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REVIEW & INTERPRETATION

How the System of Rice Intensification Can Contribute to Climate-Smart Agriculture

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ABSTRACT

Although there has been controversy over some of the high yields reported with the System of Rice (*Oryza sativa* L.) Intensification (SRI), an agroecological crop management system developed in Madagascar, substantial increases in average rice yields have been reported from more than 50 countries when these methods are used, not even necessarily fully. Most attention thus far has focused on yield and little on whether or how SRI methods can help farmers adapt to and buffer the adverse stresses of climate change as well as reduce their rice paddies' contribution to global warming. According to FAO criteria, achieving all three impacts would qualify SRI as "climate-smart agriculture" (CSA).This paper reviews how making SRI modifications in agronomic practices can elicit plant phenotypes from given rice genotypes that are more robust and adaptive as well as more productive. This effect appears to result from SRI's inducing larger, healthier root systems and enhancing beneficial soil biota. These effects are associated with improvements in a variety of morphological and physiological characteristics in rice plants. Cross-national meta-analysis has documented reductions in crop water requirements and increased water productivity under SRI management. These methods are also seen to contribute to greater drought-tolerance, resistance to storm damage, cold-temperature hardiness, shortened crop cycles that reduce crops' exposure to biotic and abiotic stresses, less susceptibility to insect pest and disease damage, and diminished net emissions of greenhouse gases from paddy fields. The efficacy of SRI management methods is increasingly accepted by governments, donor agencies and farmers, but more remains to be researched and evaluated.

Core Ideas

- System of rice intensification increases crop productivity with lesser inputs.
- System of rice intensification yields more productive and robust rice phenotypes from given plant genotypes.
- System of rice intensification crops are tolerant to biotic/abiotic stresses and it reduces GHGs from rice fields.
- System of rice intensification enables farmers to adapt to and mitigate climate change.
- This paper reviews how and why SRI can be considered as climate-smart agriculture.

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Most rice has been grown for centuries on continuously flooded soils with fairly mature seedlings transplanted in clumps of three or four (or more) plants at high density. During the Green Revolution, the yields of rice and other grain crops were increased by developing and introducing higher-yielding varieties (HYVs) with greater application of mineral fertilizers, increased irrigation, and the use of herbicides and pesticides to control various weeds, insect pests, and pathogens (Swaminathan, 2007). It became accepted that applying more water, sowing more (and better) seeds, and utilizing more fertilizers and agrochemicals was the best way to raise crop output.

This strategy has been encountering rising economic, social, and environmental costs, however, prompting efforts to optimize on input use, for example, through precision agriculture. Researchers' and practitioners' attention remains focused mostly on how much more of which inputs will give farmers the most profitable returns. The suggestion that more output could be achieved by making *reductions* in the use of agricultural inputs, by utilizing them differently, is divergent from most current practices and policies.

This deviation deserves empirical examination, however, because using more water, more seed, and more synthetic fertilizer to improve rice production can be counterproductive, as seen from research discussed below, conducted at the China National Rice Research Institute (Lin et al., 2009). Rice breeders at the International Rice Research Institute (IRRI) have acknowledged that the yields from their trials have not increased significantly over the past 30 yr (Sheehy et al., 2007). So the paradigm which guides most current agricultural research and development (R&D) should be open to review, especially since agriculture is the sector most sensitive and vulnerable to adverse climatic influences. Limitations on water availability already constrain irrigated rice production in many countries; and declining adequacy and reliability of water supply, plus concerns about degrading soil

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Abbreviations: AWD, alternate wetting and drying; CA, conservation agriculture; CSA, climate smart agriculture; GHGs, greenhouse gases; GWP, global warming potential; HYVs, higher-yielding varieties; IARI, Indian Agricultural Research Institute; ICAR, Indian Council of Agricultural Research; ICRISAT, International Crops Research Institute for the Semi-Arid Tropics; IPM, integrated pest management; IRRI, International Rice Research Institute; IWMI, International Water Management Institute; LAI, leaf area index; SRI, system of rice intensification; SRPs, standard recommended practices; SWI, system of wheat intensification.

and water quality, have made the sustainability of rice production as commonly practiced increasingly questionable (Bouman et al., 2007; Nelson et al., 2009). Maintenance of soil quality and soil health is also a growing concern (Lal, 2009, 2015).

Maintaining global food security now and in the years ahead is challenged by continuing population growth and declining arable land per capita, in addition to growing scarcity of water for agriculture and soil degradation (Fedoroff et al., 2010). Between now and 2050, food production should rise by at least 60% to satisfy the food demands of a world population expected to reach or surpass 10 billion people (FAO, 2012). Meeting this target for food security is increasingly constrained by climate changes and uncertainty (Wheeler and Braun, 2013). All these considerations have made CSA a matter of greater concern.

The question arises: to what extent can and should we be relying principally on biotechnology and input-driven agriculture to ensure our food security in the future? Prudence suggests that other strategies should at least be examined. There is some agreement that policies, research, and investments should consider various alternative approaches that can be broadly grouped under the rubric of *agroecology* (FAO, 2014). This primarily relies on and utilizes productive potentials that exist within crop plants and animals and within the soil and the aboveground ecosystems on which they (and we) depend (Altieri, 1995; Gliessman, 2007).

An agroecological perspective encompasses and values the myriad interactions and interdependencies that have evolved over many eons among plants and animals and with the microbial realm. This realm includes what is called the microbiome, which makes essential contributions to the health and growth of both plants and animals including humans, as is becoming better understood and more appreciated by both scientists and the general public. The microbiome and its implications for agricultural improvement, it should be noted, found no place in the previous thinking and practice of the Green Revolution, which still shapes most current policy and strategy for the agricultural sector.

Some proponents of the Green Revolution approach to agricultural R&D may consider agroecology as atavistic, as a backward step away from their "modern" technology. However, agroecology is a field of knowledge and practice which draws on local and traditional knowledge and, at the same time, proceeds with support from scientific advances in the fields of microbiology, soil and microbial ecology, and epigenetics. These bodies of knowledge make clear that genes represent just the starting point for organisms' development, and are not in themselves determinant. What is all-important is the phenotypical *expression* of those genetic potentials. Phenotypes are shaped by all aspects of an organism's environment, including the soil–plant microbiome, and they are what provide us with the food that we eat. Genes are essential elements in the food production process, but there are many other components.

