SICA' is used as an acronym for 'SRI' because literal translation of 'SRI' into Spanish becomes 'SIA,' the Spanish acronym for the American Central Intelligence Agency.*

Although not easily seen or never seen, the soil biota provides a great variety of services both to plants and to the soil system, such as nitrogen fixation, phosphorus solubilization, nutrient mobilization, protection against pathogens, soil aggregation and drainage, circulation of air and water in the soil, and making the soil more amenable for root growth. The microbial component of the soil biota (the plant-soil microbiome) is starting to receive the scientific attention that it deserves (Turner *et al.,* 2013; Tkacz and Poole, 2020; Primavesi *et al.,* 2024). This trend has paralleled the intensification of medical research which investigates and appreciates how pervasively the human microbiome affects our own lives and our health.

SRI can be understood in terms of four broad principles that apply to all kinds of rice production, irrigated and rainfed, with modern or traditional varieties. Because they are good agronomy, they apply also for crops like wheat, millet, and sugarcane, as noted above.

i. ***Establish new plants carefully and well***, avoiding trauma to the roots and ensuring opportunity for roots to grow prolifically because these are essential, the *sine qua non* for plants' success. This and the other three principles listed here are given effect in the field through practices reviewed in the next section, section 4.

ii. ***Minimize competition between plants***, ensuring that all of the plants have access to sunlight, nutrients and water, with no shading and no crowding that will inhibit the growth of each plant's tillers and roots. The distance between plants should be optimized rather than maximized, however. Each plant should achieve as much of its potential as possible.

iii. ***Balance both water and oxygen in the soil,*** with never too much of either as all plants need both of these elements. Because air and water occupy the same pore space in the soil, having more of either one means having less of the other available to plants. Water, soil, and weed management practices should strive to maintain a balance of water and air in the soil. Laulanié's advice was to provide paddy fields with the "minimum of water" (*le minimum de l'eau*) that would meet the needs of both the plants and the soil biota.

iv. ***Enhance and maintain the soil system's fertility***, knowing that this depends on the amount and activity of life in the soil as well as on good structure of the soil and good functioning of the soil system. The soil's fertility is a function not just of the amount of nutrients currently available in it, but also of the abundance and diversity of life in the soil.

These principles are not likely to elicit much controversy among agronomists. However, some of the SRI methods recommended for applying them in the management of plants, soil, water, nutrients and weeds contravene current practices for rice cultivation, either age-old or of modern origin.

4. Practices for Operationalizing these Principles

SRI should not be regarded as a recipe*, i.e.,* a certain fixed set of practices, but more like a menu*, i.e.,* a set of choices, in much the same way that a restaurant patron chooses from the eating establishment's menu a soup, a salad, an entrée, a dessert, etc., according to what he or she considers most suitable for the time and place.

Farmers should function as managers, as decision-makers making choices, not as robotic laborers following instructions. During training for SRI, farmers should be told more than just <u>*what*</u> *to do*. It should be explained <u>*why*</u> particular practices are recommended, and <u>*how*</u> these practices can be best used and/or adapted to local conditions.

The following practices give effect to the principles enumerated above. The practices discussed below are for irrigated rice production, where the crop is established by transplanting seedlings from a nursery. Alternatively, an SRI crop can be established by direct-seeding using somewhat different practices for the first principle, either by hand or with equipment designed to achieve the same purpose. Some examples shown in section 6. The practices are listed according to their respective principles.

Principle 1: ***Establish new plants carefully and well***

A. Start with seed selection so that only well-developed seeds are sown in the nursery. Submerge the seeds in salt water and discard the poor seeds that float to the top, as shown below in a demonstration in a West Bengal village in India. Sow only the good seeds that sink to the bottom. These are put into a bag and kept in a dark, moist, warm place to trigger germination before they are sown in a nursery under one of the options for the next practice.

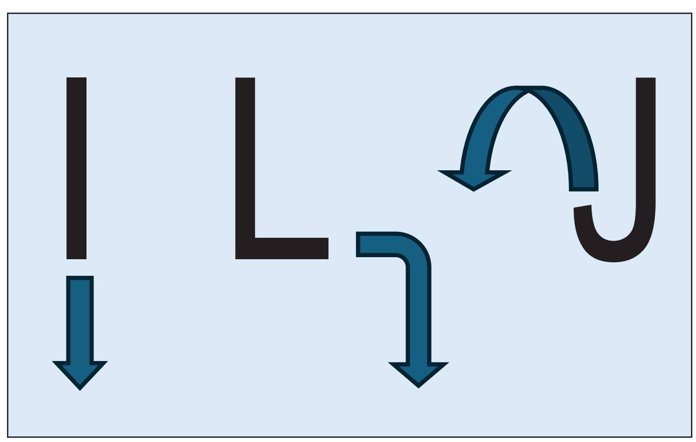
B. Grow the seedlings in a small garden-like nursery that is elevated like a raised bed and not flooded. The nursery's size will be only 10-20% as large as previously because with SRI, the seeding rate is reduced so greatly. The nursery should be close to or in the main field, wherever there is a source of water for watering the seedlings as neededas shown in A below. Alternatively, seedlings can be grown on *trays* made of metal or plastic trays that can be easily

