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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

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 agro-ecological innovation. On the plus side, Henri de Laulanié's empirical construction of SRI in Madagascar some four decades ago is benefiting tens of millions of rice-producing households in over 60 countries now. Further, it produced important new knowledge for rice production, some of it counter-intuitive.[1] For example, Laulanié established through observation and in-field experimentation with farmers.

- 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 greatly, even with 80-90% fewer plants per m^2, can increase grain yield per unit area if the plants are managed with certain complementary practices.
- 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 at the time accepted scientific knowledge (Sinclair, 2004). Recommendations from leading research institutions included, for example, transplanting seedlings more than 20 days old, not ones 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 because of SRI performance and research.

On the other hand, taking an inductive approach means 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 sceptical 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 more than 20 years ago (Stoop *et al*., 2002).

[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 in terms of phyllochron analysis for rice (Nemoto et al., 1995), summarized in Uphoff (2016), pages 154-160.

There are now reasonably robust scientific explanations for its success (Toriyama and Ando, 2010; Stoop *et al*., 2011; Thakur *et al.,* 2016) and there is a large published literature on SRI.[3] But in retrospect it would have been helpful if a clear distinction could have been made at the outset between the agronomic principles that account for the impacts of SRI methodology and the agronomic practices that operationalize SRI in the field in millions of diverse fields. Like so many things, this is clearer in hindsight than it was before the fact.

Principles are formulated to be general, while practices are specific and varying. For example, keeping paddy soil mostly aerobic is a basic principle for SRI that gets accomplished by a variety of practices that 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 article addresses this shortcoming in SRI theory and undertakes to sort out the distinction.

1. SRI as an innovation

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

- SRI crop management modifies the above- and below-ground environment in which rice plants are grown, creating more favourable conditions for their health and growth.
- 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, not requiring them to buy new inputs or to utilize new plant varieties.[4] SRI can be explained most precisely by using two technical terms that are now well-known within biological science although little-used 20 years ago: genotype (an organism's genetic endowment) and phenotype (the actual organism). Stated most succinctly, SRI methods elicit better crop phenotypes, *i.e.*, more productive, more robust rice plants, from their genotype. In the case of rice, 'genotype' refers to an established cultivar or landrace, improved or unimproved, which has a certain genetic potential.

All organisms, not just rice, begin with a 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 fulfil some or most, but seldom all, of this potential. SRI crop management rather than creating and utilizing new genetic potentials 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 makes improvements in crops' genetic resources and then utilizes more synthetic (inorganic) fertilizers, more agrochemical protectants and more water to benefit from that increment in potential. (It is often

[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 labour time that women spend in weeding SRI rice paddies by three-quarters (Mrunalini and Ganesh, 2008).*

forgotten that increased irrigation has been a major part of Green Revolution successes).

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). Their income is further enhanced because SRI practices reduce their need to spend money on (expensive) seed. It should be noted, however, that SRI improves the performance and profitability also of traditional, *i.e.*, unimproved varieties. This can make these competitive economically with the use of modern varieties, also helping to conserve rice biodiversity (Dwiningsih, 2023).

2. Pictures each worth more than a thousand words

Two pictures that have influenced my own comprehension of this innovation best communicate an understanding of SRI. 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 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 by creating more favourable conditions for them to grow in, not just improving physical circumstances but also enriching biological elements and concomitants.

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). They are thus 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 it was only 13 days old and transplanted into a rice field with wide spacing of 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, a usual 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 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 canopies, note also that the root system of the SRI plant was not only much larger, but also lighter-coloured, because its roots were not suffocating and degraded 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 favourable conditions: no crowding, no continuous flooding, and starting with young seedlings transplanted carefully so that their potential for growth is not diminished.[5]

[5] *Anticipating that some people would be sceptical 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 differentiation of 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 the acronym for 'SRI' because a literal translation of 'SRI' into Spanish becomes 'SIA,' which is the Spanish acronym for the American CIA.*

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 has 223 tillers emergent 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

While SRI has usually been described and presented in terms of certain practices, it is better understood in terms of the principles that are implemented by particular practices. It is certain practices that make rice plants more vigorous and more productive, better able to fulfil 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 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 we should keep in mind the two factors that are foundational for SRI effects. The first is the increased growth and performance of plant root systems, evident in the pictures above. The second factor is 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.