Over the past 15 yr, as reviewed here, it has been demonstrated that there are available more efficient ways to grow irrigated rice than just with the heavily input-dependent practices currently favored. Simple changes in cultivation methods can enable farmers to raise substantially the productivity of the land, labor, water, and other resources that they invest in growing rice.

Here we consider how and why the phenotypes that result from modified cultivation practices are better able to adapt to and resist the multiple stresses of climate change. Practices which raise production can also diminish the net emission of greenhouse gases (GHGs) from paddy fields, thereby lowering the global warming potential of irrigated rice production systems. Making concurrent improvements in production, adaptation to climate change, and mitigation of the forces driving climate change encompasses the three essential and complementary elements of climate-smart agriculture as defined by FAO (2010).[1]

The changes in rice crop management that are considered here for achieving these three concurrent goals are known as the SRI (Stoop et al., 2002; Dobermann, 2004). This review does not attempt to consider SRI in its entirety, but rather focuses on whether and how its methods may accomplish more than just yield increases, addressing the adaptation and mitigation dimensions of CSA, although productivity gains need also to be considered as part of any CSA assessment.

Evidence in the literature confirms that agroecologically informed crop management methods such as SRI can produce plant phenotypes which are both more productive and more robust, thereby meeting CSA objectives better than do crops produced with currently favored cultivation practices. Evidence is also starting to accumulate that similar results can also be achieved by using these ideas and methods with other crops beyond rice, for example, wheat (*Triticum aestivum* L.) (Dhar et al., 2016).

We will review here first the underlying principles and practical methods of SRI that define this methodology. Then the principal factors that are central to SRI impacts are reviewed–the enhanced growth and functioning of root systems, and the contributions of beneficial soil biota–along with their associated effects on plant phenotype. The main body of this review considers ways in which SRI practices contribute to rice crops' adaptation to climate change and, further, to its mitigation. Then the origins and spread of SRI are briefly discussed, and constraints and opportunities for its further spread are considered.

PRINCIPLES FOR MORE CLIMATE-RESILIENT RICE PRODUCTION

The recommended practices that constitute SRI crop management in operational terms reflect certain broad agronomic principles that are generalizable for achieving more intensive and sustainable crop production, not restricted to SRI or even to rice. Research has shown that rice seedlings planted singly produce larger roots and synthesize more plant hormones, that is, cytokinins, than do three or more seedlings of the same variety when planted together in one hill (San-oh et al., 2006). Similarly, planting younger seedlings is in itself a beneficial practice for rice plants' subsequent growth as they experience less competition in the nursery and less shock from transplanting (Pasuquin et al., 2008; Sarwar et al., 2014). Younger seedlings start their tillering

[1] Controversy has arisen over whether the term "climate-smart" has been coopted by agrochemical and corporate interests to serve their purposes. Some advocates prefer the designation "agroecology" and reject the term climate-smart (IATP, 2015). This becomes an ambiguous matter, however, because FAO which originated the term climate-smart agriculture also endorses agroecology as an agricultural strategy that, among other things, aims to reduce agrochemical use and does not propose relying on genetic modification or other biotechnology (FAO, 2014). We regard the two terms as essentially interchangeable, rather than as contending or conflicting approaches. However, not all climate-smart agriculture will necessarily be agroecological, and agroecology is not all that there is to climate-smart agriculture.

earlier and have greater tiller and root growth as a result. Wider spacing between plants promotes more profuse growth of roots and tillers by facilitating plants' access to nutrients, water, and light (Thakur et al., 2010b). Using organic manures and keeping paddy fields unflooded improves soil health, nutrient uptake, and the rhizosphere environment (Yang et al., 2004; Zhang et al., 2009). Each of these practices directly or indirectly enhances roots' proliferation, functioning, and longevity, resulting in improved shoot growth and functioning. Collectively they give farmers more output per unit of input as well as a more climate-resilient crop, as discussed below.

There are also significant interactions between and among these SRI practices (Uphoff and Randriamiharisoa, 2002). For example, there are benefits from transplanting seedlings grown in unflooded nurseries into unflooded main fields, rather than into flooded fields, and more benefit from transplanting them at an early age (Mishra and Salokhe, 2008). However, the proposition of synergy among SRI practices has yet to be explored fully. This should be the subject of much further research. The underlying principles for SRI agronomy discussed here are applicable not just for rice but also for other crops (Abraham et al., 2014; Behera et al., 2013).

Early, Careful, and Quick Establishment of Healthy Plants

Young rice seedlings transplanted at the two to three leaf stage maintain more of their genetic potential for tillering, panicle formation, and grain filling than do older seedlings (Mishra and Salokhe, 2008; Thakur et al., 2010a). "Young" means transplanting seedlings before the start of their fourth phyllochron of growth, in the two- to three-leaf stage, usually before 15 d after sowing (Nemoto et al., 1995; Uphoff, 2015). For best results, seedlings should be transplanted quickly, gently, and shallow, with just 1- to 2-cm depth, into well-leveled, muddy soil without standing water. This minimizes transplanting shock so that seedlings' resumption of growth starts sooner (Pasuquin et al., 2008). The best age for transplanting "young seedlings" has to be adjusted according to local conditions such as ambient temperature, field water depth, labor availability, etc. Even though there are limits on its application, the principle of using optimally young seedlings has general relevance (Khakwani et al., 2005).

Actually, transplanting is no longer the only option for SRI crop establishment. In some countries, farmers who want to reduce their labor requirements have adapted SRI practices to *direct seeding*. This particular practice is quite consistent with the principle of minimizing trauma to young plant roots, so this first principle covers both transplanted and direct-seeded rice. The operative proposition is that plant roots should not be traumatized or desiccated since these provide the basis for any plant's survival and success. This principle addresses the desirability of each plant realizing its own genetic potentials as fully and as quickly as possible.