(A) SRI seedling nurseries adjacent to a main field in Madhya Pradesh state of India. (B) SRI seedlings in Lombok, Indonesia, being grown on small metal trays that are easily carried to the field. (C) Farmers in Karnataka state showing SRI seedlings being grown in plastic trays, a method made practical because SRI requires only 10-20% as many seedlings as in usual practice. (D) SRI seedlings grown in Costa Rica in a tray filled with soil and planting material that can be rolled up like in a rug for easy transportation and then transplantation by machine.

transported to the field (B); or in the kind of plastic trays that are designed for vegetable setts, which avoid any root disturbance (C); or on *mats of soil and other organic material* that can be rolled up and used in mechanical transplantation (D). There are thus several ways to raise SRI seedlings as shown in the pictures below; and in some places there is the option of direct-seeding with no hand or mechanical transplanting.

C. **Transplant seedlings into the field when they are still at a young age,** usually just 8-14 days old, at the 2-3 leaf stage, before tillering starts. Remove the young plants from the nursery or tray carefully, keeping soil around the roots attached to them. This will minimize trauma to the roots and reduce the 'transplant shock' that will delay the seedlings' resumption of growth. Also, seedlings benefit from shallow transplanting, just 1-2 cm, because deeper placement in the soil reduces the plants' tillering. The pictures below show young seedlings being lifted out of a nursery with a trowel, and a young seedling that is ready for transplanting.

D. **Transplant the young seedlings into the soil quickly and carefully**, never letting their roots dry out. Young seedlings should not be thrust straight downward into the soil unless their tips are held gently so that *the tips do not get turned upward*. Ideally, the plant and root will be vertical, like the letter **I**. But it may be quicker to lay the seedling into the moist soil with a gentle sidewise motion, keeping the root horizontal like in the letter **L**. If after transplanting the tip is pointed *upward* like the letter **J** as seen below, the seedling's resumption of growth can be delayed for a week or more while the tip of the root re-orients itself for *downward* growth.



Principle 2: *Minimize competition between plants*

E. **Seedlings should be spaced widely apart in a square pattern**, one plant per hill (possibly two per hill if the soil is not very fertile). As seen in the pictures below from Indonesia and from India, a grid pattern is marked on the field with a rake or a roller-marker (or possibly with a rope or cord, which is less efficient). This marking establishes equal distances between the plants in all directions and makes possible mechanical weeding in perpendicular directions.

Optimal spacing is most often 25 x 25 cm; but in soil that is less fertile, spacing of 20 x 20 cm may give a higher yield, while in very fertile soil, 30 x 30 cm distance between plants and rows can give better yield. Farmers should determine the optimum distances for their own field by trying different spacings and evaluating the results.

Principle 3: *Maintain both water and oxygen in the soil, with not too much of either*

F. **During transplanting, the soil should be wet and muddy, but not covered with standing water**. Continuous flooding of the field should be avoided because this deprives the soil of oxygen and will suffocate the plants' roots and most soil organisms. The field will then be flooded intermittently when irrigation water is applied, as much as 5 cm depth at a time; this water will be absorbed into the soil and should not keep the soil sealed off from the air.

G. **During the crop season, irrigation water should be provided intermittently** by what is commonly called *alternate wetting and drying* (AWD). Any schedule for flooding the field and then letting the water seep into the soil so that it dries out superficially should be adjusted according to the soil type, topography, and climatic conditions.

Most soils should be allowed to dry until small cracks form on the surface, an indicator that it is time to irrigate again. Note that *heavy clay soils* should NOT be allowed to dry out to the crack-forming stage because then they become too hardened for roots to grow through them easily. Aerobic soil is more hospitable to earthworms and other beneficial organisms in the soil, as seen from the earthworm castings in the picture below on the right. These castings are an indicator that the soil has been kept mostly aerobic.