Although not easily seen or never seen, the soil biota provides a great variety of services both to plants and to the soil system, e.g., 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, known as the plant-soil microbiome, is starting to receive the scientific attention it deserves (Turner *et al*., 2013; Tkacz and Poole, 2020; Primavesi *et al.,* 2024). This parallels the intensification of medical research, which investigates and appreciates how 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 beyond rice, as noted above.

i. Establish new plants carefully and well, avoiding trauma to the roots and ensuring good opportunity for roots to grow 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.

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. However, the distance between plants is something to be optimized rather than maximized.

iii. Maintain both water and oxygen in the soil, with never too much of either. All plants need both water and oxygen. Because air and water occupy the same pore space in the soil, having more of either one leads to having less of the other available to plants. Water, soil, and weed management practices should strive for a balance of water and air in the soil. The advice of Laulanié was to provide plants with "the minimum of water," while meeting also the needs of the soil biota.

iv. Enhance and maintain the soil system's fertility, knowing that this depends on the 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, diversity, and activity of life in the soil.

These principles are not likely to elicit much controversy among agronomists. However, some of the SRI methods 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 that operationalize 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 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 robots following instructions. During training for SRI, farmers should be told more than just what to do. They should be helped to understand why particular practices are recommended, and how these practices can be best used and/or adapted to local conditions. The following practices materialize the principles that are enumerated above. Note that the practices described 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 are shown in section 6.

Principle 1: Establish new plants carefully and well

A. Start with purposeful 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. Use 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.

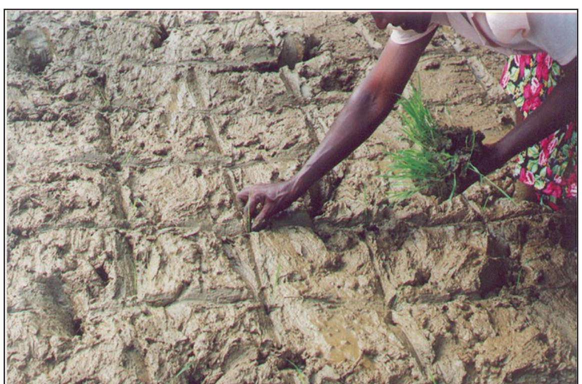
B. Grow the seedlings in a small garden-like nursery that is elevated like a raised bed and unflooded. The nursery's size is only 10-20% as large as previously because with SRI the seed rate is reduced so greatly.

The nursery should be close to or in the main field, wherever there is a source of water for watering the seedlings as needed. Or, seedlings can be grown on trays made of metal or plastic that can be easily transported to the field, or in plastic trays designed for vegetable setts that avoid any root disturbance. or on mats of soil and organic material that can be rolled up and used in mechanical transplantation. There are thus several ways to raise SRI seedlings, not just one, as shown from the pictures below. And in many places there is the option of direct-seeding with no hand or mechanical transplanting.

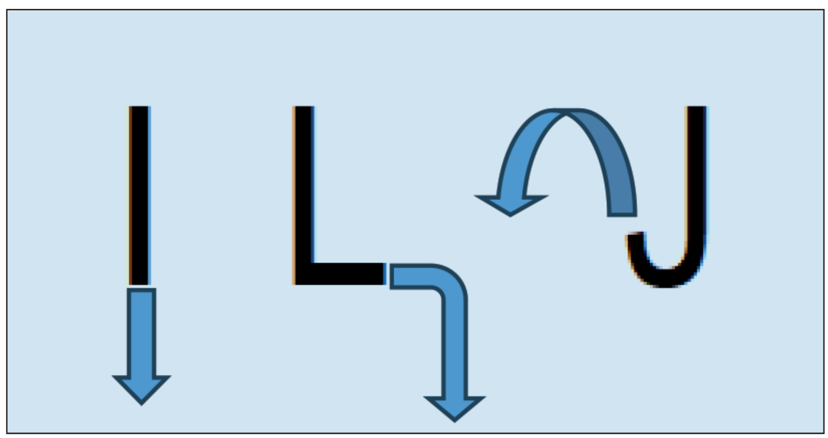
(A) SRI seedling nurseries adjacent to the main field in Madhya Pradesh state of India. (B) SRI seedlings in Lombok, Indonesia, being grown on small metal trays that are easily carried to the field. (C) Farmers showing SRI seedlings being grown in plastic trays in Karnataka state, a method made practical by SRI's requiring 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.

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 plant's resumption of growth can be delayed for about a week or even more while the tip of the root re-orients itself for *downward* growth.