Reduced Plant Density to Lessen Competition between Plants

System of rice intensification plants are established singly and in a square geometric pattern to maximize the growth and yield potential of each individual plant, having 360° exposure to sunlight and air circulation. System of rice intensification management lowers the number of plants m^{-2} by 80 to 90%, so that competition among their roots for nutrients and water is minimized, and inter-plant shading is reduced (Thakur et al., 2010a). Reducing plant density increases yield potential and crop productivity in part by minimizing genetic and acquired competition (Fasoula and Fasoula, 1997).

Larger root systems and canopies that result from wider spacing give all of the crop plants greater access to soil nutrients as well as to water and light. The result is increased cytokinin flux from the roots toward the shoots, delayed senescence of leaves, more light interception, and higher rates of photosynthesis (San-oh et al., 2004, 2006; Thakur et al., 2016). With more room to grow, fewer plants can produce more tillers m^{-2} and their panicles are also larger, provided that the other SRI principles are also satisfied. The crowding of plants under conventional crop management, conversely, inhibits these processes. However, the optimum number of plants (seeds) m^{-2} under SRI must be determined empirically for specific climatic, varietal, and soil conditions to get the most productivity from the methods (Thakur et al., 2010b).

Improved Soil Environment for Root Growth

Applying mineral fertilizers provides plants with nutrients mostly for their short-term benefit, but it also entails some longer-term problems of environmental pollution, like eutrophication, GHG emissions, and soil acidification (Chen et al., 2011). Conventional flooded rice has very low fertilizer-use efficiency due to losses from fields and reduced uptake from degenerated root systems (Thakur et al., 2013). Although SRI recommends the use of organic manures, as much as available, mineral fertilizers can be applied in SRI production if organic material is not sufficient to meet the crop's nutrient demand–unless producers and consumers want their rice to be organically grown. Researchers have found that mineral fertilizers can be used beneficially with SRI practices as these improve plants' fertilizer uptake and efficiency due to their greater root growth (Thakur et al., 2013; Zhao et al., 2009). Integrated nutrient management with SRI seeks to optimize nutrient availability from a combination of organic and inorganic sources, recognizing that chemical fertilizers themselves do little to improve the structure and functioning of soil systems, which are the key to greater and more sustainable crop production over time.

The soil's fertility and productive capacity depends not only on available nutrient stocks, but also on the flux of nutrients within soil systems, one of the multiple services and protections provided by the soil biota (Redman et al., 2011; Watts and Dexter, 1998). The soil's biological environment with rhizobacteria, mycorrhizal fungi, and other organisms affects the retention of nutrients in the soil and their continuous cycling, as well as the availability of water within soil systems and its use by plants. The soil's biotic populations are enhanced and renewed when it is provided with sufficient organic matter while maintaining mostly aerobic conditions.

Microorganisms and the higher life forms that pyramid upward from this biological base furnish plants with micro- as well as macronutrients and also enhance the soil's porosity and aeration which promotes the proliferation and activity of roots (Yang et al., 2004). The soil biota in its entirety reduces the soil's bulk density and creates more favorable environments for root growth. The presence of microorganisms has been shown to be directly associated with the greater length, biomass, and surface area of rice roots (Yanni et al., 2001).

The building up of soil organic matter is desirable for its long-term environmental benefit of C sequestration while it enhances the greater productivity and sustainability of soil systems as a direct and immediate benefit. In some places, SRI is starting to converge with the climate-smart practices of conservation agriculture (CA) (Lu et al., 2013; Sharif, 2011). Minimizing or avoiding soil disturbance with CA enhances the fertility and functioning of soil systems according to the same principles as are operative with SRI.

Reduced and Controlled Water Applications

The continuous flooding of paddy fields creates hypoxic soil conditions that stunt and senesce plants' roots and reduce their functional capacity. In continuously flooded fields, about three-fourths of rice plants' roots degenerate by the time of flowering in plants' canopies which starts their grain production. On the other hand, when in well-drained, aerobic soil, rice plant roots are subject to little deterioration (Kar et al., 1974). Chapagain and Yamaji (2009) found that at the flowering stage of a rice crop grown under SRI management with intermittent irrigation, the average proportion of whitish (functional) roots vs. black (non-functional) roots was 74:26, while conversely, with continuously flooded rice plants this ratio was 46:54.

Continuous flooding also impedes the survival and services of aerobic soil organisms such as growth-promoting rhizobacteria and various mycorrhizal fungi which require an oxygenated environment as do other beneficial soil organisms like earthworm (*Lumbricus terrestris*) (e.g., Watanarojanaporn et al., 2013). Growing rice in unflooded soil together with SRI practices leads to root systems that are greater in size with lighter coloration and more efficient in their functioning. This effect can be enhanced by actively aerating the soil (Fig. 1).

Active Soil Aeration

When paddy fields are not kept flooded, weed growth will be a constraint. Planting single seedlings in a square pattern permits farmers to control weeds with a simple mechanical weeder by making perpendicular passes over the field, both between and across rows, rather than doing manual weeding or using herbicides. Breaking up the top few cemtimeters of soil and uprooting/burying weeds can have positive effects on soil fertility and plant performance, promoting the growth of roots by oxygenating and decompacting the soil while supporting also the growth of aerobic soil biota. Farmers in Afghanistan, Nepal, and Madagascar have found that doing multiple soil-aerating weedings of their SRI crop can raise their yield by several t ha^{-1} (Thomas and Ramzi, 2011; Pandey, 2009; Uphoff, 1999). This makes weeding a benefit rather than just a cost. The number of weedings that farmers can do is limited by labor availability and cost, and by the growth and closure of the canopy. Both the agronomics and economics of this effect remain to be more thoroughly studied, however. That crop production gains from active soil aeration is not a new idea (Cannon and Free, 1917).

Fig. 1. The pair of rice plants on the left was grown respectively with system of rice intensification (SRI) vs. standard methods of rice cultivation at the Haraz Extension and Technology Development Center in Amol, Iran. The dark color and stunting of the right-hand plant's roots reflect their degeneration for lack of oxygen (Kar et al., 1974). The pair of rice plants on the right, grown on a farm in Cuba, are the same age (52 d) and same variety (VN 2084). The plant on the right with 43 tillers was transplanted into an SRI growing environment while only 9-d old. The plant on the left, just removed from the nursery for transplanting at a conventional age in Cuba, has only five tillers. The differences in root growth and coloring, lighter vs. darker, are similar to those seen on the left.