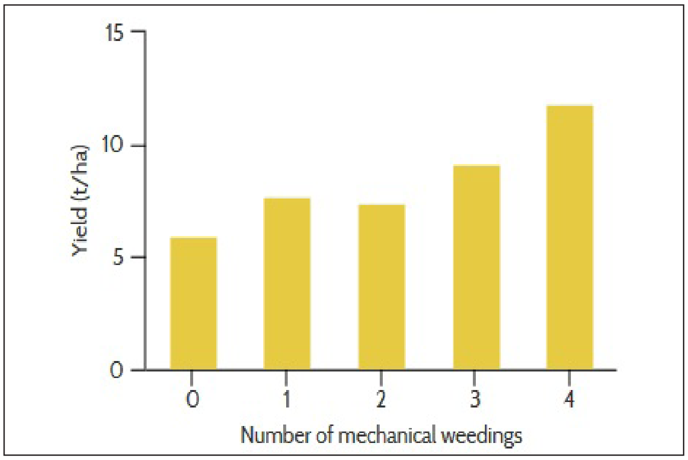
The original recommendation for SRI practice was to practice AWD until the rice plants start to flower and form grains, *i.e.,* until panicle initiation (PI). And thereafter to keep a shallow layer of water on the field (1-2 cm) until 10 days before harvest. However, research at the ICAR-Indian Institute for Rice Research in Bhubaneswar has indicated that with SRI, AWD should continue beyond PI and during the plants' reproductive stage (Thakur *et al.,* 2018). The schedule for a particular field and crop should be determined empirically so that the water needs of plants and the soil biota are being met but not exceeded.

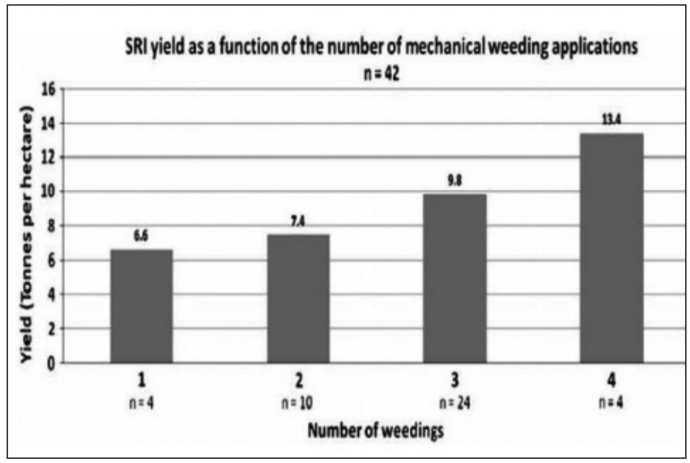
H. **In SRI management, active soil aeration is incorporated into weed control.** When rice paddies are not kept flooded all the time, there will be more growth of weeds, at least until their seeding cycle has been broken. Weeding several times during the season using a simple mechanical weeder, possibly a motorized weeder to make the work easier, is preferable to manual weeding or using herbicides because the mechanical implement aerates the topsoil while churning weeds into the ground (as green manure). This active soil aeration through mechanical weeding complements and intensifies AWD's effect of *passive soil aeration*.

The first mechanical weeding should be done 10-15 days after transplanting and in *perpendicular directions*, as shown in the picture below on the left from Indonesia. The soil should be recently wetted or flooded before weeding to make the task easier and more effective. A second weeding should then be done another 10-15 days later. This may be sufficient to control weeds, but because soil-aerating weeding aerates the soil while it controls weeds, it is recommended that a 3rd and even a 4th weeding be done at 10-15 day intervals, or until the canopy closes and further weeding is no longer possible.

Weeding in two directions is not absolutely necessary, but it has the benefit of breaking up the topsoil all around each plant and enhancing yield, as seen below. A motorized mechanical weeder, shown in the right-hand picture below from Colombia, reduces the time and effort needed for soil-aerating weeding.

Mechanical weeding, manual or motorized, can increase grain harvest by one or more tons per hectare without applying additional fertilizer because of the microbial nitrogen fixation, phosphorus solubilization, etc. associated with active soil aeration. SRI weeding enhances yield as shown in the graphs below, from Madagascar (N = 74 farmers) and Afghanistan (N = 42 farmers). Note that all of the Afghan farmers who did four weedings were second-year SRI users, having gained confidence in the new methods from their first year (Thomas and Ramzi, 2011). This SRI effect of active soil aeration should be studied and documented more widely.





Principle 4 - *Enhance the soil system's fertility*

I. Provide the soil with as much organic matter as possible within the constraints of availability and cost of biomass and labor. All of the practices of plant, soil, and water management recommended above are conducive to greater soil fertility, but it is recommended that at least some biomass be added directly to the paddy soil to build up its soil organic matter (SOM).