Careful transplanting of single, young seedlings, widely spaced



Principle 2: Minimize Principle 2 wrong plate 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 below in pictures 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. Such marking establishes equal distances between the plants in all directions and makes possible mechanical weeding in perpendicular directions. Optimal spacing is most often 25x25 cm; but in soil that is less fertile, spacing of 20x20 cm may give a higher yield, while in very fertile soil, 30x30 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 plant roots and most soil organisms. The field will be flooded intermittently when irrigation water is applied, as much as 5 cm, but 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 with heavy clay soils, these 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.

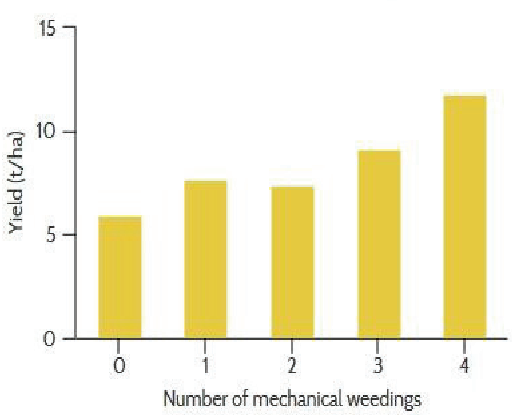

The original recommendation for SRI practice was to practice AWD until the rice plants start to flower and form grains, *i.e.*, until panicle initiation (PI). In addition, thereafter to keep a shallow layer of water on the field (1-2 cm) until 10 days before harvest. However, research at the ICAR-Indian Institute for Rice Research in Hyderabad 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.

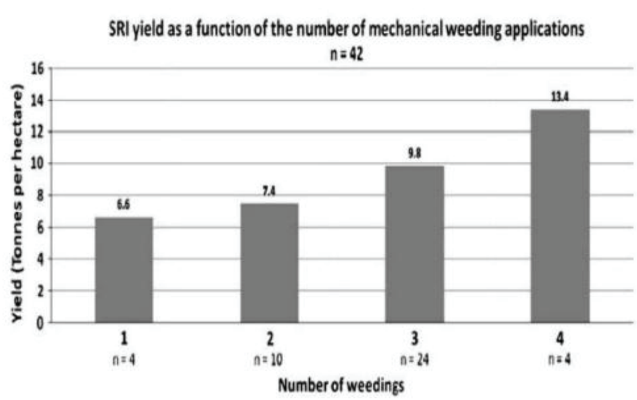
H. In SRI management, active soil aeration is linked with weed control. When rice paddies are not kept flooded all the time, there will be more growth of weeds, at least until their seeding cycle has been broken. Weeding several times during the season using a simple mechanical weeder, possibly a motorized weeder to make the work easier, is preferable to manual weeding or using herbicides because the implement aerates the topsoil while churning weeds into the ground. Such 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 to make the task easier and more effective. A second weeding should be done another 10-15 days later. This may be sufficient to control weeds, but because soil-aerating weeding aerates the soil while controlling 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. that are associated with active soil aeration. SRI weeding enhances yield as shown in the two 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 labour. 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 are also beneficial. These materials improve the life in the soil as well as the soil 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.

Either inorganic or synthetic fertilizer can be used together with other SRI practices, or some combination of both, 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 get a premium price, besides being free of chemical residues. Farmers using SRI methods generall7 appreciate the importance and value of the activities of 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 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 labour 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 controls.

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 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, the 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]

[6]*Unfortunately, little attention has been paid to this crucial parameter. 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*

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). However, 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 labour 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. **Levelling 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-levelling and specialized machinery, as has been done as part of the large-scale application of SRI methods in Punjab, Pakistan (Sharif, 2011). Levelling 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 that is 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 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.

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.

i. 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 suffocating will become dark-coloured and will eventually turn black.

ii. Simply observing the colour 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 turn brown and then black when deprived of oxygen, while healthy plants will have dark green coloration.

iii. 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 labour 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 labour 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 ready access to enough space for their root and tiller growth, and to sunlight, nutrient 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 are 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 SRI/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 labour (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-levelled 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 labour 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 Rahman, 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, shaped 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 genetic potential 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 effects. 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 plants growing larger and 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. 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 which passed over a few days before the pictures were taken.[7]