These five principles have been found to apply beyond irrigated rice cultivation. Farmers in rainfed areas have been adapting them to improve their unirrigated rice production, with similar benefits. Increases in crop productivity with more resilience to adverse climatic conditions have been reported for rainfed SRI rice production in Cambodia, Myanmar, and India, for example (Anthofer, 2004; Kabir and Uphoff, 2007; Sinha and Talati, 2007). Also, farmers have begun applying these principles to crops such as wheat, finger millet [*Eleusine coracana* (L.) Gaertn.], maize (*Zea mays* L.), sugarcane (*Saccharum officinarum* L.), mustard (*Brassica juncea* L.) , teff [*Eragrostis tef* (Zuccagni) Trotter], various legumes, and some vegetables, with the same kind of positive responses reported here including climate resilience (Abraham et al., 2014; Araya et al., 2013; Behera et al., 2013; Dhar et al., 2016; Prasad, 2008; SRI-Rice, 2014).

The practices that are based on these principles can be characterized as "just good agronomy," but they have not been commonly used in combination as recommended for SRI and for the broader System of Crop Intensification discussed in the references cited above. The common denominator for this agroecological strategy is that these practices respectively and collectively enhance root growth and the soil biota, as discussed in the next section. Neither of these focuses for improving agronomic results–plant roots and soil organisms–figured prominently in the research and promotion that were undertaken during or after the Green Revolution.

MORPHOLOGICAL AND PHYSIOLOGICAL IMPROVEMENTS WITH ROOT GROWTH AND MICROBIOLOGICAL MOBILIZATION

Since the advent of the Green Revolution, most crop improvement programs have emphasized modifying and increasing the genetic potentials of plants through plant breeding, coupled with greater or optimizing use of various purchased inputs, particularly increasing chemical fertilizers. System of rice intensification experience and research is showing, on the other hand, that crops' productivity and hardiness can be enhanced by making modifications in their growing environments above- and belowground, with less reliance on agrochemical inputs. The latter may be used together with SRI methods where net and sustainable benefits can be demonstrated, and where there is no preference for organic production methods. However, organic fertilization is generally favored

Table 1. Effects of system of rice intensification (SRI) principles/practices on rice roots and the soil biota.

SRI principles	Effects on roots	Effects on soil biota	Indirect/joint effects
Early, careful, and quick establishment of healthy plants	Rice seedlings transplanted before their fourth phyllochron of growth conserve more of their potential for root growth (and tillering) (Nemoto et al., 1995); root (and tiller) growth resumes more quickly when trauma to roots is minimized	Indirect effects only	Larger root systems support through their exudates larger and more diverse populations of microorganisms in the soil rhizosphere; enhancement of the soil biota can occur through positive impacts on root growth
Reduced plant density	Large and deeper roots (Thakur et al., 2015; Barison and Uphoff, 2011)	Indirect effects only from having larger plant root systems	Larger root systems support larger and diverse populations of microbes by releasing greater root exudates
Improved soil conditions with organic matter amendments	More friable soil makes greater root growth and its activity (Yang et al., 2004)	More organic matter in soil supports larger, more diverse, more active populations (Anas et al., 2011), populations of fluorescent pseudo-monads (FLPs) in the rhizosphere increased (Suresh et al., 2014).	Microorganisms can stimulate greater root system growth (Yanni et al., 2001); FLPs produce growth-promoting phytohormones (IAA and GA), siderophores (Fe-chelating compounds), also facilitating P solubilization from the soil.
Reduced and controlled water applications	Roots under moderate and/or intermittent water stress will grow more deeply (Mishra and Salokhe, 2008)	Mycorrhizal fungi can inhabit unflooded rice roots and acquire water and nutrients for plants (Ilag et al., 1987)	Microorganisms that produce phytohormones can promote root (and shoot) growth (Frankenberger and Arshad, 1995)
Active soil aeration with mechanical weeder	More extensive growth of root systems with less and slower senescence of roots; surface root pruning can induce growth of deeper roots (needs more research)	Soil conditions favor aerobic over anaerobic organisms; food web from microbes upward supports meso- and macro-organisms in the soil (Thies and Grossman, 2006)	Larger root systems can support more and more diverse life forms in the soil; more aerobic soil organisms, including earthworm, support greater root growth

with SRI methods because of its beneficial effects on the soil biota and on soil systems' structuring for better root growth.

Soil Biota

Evidence is accumulating that SRI practices have significant impacts on beneficial microbial populations within plant rhizospheres (Adak et al., 2016; Anas et al., 2011; Gopalakrishnan et al., 2013; Lin et al., 2011; Mishra and Uphoff, 2013; Zhao et al., 2010). These populations include the symbiotic microorganisms that live around, on and within plants, which have started to receive the attention and research that they deserve, for example, Mendes et al. (2013); Turner et al. (2013); Schlaeppi and Bulgarelli (2015). This microbiome has positive influences on plants' growth and health (Chi et al., 2005; Dazzo and Yanni, 2006; Rodriguez et al., 2009) that parallel the impacts that we are learning the human microbiome has on our own growth and health. That symbiotic endophytes affect plant cells' expression of their genetic potentials (Chi et al., 2010; Uphoff et al., 2013) suggests that our understanding of the environments that affect plant phenotypes must take more account of microbiological elements than heretofore.

Root Systems

Studies of roots' growth and functioning have shown significant differences in the structure and physiology of rice plants under SRI management, exhibiting larger, deeper, and longer-lived root systems (Thakur et al., 2010a; Barison and Uphoff, 2011; Mishra and Uphoff, 2013). These changes are accompanied by improvements in N uptake and utilization when using SRI methods (Barison and Uphoff, 2011; Lin et al., 2009; Thakur et al., 2013; Zhao et al., 2009).

Of particular relevance here is positive feedback between roots' growth and the presence or proliferation of soil biota (Yanni et al., 2001). Microbes produce some of the same phytohormones that plants need while simultaneously benefiting from the carbohydrates, amino acids, and other compounds that plant roots secrete into the rhizosphere as exudates in a mutually beneficial relationship (Pinton et al., 2007). Ways in which SRI agronomic principles and practices contribute to furthering this relationship are summarized in Table 1. It shows why agronomic practices with impacts on either plant roots or soil biota have complex rather than simple effects.