The SRI recommendation for nutrient management is to increase SOM through recycling of rice straw into the soil (no burning of straw) and adding organic compost made of weeds, loppings and other vegetative material and/or animal manure. Organic mulches and/or green manures (e.g., *Gliricidia*) are also beneficial. These materials improve the life in the soil as well as the soil's structure, making it easier for rice plant roots to proliferate. Also, soil with higher levels of organic matter will absorb more rainfall, reduce runoff, and increase water retention for subsequent plant use.

Inorganic or synthetic fertilizer can be used together with other SRI practices because SRI is not necessarily or always an 'organic' method of production. But many SRI farmers choose not to use inorganic fertilizer or other agrochemical inputs so that their SRI production is fully organic and may earn a premium price, besides being free of chemical residues. Farmers who use SRI methods generally appreciate the value of the beneficial soil organisms that live around, on, and even inside their rice plants. The SRI recommendation is to rely as much as possible on organic matter to enhance the soil's fertility in preference to using inorganic sources of nutrients.

How much organic matter It is feasible to apply to an SRI field will depend on the availability and cost of *biomass* (composted vegetative matter, straw, mulch, manure, etc.) as well as on the cost and opportunity costs of *labor* to collect, transport, process, and apply this material. SRI farmers are mindful that inorganic fertilization and chemical control of pests and diseases can have some adverse effects on the beneficial organisms that live in the soil, so preference is given to organic materials and methods of pest control.

As noted above, the suite of SRI practices is eco-friendly. When the soil is not kept continuously flooded and when there is more space left between plants, plant root systems grow larger, and there is more plant root exudation of organic compounds into the soil. Also, unflooded aerobic soil is more hospitable for populations of earthworms and beneficial fungi like arbuscular mycorrhizae that require oxygen. When these die and when plant roots decompose, they add to the soil's stock of organic matter. At the same time, soil-aerating weeding enhances the amount of life in the soil.

Some agronomists object that larger populations of organisms living within the soil system will compete with plants, consuming available nutrients. But this is a short-run view. What soil scientists refer to as the 'immobilization' of nutrients within the soil system actually *conserves* nutrients within the soil, keeping them from leaching through it or exiting in water runoff. When soil organisms die, their immobilized nutrients return to the flux and cycling of nutrients within soil systems.

It is well-known that soil with life in it is more fertile than soil that is 'dead.' Soil organisms, both large and small, improve the structure and functioning of soil systems by aggregating soil particles and by facilitating the passage of air and water through the mineral portion of the soil. This makes the soil system itself more stable and sustainable. Building up soil organic matter is imperative in India where SOM levels have been declining disastrously since the mid-1950s.[6]

The highest yields with SRI management have come with some *combination* of nutrient sources (compost and fertilizer) as an effort at optimization, in what is called Integrated Nutrient Management (INM). Whether or not this will give farmers the *greatest net income* will depend on their costs of purchasing inorganic fertilizer vs. producing alternative organic fertilizer. The opportunity costs of labor and the availability of biomass need to be considered when assessing net benefits. There are environmental benefits from relying mostly or entirely on organic fertilization that should be considered, including long-term productivity and the sustainability of the farming system.

J. Complementary practices: There are some other things that should or can be done in connection with SRI rice cultivation that are not particular to SRI. Thus, they are not considered to be part of SRI, although they should be noted here.

i. **Leveling of the paddy field well before planting** so that water can be evenly distributed to all parts of the field. This is good practice for any irrigated rice cultivation, saving water and benefiting the plants. The most advanced and precise field preparation can be done with laser-leveling and specialized machinery, as has been done as part of the large-scale application of SRI methods in Punjab, Pakistan (Sharif, 2011). Leveling fields should be a one-time operation, and it can be done manually; the smaller the field or plot, the easier it is to make it quite level.

ii. **Seed priming** has been shown to be beneficial with SRI by research done in Pakistan (Khalid *et al.,* 2015). As this is not uniquely beneficial with SRI, it is considered as an auxiliary practice rather than as something intrinsic for SRI.

iii. **Crop protection** is a challenge for almost all farmers and crops. One of the reported benefits of SRI management is that damage to rice crops from most insect pests and diseases is less than with conventional rice crop management, particularly with the use of organic inputs (Chintalapati *et al.,* 2023). Chemical means of protection can be used in

[6]*Unfortunately, little attention has been paid to the crucial parameter of SOM. The National Rainfed Areas Authority has started publicizing this degradation of India's soil systems. See 'Soil organic content fell from 1% to 0.3% in 70 years in India: NRAA,' Business Standard, March 26, 2022: https://www.business-standard.com/article/current-affairs/soil-organic-carbon-content-fell-from-1-to-0-3-in-70-years-in-india-nraa-122032600305_1.html*