On the left are seen two adjacent rice fields with a farmer holding up representative rice plants uprooted 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 other members of her farmer field school group giving a closer view of the plants. These women took it upon themselves to carry these plants to other villages to show their neighbours 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 neighbour's field on the left had been planted with a modern variety (*Ciherang*) and managed with fertilizer and agrochemical inputs, while Miyatti's field on the right was growing a traditional aromatic variety of rice (*Sinantur*) and without fertilizer or

[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 cultivate rice and to talk with them about their SRI experience; see pages 2-6 of http://sri.cals.cornell.edu/countries/vietnam/vnntutr106.pdf.*

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 neighbour 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. Their larger root systems and stronger tillers make SRI plants better able to resist lodging. In addition, deeper root systems give SRI plants access to water reserves in the soil at lower horizons, buffering them against water stress and drought. Their increased uptake of silicon from more soil that is more aerobic soil to tougher leaves and tillers that can resist insect damage

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

7. Regarding SRI as 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 'SRI' is better used as an adjective than as a noun, to make a semantic distinction since SRI is not a 'thing' but a set of ideas and insights that can be applied beneficially when growing rice.

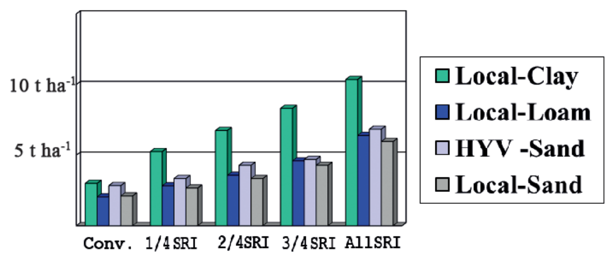
Also, the care and thoroughness with which SRI practices are employed can vary, and this will affect the crop's performance. For example, seed selection can be done hastily or rigorously; and mechanical weeding can just eliminate most of the weeds or with a little additional care, it can also aerate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

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: on the west coast of Madagascar near sea level; and 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 from a traditional local variety (Riz Rouge) vs. a modern improved variety (2798). The second set of trials (N=240) were near Anjomakely had better soils and a temperate climate and compared clay vs. loamy soils.[8]

[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.

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, shown in the figure below, compared yields in tons ha-1 from (a) conventional practices [older seedlings, 16 or 20 days; 3 per hill; flooded soil; and NPK fertilizer] with (b) just one of the 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 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, any one, of the SRI practices, *i.e.,* going from zero SRI to 25% SRI, raised plot yields by 35% on average across the different combinatorial trials.
- Using any two of the four SRI practices evaluated or to any three of the practices, *i.e.,* going to 50% SRI or to 75% SRI, added respectively another 24% and then another 26% to yield beyond what resulted from adopting any single SRI practice.
- Using all four of the recommended practices, *i.e.,* 100% SRI, added on average another 37% to yield beyond what was produced then 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.

Unfortunately, the effects of active soil aeration through mechanical weeding were not evaluated in these trials, as explained in footnote 9. The data reported 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 Irrigation Management Institute (IIMI) 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 most 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 a meta-analysis done in China that included all of the studies published by Chinese rice researchers who had evaluated SRI vs. best management practices (BMP) through 2013 (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 article 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.

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

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). Scoring 20 points of 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 only cases with 'good' use of SRI methods were considered, 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., using very young seedlings but keeping the field flooded (no AWD) would stunt the small rice plants; or not having optimally wide spacing of plants constrains their achievable root growth.

When trials making 'full' use of SRI methods were evaluated, the average yield advantage of SRI over BMP was 30%, quite the reverse of the results of McDonald *et al*., However, the number of such trials in the data base was not great enough for testing statistical significance. Few of the researchers, it turned out, had been willing to rely fully on organic fertilization in their SRI trials.

8. Conclusion

SRI results will always vary because they depend on the growing environment of rice plants, more than on the seeds (genotype) planted and 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 favourable 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 roots and the soil biota go together as a result of root exudation. This creates positive feedback between 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) the canopy can intercept and the more photosynthate that it produces, the more organic compounds can be shared with the root system and 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: Consider crop agriculture as a matter of growing plant roots - rather than 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 of plant, soil, water and nutrient management to grow larger, healthier, longer-lived, better-functioning root systems, then crop plants will be better able to thrive and to deal with most kinds of biotic and abiotic stress, giving better yields.
- For policy-makers: Invest in soil fertility and sustainability as this is one of the most crucial and productive investments that can (must) be made for the welfare of both people and country. In India, for example, the MGNREGS 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, as important and tangible as roads or bridges for the country's well-being and stability.

These conclusions range well 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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