Phenotypical Effects

Morphological and physiological evaluations of SRI plants have shown that rice genotypes can be made significantly more productive by modifying the conditions under which they are grown. Research at the ICAR-Indian Institute of Water Management in Bhubaneswar using a given rice variety with the same soil, climatic and other conditions shows that rice plants cultivated with SRI methods have significant improvement in numerous morphological and physiological parameters compared with prevailing recommended management practices (Thakur et al., 2010a, 2010b, 2011, 2015).

- Increased tillering and more panicle-bearing tillers; more grains per panicle; greater grain filling; and often although not always heavier grains, with 40 to 52% higher crop production;
- Larger, deeper, and better-distributed root systems, with greater rates of xylem exudation;
- A more open plant architecture, with more erect and larger leaves having a higher leaf area index (LAI) which results in greater light interception: 14% more at panicle initiation, even with 83% fewer plants m^{-2};
- Greater chlorophyll content in the leaves; delayed senescence; and correspondingly higher rates of photosynthesis;
- Thicker and thus sturdier tillers, with more resistance to lodging.

These morphological and physiological effects culminate in higher yields from reduced plant populations on a unit area basis. These results are confirmed by parallel studies done at the ICAR-Indian Institute of Rice Research at Hyderabad in collaboration with scientists from ICRISAT (Gopalakrishnan et al., 2013).

PHENOTYPICAL IMPACTS ON AGRICULTURAL PRODUCTIVITY

Systematic research on how SRI methods produce more productive phenotypes of rice has been conducted also at the China National Rice Research Institute (e.g., Tao et al., 2002; Zhu et al., 2002). A 2-yr study compared the results of an SRI-based "new rice management" (NRM) with those from standard rice management (SRM) in trials of hybrid rice (Lin et al., 2009).[2]

- At a density of 210,000 plants ha^{-1}, NRM phenotypes when given 180 kg N ha^{-1}, half of this organic, yielded 9142 kg ha^{-1}. This was 0.5 t ha^{-1} more than the 8620 t ha^{-1} produced by SRM plants at the same density which were provided with 210 kg N ha^{-1}, all of it as inorganic fertilizer.
- At a lower plant density of 150,000 plants ha^{-1}, the yield advantage of NRM phenotypes was twice as great. They produced 9042 t ha^{-1} with just 120 kg N ha^{-1} while SRM plants yielded 7993 t ha^{-1} with 210 kg N ha^{-1}.

Thus both hybrid varieties when grown with mostly SRI practices gave higher yields with *reductions* in seed, with *less* application of irrigation water, and with *less* use of chemical fertilizer. At the lower plant density, younger, more widely spaced seedlings with 43% less N provided and with less water produced 1 t ha^{-1} more than did standard-grown hybrid rice. Thus, more rice was produced with *reduced* amounts of seed, water, and fertilizer. That these inverse relationships are associated with greater root growth and with enhancement of the soil biota was shown in subsequent research (Lin et al., 2011). See also report on SRI use with hybrid rice by Yuan (2002).

[2] Standard rice management involved 30-d seedlings at 20-cm spacing, with continuous flooding and 100% inorganic N fertilization; NRM used 20-d seedlings at 30-cm spacing, with alternate wetting and drying, and 50/50 organic/inorganic fertilizers. Trials were done with four different levels of N soil amendments, but all comparisons involved the same levels of total N provided. "New rice management" was less than full SRI because the researchers thought that Chinese farmers would not accept all of the SRI practices at one time, for example, the seedlings were older than recommended for SRI, and weed control was done with herbicides rather than soil-aerating weeding.

The first requirement for CSA is that the practices and overall farming systems raise the productivity of the resources employed, so that both food production and farmer incomes are enhanced (FAO, 2010). These effects have been evident with the phenotypes produced by SRI methods under a wide range of conditions, although not necessarily under all conditions. Impacts on output are summarized below.

Higher Yields

By following SRI management recommendations, the same varieties planted on the same soil usually give yields 20 to 50% higher, with increases sometimes being 100% or more (FAO, 2016). Percentage increases are naturally greater when current production levels are low, but >20% increases on already-high levels are reported on a large scale in China (Zheng et al., 2013). The basis for such increases is easily seen in the larger root systems, the greater number of tillers, the more numerous and longer panicles, and less senescence of roots and leaves (Gopalakrishnan et al., 2013; Thakur et al., 2016; Zheng et al., 2013).

Improvements in yield components are consistent with the measured increases in yield reported in hundreds of journal articles (SRI-Rice, 2017). The amount of yield increase varies, often widely. Much of the variation arises because of edaphic, varietal, and climatic factors as well as reflecting the quality of agronomic management. However, variation stems also from SRI results being driven more by biological dynamics than by the use of external inputs or by a genetic blueprint. The SRI impacts on crop production derive primarily from crops' greater expression of their existing genetic potentials which can be affected, among other things, by the results of microbial activity rather than being input-determined.

Additional Food Production

The SRI rice crops usually produce more edible food per bag of paddy rice harvested due to having fewer unfilled grains and reduced chaff. Also there is usually less breakage of grains during the milling process (Xu et al., 2005). An evaluation of grain quality in the Mwea irrigation scheme in Kenya found that SRI paddy rice when milled yielded 11% more head rice (milled grains at least three-fourths of their original length) and had 33% fewer broken grains, compared to paddy grown with farmers' methods (WARREC, 2015). An analysis at the Sichuan Agricultural University in China found that SRI grains had 30 to 60% less chalkiness as well as less breakage, with 15 to 16% more polished rice available for consumption from a given volume of paddy rice (Xu et al., 2005).

Greater root activity during the grain-filling phase is known to be associated with less chalkiness of grains (Zhong and Huang, 2005). More root biochemical activity and slower senescence of roots during the grain-filling period has been documented under SRI management (Thakur et al., 2016). With less breakage of grains during milling, about 10 to 15% more edible rice is produced per bag of harvested SRI paddy compared with paddy rice grown using current methods.