SRI where pest or disease problems become great enough to make their use economic. In general, SRI farmers practice organic means of pest and disease control such as Integrated Pest Management (IPM) methods or biocontrol. SRI farmers pay more attention than most farmers to the conservation of beneficials, *i.e.,* to insect and other predators that control crop pests (e.g., Karthikeyan *et al.,* 2010; Kakde and Patel, 2018).

iv. **Intercropping:** With wider spacing between rice plants, some experimentation has been done in Kashmir, planting pulse crops between the rows of SRI rice. Beans, for example, when intercropped with SRI rice have been found to fix nitrogen in the soil and reduce the need for weeding between the rice rows, reducing the costs of production while bringing in income from a supplementary cash crop (Shah *et al.,* 2021). This underscores that SRI is not a fixed technology or a recipe as SRI farmers are expected to make adjustments and adaptations of various sorts once they understand the principles and their purposes.

v. **Irrigation should be stopped about 10 days before the crop has become mature enough to harvest.** This will let the soil dry out. It has been observed that SRI rice crops frequently mature about 5-15 days sooner than when the same variety of rice is grown under conventional crop management. This means that SRI methods are producing their higher yield in a shorter period of time.

K. **Monitoring:** Monitoring the progress of the crop during the growing season is important, adjusting the amount and timing of water issues, or the timing of weeding, or taking steps to protect the crop against pests or disease if necessary, preferably with organic (IPM) practices.

- The simplest gauge of a crop's progress and health is to periodically pull up a typical plant (or a struggling plant) and inspect its roots, to see if these are growing well and have good white or light coloration. Roots that are dark-colored are suffocating and will eventually turn black.
- Simply observing the color of the lower portion of the plants' *tillers*, their lower 3-4 cm, is an indicator of whether the plant is getting enough oxygen. The bottom lengths of rice tillers will turn brown and then black when deprived of oxygen, while healthy plants will have dark green coloration.

At present, farmers seldom monitor and inspect their crop's roots and tillers in this way, but neither do technicians. Tillers are easier to observe, but they do not reveal as much as do the roots. Uprooted plants resume their growth when they are replanted in the soil.

5. Distinguishing between principles and practices: Relevance for the mechanization of SRI

SRI was developed to improve irrigated rice production where the crop is established by transplanting seedlings from a nursery, but its principles can similarly inform and improve rice production when the crop established by direct-seeding rather than by transplanting. And the practices for direct-seeding will be different whether done by hand or, more efficiently, with equipment designed for the same purpose. Practices differ, but the principles stay the same.

Direct-seeding saves farmers the labor needed to make and manage a nursery, and it takes less time than transplanting. The critical consideration is whether, under the given soil, water, temperature, and other conditions, the rate of seed germination will be satisfactory. Transplanting has the advantage of ensuring that rice plants will all grow and will grow evenly across the field, especially important where landholdings are small and labor is relatively more abundant than land.

Fr. Laulanié determined that having optimally more spacing between plants was beneficial for plant performance, giving all of them access to enough space for their root and tiller growth, and to sunlight, nutrients, and water so they can express their genetic potential more fully. He also concluded that roots should be treated with care when seedlings are transplanted, to minimize trauma and 'transplant shock' as discussed above. The principle is to *protect and nurture plant roots*, not to plant seeds or seedlings in a certain way. Practices can and will vary, but the principle of nurturing roots is of general importance. Direct-seeding avoids transplant shock altogether, so it can offer some advantages for crop growth provided that spacing is optimized, and there is a sufficiently high rate of seed germination.

The machinery used for direct-seeding can range widely, from simple to complex. On the left below is a drum-seeder developed in Andhra Pradesh, India, and on the right, a tractor-mounted planter designed and used in Arkansas state of USA for a mechanized version of SRI. The US machine places rice seeds into the soil through pneumatic tubes with precise spacing and at desired shallow depth. The seeds are implanted through a cover-crop mulch that enhances nitrogen in the soil as it suppresses weeds.

Various mechanization opportunities for SRI have been reviewed in Uphoff (2021), and more are being developed all the time. Mechanical transplanters for rice seedlings have been developed for conventional rice production in Asian countries for many years. See the evaluation of MSRI (modified or mechanized SRI) done by researchers in the ICAR-Indian Institute for Rice Research on the incorporation of mechanical transplantation into SRI methodology (Kumar *et al.,* 2023). With appropriate adjustments for spacing and with modifications for handling smaller/younger seedlings, existing mechanical transplanters can be used for SRI cropping, as done by Oscar Montero in Costa Rica. The crop that he planted with a Yanmar

transplanter that he modified for SRI use, shown below on the left, gave him a yield of 8 tons ha^{-1} with greatly reduced expenditures for labor (Montero, 2008).