This is a "bonus" not accounted for in the data which report increased SRI paddy yields. Also, grain quality appears to be increased. Adak et al. (2016) have reported that SRI methods used in combination with beneficial soil microbes (cyanobacteria) improve the nutritional quality of grain, with 13 to 46% increases in Fe and 15 to 41% increases in Zn as well as increases in Cu and Mn. A parallel evaluation of rice plants' nutrient uptake and the micronutrient levels in their grain has found 28 to 63% higher concentrations of S, Fe, Zn, Cu, and Mn in the grain of rice plants grown with SRI management compared to conventional management (Dass et al., 2017). This is an area where more research is warranted.

Greater Net Income

This economic "bottom line" is crucial for farmers and for their willingness to adopt new methods. An evaluation of rainfed SRI experience in West Bengal state of India by researchers for the International Water Management Institute (IWMI), for example, reported an average of 67% increase in net income ha^{-1} compared to farmers' current practices (Sinha and Talati, 2007). Economic evaluations of SRI impacts in Tamil Nadu and Andhra Pradesh states have found 31 and 41% net increases in income, reflecting both increased yield and reductions in cost (Barah, 2009; Rama Rao, 2011). Such evaluations show that SRI can make the adoption of CSA practices more profitable and thus attractive to farmers.

A broad evaluation of SRI economics in India was conducted by IWMI researchers, surveying 2334 farmers sampled across 13 states (Palanisami et al., 2013). Even though the majority of the farmers surveyed had used only some, not all, of the recommended SRI practices, these methods reduced farmers' production costs by US$28 per tonne in addition to raising their yields. Even partial SRI use increased rice farmers' incomes by 18% on average, so adopting most if not all of the recommended methods gave farmers cost-effective improvements in yield and income; those farmers who used all of the methods received greater economic benefit. Similarly, in the Mekong Delta of Vietnam, a project supported by the German development agency evaluated the profitability of farmers' using SRI practices compared with their current rice-growing methods. It reported that by lowering costs and increasing yield, SRI methods raised farmers' net income ha^{-1} from US$611 to $1558, an increase of 155% (Dill et al., 2013).

However, such agronomic and economic gains, even if substantial, do not qualify an agricultural production system as CSA because CSA has three elements. There must be also greater *adaptation* to the multiple stresses of climate change, while also contributing to the *mitigation* of climate change (FAO, 2010; 2013). What SRI insights and practices can contribute to achieving these latter objectives is considered in the next two sections.

CROP ADAPTATIONS TO CLIMATE CHANGE

Increased Water Productivity with More Yield and Water Saving

With water for agricultural production becoming more limited and less reliable, water productivity and water savings are urgent considerations (de Fraiture and Wichelns, 2010). Not keeping paddy fields continuously flooded can reduce water consumption with little or no yield penalty (Bouman et al., 2007). However, if SRI methods of crop management are used along with alternate wetting and drying (AWD), not only is less water consumed, but paddy yields are *enhanced*, which makes water-saving methods profitable for farmers (Thakur et al., 2014).

A meta-analysis of water productivity associated with SRI management has been done on the data reported in 29 published studies with 251 comparison trials conducted across eight countries (Jagannath et al., 2013). Irrigation water applications under SRI management in mostly on-station comparisons were water measurement could be quite accurate were found to be reduced, on average, from 11.1 to 7.2 million L ha^{-1} with higher yield. Total crop water requirements ha^{-1} (irrigation + rainfall) averaged 12.03 million L with SRI, compared with 15.33 million L for whatever the researchers considered to be best management practices for purposes of comparison. Irrigation water requirements ha^{-1} were thus reduced by 35% under SRI, while total water utilized ha^{-1} was 22% less (Jagannath et al., 2013).

Since SRI yields were higher in all of the comparison trials, SRI management raised total water productivity by 52%–0.6 g of paddy rice were produced per liter of water (rainfall + irrigation) compared with 0.39 g when researcher-selected practices were used. In these comparison trials, the productivity of irrigation water was increased by even more, by 78%, even without full or complete use of SRI methods (Jagannath et al., 2013).

These relationships were robust as the higher water productivity with SRI management was documented across all of the agro-climatic zones studied (Köppen-Geiger classification scheme); with different soil textures and soil pH; in both wet vs. dry seasons; and with short, medium, and long duration varieties (Jagannath et al., 2013). Water saving and greater water productivity with SRI practices has been confirmed by studies in countries as varied as Afghanistan (Thomas and Ramzi, 2011), China (Zheng et al., 2013), India (Satyanarayana et al., 2007; Thakur et al., 2011), Indonesia (Sato and Uphoff, 2007), Iraq (Hameed et al., 2011), Kenya (Ndiiri et al., 2013), Sri Lanka (Namara et al., 2008), and Taiwan (Chang et al., 2016).

At the level of individual plants, phenotypes resulting from SRI methods are physiologically more water-efficient, synthesizing more carbohydrates in their leaves per unit of water taken up by their roots. The SRI-grown rice plants have been found to fix 3.6 μmols of CO_2 per mmol of water transpired, which was more than double the 1.6 μmols of CO_2 that conventionally grown plants of the same variety converted into photosynthate per mmol of water transpired (Thakur et al., 2010a). With water constraints for agriculture becoming more limiting, such phenotypic increases in water use efficiency, literally more crop per drop, will become more important.

One cannot expect AWD to be practiced where farmers have no assured source of irrigation and water control, or where irrigation bears no cost so that there is no incentive to economize on water applications. The AWD cannot be practiced under rainfed conditions because there is no control over water supply. But farmers can manage what water is available so as to avoid or minimize anaerobic soil conditions when rains come. Farmers can undertake to minimize continuous flooding of rice paddies during monsoon rains to improve their roots' health and longevity and to gain more benefits from aerobic soil organisms such as mycorrhizal fungi. The production and profit possibilities with SRI make private and public investments in improving drainage facilities more economically justifiable.

Where farmers have no independent source of and control over water, for example, within large-scale irrigation systems that have inflexible water delivery schedules, in-field measures can be taken to reduce standing water and improve soil aeration, such as through raised beds and drainage channels within paddies (Sato et al., 2011). The AWD in support of SRI crop management will be most feasible and profitable where crops are irrigated with ground water, and farmers have both the technical means and an economic incentive to reduce water applications.