A novel approach was devised in Pakistan by Asif Sharif, who fabricated a multi-task machine that punches holes in the surface of machine-made, laser-leveled raised beds. Laborers riding on this machine, seen below on the right, drop 10-day-old seedlings into the holes 22.5 x 22.5 cm apart, to which water plus compost and a little fertilizer are added as the machine passes over the holes. Sharif's paddy yield from an 8-hectare 'test plot' averaged 12 tons ha^{-1}, with 70% less water and 70% less labor than is required with usual farmer practices (Sharif, 2011).

As discussed above, for SRI the practice of weeding is preferably mechanized at least to the extent of using a mechanical rotary weeder or a cono-weeder that can be pushed between the rows of plants in perpendicular directions to aerate the soil as it controls weeds. Having a mechanical weeding implement that is *motorized* greatly reduces the time and effort needed to perform this operation, and the soil aeration can be greater. There are now even some prototypes of solar-powered weeders that avoid the costs and emissions of fossil-fuel engines (e.g., Saha and Raheman, 2022). But this concerns SRI practices, not principles.

For any method of SRI crop establishment, whether, for example, by transplanting or by direct-seeding, as for weeding, the principles that guide rice production remain the same while the respective practices and implements will vary. As discussed above, SRI is not a usual kind of technology with a set of material things or certain practices. Rather, SRI represents *a change in thinking* about how to get the most benefit from the resources used in agricultural production, informed by an agroecological understanding crop performance rather than by industrial models.

6. The Importance of Eliciting Better Phenotypes from given Genotypes: Promoting Climate-Change Resiliency

The principles and practices of SRI that induce better expression of rice plants' genetic potentials offer an additional benefit for farmers and consumers, over and above raising yield, reducing costs of production, saving water and seed, and minimizing agrochemical expense and impacts. They enable resulting rice crops to *resist climatic and other stresses*: drought, water stress, flooding, storm damage, and pests and diseases, hazards that are growing in most countries and are expected to increase in the years ahead. This advantage comes from rice plants growing larger, deeper root systems as well as stronger tillers that have better architecture (Thakur *et al.,* 2010). An additional reason for reduction of storm damage is the wider spacing between plants, which allows wind to pass through crops with less resistance; this is a result of management practices and not of phenotypic differences.

Below are pictures of Vietnamese farmers who learned about SRI through their farmer field school supported by the Ministry of Agriculture and Rural Development and the FAO/IPM Program. The differences shown between rice crops are in plant phenotype, not plant genotype. The farmers' village and their rice paddies had been struck by the wind and rain of a tropical storm that passed over the area a few days before the pictures were taken.[7]

On the left are two adjacent rice fields with a farmer holding up representative rice plants removed from their respective fields. The SRI field and an SRI plant are on the left, while the field and rice plant on the right were managed with farmers' usual methods. On the right are this farmer with three other members of her farmer field school group giving a closer view of the plants. These women took it upon themselves to

[7] *The pictures were taken and shared by Elske van de Fliert, FAO/IPM program, Hanoi. I was subsequently able to visit the village of Dông Trù where these farmers live and to talk with them about their SRI experience; see pages 2-6 of http://sri.cals.cornell.edu/countries/vietnam/vnntutr106.pdf.*


carry these plants to other villages in the district to show their neighbors what could be achieved with SRI crop management.

Then below is another picture, this one from East Java in Indonesia, taken by the farmer who managed the organic SRI field seen on the right, Miyatti Jannah. Her neighbor's field on the left had been planted with a modern variety (*Ciherang*) and then managed with fertilizer and agrochemical inputs, while Miyatti's field on the right was growing a traditional aromatic variety of rice (*Sinantur*) without synthetic fertilizer or chemical inputs. This picture was taken after both

fields had been hit by a brown planthopper pest attack and then by a tropical storm. From her paddy field of 1000 m^2, Miyatti got a yield of 800 kg (8 tons ha^{-1}), while her neighbor despite his greater expenditure on inputs had little marketable harvest.

These pictures show the kind of protection against biotic and abiotic stresses that SRI management can give to rice plant phenotypes. Larger root systems and stronger tillers make SRI plants better able to resist lodging. Also, deeper root systems give them access to water reserves in lower horizons of the soil, buffering them against water stress and drought. Their increased uptake of silicon from soil that is more aerobic makes for tougher leaves and tillers that can resist insect damage.

Better plant phenotypes are more resilient to the stresses that are escalating due to climate change in most countries. As a bonus, SRI crop management, particularly its AWD water management, *reduces the net emissions of greenhouse gases from rice paddies*. SRI practices can thus help to mitigate the dynamics that drive climate change while enabling farmers to cope with the constraints imposed by climate change (Dahlgreen and Parr, 2024).

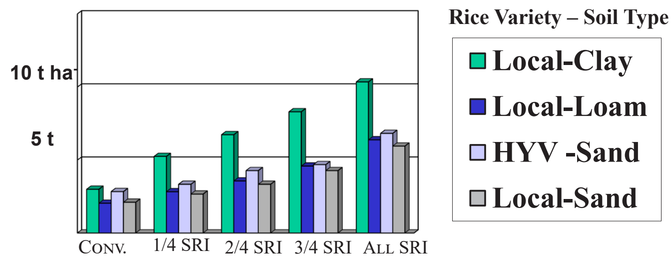
7. SRI is a Matter of Degree

Understanding SRI in terms of complementary principles and practices makes the methodology more a matter of degree than of kind. Asking whether a certain rice crop **is SRI** or **is not SRI?** misdirects attention. It is more informative to ask instead: **to what extent** is the crop grown according to (and benefiting from) SRI principles and practices? This is another reason why SRI should be regarded as a system rather than as a technology, and why it is better to use the term 'SRI' as an adjective than as a noun. SRI is not a 'thing' but rather a set of ideas and insights that can be applied beneficially when growing rice (as well as other crops – Adhikari *et al.,* 2018).

Also, the care and thoroughness with which SRI practices are employed can vary, and this will affect the crop's performance. For example, seed selection can be done hastily or rigorously; and mechanical weeding can just eliminate most of the weeds or with a little additional care, it can also aerate the topsoil around the plants more thoroughly. So, the quality of crop management has some effect on agronomic results.

The first multi-factorial evaluations of SRI practices done in Madagascar showed that the *extent* of using SRI practices can have a consistent, significant, and cumulative effect on crop performance. In 2000 and 2001, baccalaureate thesis research projects were done by the top students in their respective graduating classes of agronomists at the University of Antananarivo. These trials were conducted on farmers' fields under contrasting agroecological conditions: first, on the west coast of Madagascar near sea level; and then on its central plateau at 1200 m elevation. The first set of trials (N=288) was done on poor sandy soils near Morondava with a tropical climate, also comparing the results with a traditional local variety (*riz rouge*) vs. a modern improved variety (2798). The second set of trials (N=240) were conducted near Anjomakely, with better soils and a temperate climate, also comparing SRI results on clay vs. loamy soils.[8]

The four practices evaluated were: (i) age of seedling [16 or 20 days vs. 8 days];[9] (ii) number of seedlings per hill [3 vs. 1]; (iii) water management [flooded vs. aerobic soil]; and (iv) fertilization [NPK fertilizer vs. compost]. A summary analysis of the results is shown in the figure below, comparing yields in tons ha^{-1} from (a) conventional practices, *i.e.,* older seedlings, 16 or 20 days; 3 per hill; flooded soil; and NPK fertilizer, with (b) just one of these SRI recommended practices: 8-day single seedlings, flooded soil, or compost fertilization, i.e. 25% SRI; (c) two of these practices (= 50% SRI); (d) three practices (= 75%), or (e) all four practices [= 100%]. Detailed results of the respective trials are reported in Randriamiharisoa and Uphoff (2002) and in Uphoff and Randriamiharisoa (2002).



In the data from these multi-factorial evaluations, there is evidence of synergy among the practices.

- Going from all conventional practices to ***just one*** of the SRI practices (any one), going from zero SRI to 25% SRI, raised average plot yields by 35% across the different combinatorial trials.
- Using ***any two*** of the four SRI practices evaluated or using ***any three*** of the practices, *i.e.,* going to either 50% SRI or to 75% SRI, added, respectively, another 24% and then another 26% to yield beyond what resulted from adopting just any single SRI practice.
- Using ***all four*** of the recommended practices, going to 100% SRI, added on average another 37% to yield beyond what was produced when any three of the four practices were used.

Thus, while all of the practices had a positive effect, the greatest increment was achieved by using the full set.

[8] *The research design was the same in both locations evaluated six factors with random bloc distribution and three replications of test plots (2.5x2.5 m), hence the large number of trials. Soil-aerating mechanical weeding vs. hand or chemical weed control was not evaluated because this would have doubled or tripled the number of trials required. Because there was no difference between the spacings (25x25 vs. 30x30 cm), all of the combinations analyzed and compared had six replications, which added to the evaluations' statistical significance.*

[9] *At higher elevations, rice phyllochrons are shorter because of lower temperatures, so the different calendar ages represent equivalent biological ages for seedlings in the two respective areas.*

Unfortunately, the effects of *active soil aeration* through mechanical weeding were not evaluated in these trials, as explained in footnote 8. The data reported in graphs above from Madagascar and Afghanistan show large increments in yield when mechanical weeding (active soil aeration) accompanies the other practices recommended for SRI.