Drought Resistance

The SRI rice plants are better able to tolerate water stress because they have roots that are deeper and do not senesce as much or as rapidly as those of rice plant roots under hypoxic, flooded conditions (Thakur et al., 2014). This effect of drought resistance is reinforced when the soil biota is abundant since soil microbial consortia represent a continuous reservoir of water in the soil in addition to making the soil better-structured and more porous so that it can better absorb and retain water. This life in the soil enhances its capacity for storing and providing "green water" as distinguished from "blue water," to make the distinction proposed by Falkenmark and Rockström (2006).

Large-scale evidence of this effect has been seen in data from the Department of Agriculture in China's Sichuan province, where SRI use went from 1133 ha in 2004 to 383,533 ha in 2012. During this period, the average yield advantage conferred by use of SRI methods was calculated by the Department as 1.67 t ha^{-1} more than the provincial average production achieved with present practices. This added up to an additional 2.8 Tg of paddy produced by Sichuan farmers in this period, with a 25% reduction in the amount of irrigation water used for rice production (Zheng et al., 2013).

Of particular relevance here are the provincial data from 2006 and 2010, which were major drought years in Sichuan during the period 2004 to 2012. In these 2 yr, the average yield advantage conferred by SRI management was 1.81 t ha^{-1}, which was 10.5% above the average SRI yield advantage of 1.62 t ha^{-1} achieved in the other 7 yr when rainfall was more normal (Zheng et al., 2013).

Direct data on drought resistance at the plant level are reported from an IWMI evaluation of SRI in two provinces of Sri Lanka. The paddy crop in the 2003/2004 main season was subjected to 75 d of severe drought. It was found that 80% of the tillers on SRI-grown plants formed panicles, while only 70% of the rice plants grown with usual farmer practice did so. In this drought-stressed season, even though the farmer-practice fields had 10 times more rice plants m^{-2}, in SRI fields the number of panicle-bearing tillers m^{-2} was 30% higher. The number of grains $panicle^{-1}$ on SRI plants was also greater, and harvested yield was 38% more (Namara et al., 2008). This reflects SRI phenotypes' better translocation of photosynthates into the grains under drought conditions.

As climatic hazards become more severe and constraining, more emphasis should be given to reducing farmers' risks of crop loss due to the stresses of climate change, rather than focus so much on the average production advantages that certain practices or cropping systems confer under *typical* conditions. Researchers at the Indian Agricultural Research Institute (IARI) evaluated an extrapolation of SRI methods to the cultivation of wheat (system of wheat intensification, SWI) over two seasons. In the first year, a normal season, SWI methods were found to confer a yield advantage of 30% over IARI scientists' standard recommended practices (SRPs) for wheat. In the next season when both temperature and rainfall were adverse, the SWI yield declined by only 12.5% while yields dropped by 18 to 31% for the four SRP systems with which researchers were comparing SWI. Under adverse climatic conditions, SWI's yield advantage was thus 46%, that is, 50% more than when the crop was not growing under climatic stress (Dhar et al., 2016).

A similar advantage was documented in trials evaluating rainfed SRI in eastern India, comparing rice production results in climatically normal vs. drought-stressed seasons (Thakur et al., 2015). Under drought conditions, the rainfed SRI rice plots were seen to suffer relatively less yield decline. Inducing morphological and physiological improvements in crop phenotypes so that they can better tolerate drought stresses will become more needed in the years ahead.

Resistance to Storm Damage

Rice plants that have larger, deeper, non-senescing root systems and stronger, thicker shoots anchored onto a single root base are better able to withstand the pounding of rain and wind during storms, which are becoming more frequent and more severe with climate change. Along with the deeper, more robust root systems of SRI-grown rice plants, Thakur et al. (2011) found that the average circumference of tillers was 38% greater than with conventionally flooded rice of the same variety, which helps to explain their resistance to lodging. Chapagain and Yamaji (2009) report that 93% of the rice plants under conventional management in their trials in Japan lodged under wind stress compared to only 9 to 10% of those plants of the same variety grown with SRI methods. Moreover, those SRI-managed plants that did lodge were only partially lodged, whereas nearly half of the conventionally grown lodged plants were completely lodged (Chapagain et al., 2011).

Apart from inducing deeper and greater root anchorage and more tiller strength, SRI's wider spacing between hills may also be allowing winds to pass through without damaging the plants. This effect of lodging resistance has not been much studied, however, so the best available evidence is visual, such as seen in Fig. 2. This picture from Vietnam shows SRI resistance to lodging that the authors have themselves observed in Chinese, Indian, and Pakistani fields.

Fig. 2. Paddy fields in the Mekong Delta in Vietnam, a regular field in the foreground on left, and an system of rice intensification (SRI) field next to it on the right after both fields had been hit by a tropical storm which lodged the regular paddy crop (Dill et al., 2013).

Table 2. Effects on yield of test plots comparing system of rice intensification (SRI) and normal practices for an integrated pest management (IPM) evaluation with changes in temperature, Hyderabad, India. Source: Sudhakar and Reddy (2007).

Season	Normal		SRI
	t ha^{-1}		
Rabi (winter) 2005–2006	2.25		3.47
Kharif (monsoon) 2006	0.21†		4.16
Period in *kharif* season	Mean maximum temperature,	Mean minimum temperature,	Number of sunshine hours
	°C		
1–15 November	27.7	19.2	4.9
16–30 November	29.6	17.9	7.5
1–15 December	29.1	14.6	8.6
16–31 December	28.1	12.1‡	8.6

† Very low yield in this season due to cold injury arising from the temperatures shown below.

‡ There was a sudden drop in minimum temperatures for 5 d, 16 to 21 December (9.2–9.8°C).

Resistance to Colder Temperatures

The well-developed root systems of rice plants grown with SRI methods also help them to tolerate cold spells better. This was seen, unexpectedly, from integrated pest management (IPM) trials conducted at the Andhra Pradesh state agricultural university in India in the 2006 monsoon season. The trials, which had been designed to assess possible differences in pest resistance, generated unplanned-for data on cold resistance when the trial plots were hit by a short but severe cold period, when night time air temperatures dropped below 10°C for five successive days (Table 2). This chill caused the plots under standard rice crop management to produce almost no harvestable grain, while adjacent SRI plots yielded >4 t ha^{-1} (Sudhakar and Reddy, 2007).