A large evaluation of SRI effects in India undertaken in 2012 by the International Water Management Institute (IWMI) reinforces these findings from Madagascar. A survey of over 2,200 farmers across 13 states found that all of the farmers who had adopted SRI to some extent had benefited from higher yield as well as from lower production costs (Palanasami *et al.,* 2013). Of relevance here is that the 20% of surveyed farmers who had adopted all of the recommended practices reported higher yields than those who had adopted the new methods only partially.

This is consistent also with the findings of a meta-analysis done in China that included all of the studies that had been published through 2013 by Chinese rice researchers who had evaluated SRI vs. best management practices (BMP) (Wu *et al.,* 2015). Both the data base, which covered 26 sets of field trials from seven major rice-producing provinces of China, and the methodology employed were more rigorous than the data base and methodology for a previously published meta-analysis that attempted a similar comparison of SRI vs. BMP methods (McDonald *et al.,* 2006).

The McDonald study calculated from its data set, which excluded all data from Madagascar and was not inclusive, that BMP had a yield advantage of 11% over SRI. The analysis by Wu *et al.,* on the other hand, found that for the whole data set, SRI had an average yield advantage of 11% over BMP.

Because most of the Chinese evaluations had not evaluated the full set of SRI practices – only 20% of the studies had followed an SRI protocol fully – a weighting matrix was developed to quantify the degree to which SRI methods were used (see appendix of that article). Scoring 20 points or above (out of a possible 27 points) was considered to be 'good' use of SRI principles and practices; scoring only 10-14 points or fewer was classified as 'minimal' use.

When considering only cases with 'good' use of SRI methods, the SRI yield advantage was 20%, while with 'poor' (*i.e.,* limited) use of SRI practices, there was a BMP advantage of 4%. This reflects the synergy among practices, e.g., if very young seedlings were used but the field was kept continuously flooded (no AWD) this would stunt the small rice plants; or not having optimally wide spacing of plants would constrain their achievable root growth.

The data base did not contain enough results from full SRI vs. BMP trials to assess the statistical significance of 100% SRI management. Few of the researchers, it turned out, had been willing to rely fully on organic fertilization in their SRI trials. But the published results reported from China showed that SRI had a 30% advantage over BMP.

8. Conclusion

SRI results will always vary because they depend upon the growing environment of rice plants, more than on the seeds (genotype) planted or on exogenous inputs. As noted at the beginning of this paper, by inducing greater root growth and enhancing the life in the soil SRI practices create a much more favorable growing environment for the plants. Increasing organic matter in the soil, for example, makes it better able to absorb and retain rainfall as well as to support an active and diverse soil biota, including the plant-soil microbiome.

Enhancement of the root systems and the soil biota go together as a result of roots' exudation. This creates a positive feedback loop between the plants' root systems and their canopies (leaves and tillers). The better the root system can acquire water and nutrients from within the soil system, the better the canopy will grow and function, and vice versa. The more sunlight (energy) that the canopy can intercept and the more photosynthate that it produces, the more organic compounds can be shared with the root system and with the soil biota. The life in the soil in turn benefits the roots and the canopy through N fixation, P solubilization, mineralization, and other processes.

These processes apply for all kinds of rice and for other plants. But they are becoming more important as farmers are confronted by the challenges of climate change and by the declining levels of carbon (energy) in their soils. I would like to conclude this article with two particular observations.

- For farmers: ***Crop agriculture should be regarded particularly as a matter of growing plant roots*****,** rather than just as a task of growing plants, *i.e.,* what can be seen above-ground. This may sound inverted, but if plants are enabled through appropriate practices to grow larger, healthier, longer-lived, better-functioning root systems, then the plants as a whole will be better able to thrive and to deal with most kinds of biotic and abiotic stresses, accordingly giving better yields. Plants with good root systems can take care of themselves.
- For policy-makers: ***Substantial and urgent investments should be made in soil fertility and sustainability.*** This is one of the most crucial and productive investments that can (must) be made for the welfare of both people and country. For example, in India, the MGNREGA program could be utilized on a large scale to get greater amounts of organic matter into its carbon-depleted soils as a purposeful investment in India's future productivity. This is something as important and tangible as roads or bridges for the country's well-being and stability.

These conclusions range beyond the subject of the System of Rice Intensification, but they represent some of the consequential lessons that have been learned from SRI research and experience, reaching beyond rice.

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