There will, of course, be limits as to how much cold, and at what crop stage, a rice crop can withstand when temperature drops without significant yield loss. But climate change is creating conditions where crops will be subjected more frequently to irregular weather patterns that can bring on extreme temperatures for unexpected periods. So any increased tolerance of extreme temperatures is desirable. The SRI rice plants are also reported to be better able to maintain themselves under some hotter-than-normal temperatures that stifle plants grown with usual cultivation methods; however, this has not been evaluated scientifically.

Resistance to Insect Pests and Diseases

The SRI-grown rice crops exhibit also some phenotypical advantages in terms of reduced susceptibility to infestation and damage by insect pests and diseases. This constraint on agricultural production will be heightened by the changes in precipitation and temperature that occur with climate change. Most studies of this effect have found that SRI plants are less vulnerable to most, although not necessarily all, insect pests and bacterial and fungal diseases (e.g., Mahinder Kumar et al., 2007; Padmavathi et al., 2009; Karthikeyan et al., 2010; Chapagain et al., 2011; Pathak et al., 2012; Visalakshmi et al., 2014).

An extensive on-farm evaluation of pest and disease resistance with SRI management was done in Vietnam by the Ministry of Agriculture and Rural Development's IPM program during the spring and summer seasons in 2005–2006 (Dung, 2007). In on-farm trials conducted in eight provinces, there were reductions of 55 to 70% in the incidence of Vietnam's major rice pests and diseases on side-by-side plots under SRI vs. farmer methods of crop management (Table 3).

A study at Tamil Nadu Agricultural University in India reported that there were *increases* in both stem borers and leaf folders in the SRI field plots compared with plots grown with the practices being recommended by that university's rice scientists, but increases of these two pests were not observed in the SRI nurseries. All of the other important rice pests–that is, cutworm (*Agrotis* spp.), thrip (*Stenchaetothrips biformis*), green leafhopper (*Nephotettix virescens*), brown leafhopper (*Orosius orientalis*), whorl maggot (*Hydrellia sasakii*), and gall midge (*Didymomyia tiliacea*)–were greatly *reduced* in both the SRI nurseries and SRI field plots, on average by 62% compared to control nurseries and plots (Ezhil Rani, 2004; Uphoff, 2016). Resistance to damage by pests and diseases will become an increasingly important characteristic for climate-stressed rice crops.

Table 3. Prevalence of major rice pests and diseases with different rice crop management methods as measured in on-farm trials in eight provinces of Vietnam, 2005–2006. Source: Dung (2007).

	Spring season			Summer season		
Rice pests and diseases	SRI† plots	Farmer plots	Difference	SRI plots	Farmer plots	Difference
			%			%
Small leaf folder‡	63.4	107.7	41	61.8	122.3	49
Brown plant hopper‡	542	1440	62	545	3214	83
Sheath blight	6.7%	18.1%	63	5.2%	19.8%	74
Leaf blight	–	–	–	8.6%	36.3%	77
Average			55			71

† System of rice intensification.

‡ Insects m^{-2}.

Stress Avoidance Due to a Shorter Crop Cycle and Early Maturity

With weather becoming more variable along with increasing pest and disease pressures, farmers will benefit from having a shorter crop cycle between seeding and harvest, so that they can get their crops out of the field sooner. Farmers often report that with SRI management, their rice crops can be harvested 5 to 15 d earlier, and with higher yield, than with their usual cultural methods.

Gbenou et al. (2016) reported that adopting SRI method by a group of 90 rice farmers in Benin has shortened their growing season by 14 d along with 54% increase in yield. Similarly in Nepal, the Morang District Agricultural Development Office gathered data on planting and harvest dates, as well as on yield, from 413 farmers who had used SRI methods with eight rice varieties in the 2005 main season. The time to maturity reported by the Ministry of Agriculture for these varieties ranged from 120 to 155 d (average 141 d). However, SRI crops were harvested that season at 115 to 133 d (average 126 d). Farmers' average SRI paddy yields were 6.3 t ha^{-1}, while with their average yields from the same varieties was 3.1 t ha^{-1} with their usual production methods on the same soils and with the same climate (Uphoff, 2011).

In Bangladesh, Latif et al. (2009) reported increased duration of SRI crop in the field, but a more recent and extensive evaluation by Uzzaman et al. (2015) of 16 rice varieties under SRI management found that all of them showed earlier maturity under SRI management than was advertised by their rice breeders–by 3 to 23 d. With higher yield and faster maturation, SRI's area productivity d^{-1} increases by even more than ha^{-1}. Another advantage from earlier maturity of SRI rice crops is that this gives farmers more time for growing a following crop, and the rice crop can escape terminal water or heat stress.

These various manifestations of resistance to climate-related stresses–water shortage and drought, wind and rain damage from storms, temperature extremes, and pest and disease incidence–can be ascribed to the effects induced by SRI management practices on rice plants' growing environments both below- and aboveground. It is easy to observe the greater growth and health of SRI plants' root systems (Fig. 1; Chapagain and Yamaji, 2009; Thakur et al., 2010a, 2011). Less visible are the influences that SRI practices have in enhancing the life in the soil, discussed above. Much remains to be known about how the soil–plant microbiome performs its various services for rice under SRI management, but such research is starting to be conducted, for example, Watanarojanaporn et al. (2013); Adak et al. (2016); and Doni et al. (2016).

MITIGATION OF CLIMATE CHANGE

The emission of methane gas from irrigated rice paddies is one of the major impacts that the agricultural sector has on raising the level of GHGs that are driving global warming and climate disruption. While estimates vary, irrigated rice production is probably responsible for about 10% of human-induced CH_4 emissions, and about 20% of total agricultural CH_4 emissions (Kumaraswamy et al., 2000). Methane (CH_4) is 25 times more potent in terms of global warming potential (GWP) than is CO_2, the most ubiquitous GHG. Methane derives from a variety of sources including the production and transportation of synthetic fertilizers and other uses of hydrocarbon products. Even more potent than CH_4 in terms of its impact on climate change is nitrous oxide (N_2O), which is emitted in small amounts from aerobic soils through bacterial activity. Its GWP is 12 times greater than that of CH_4 and about 300 times more than CO_2.

In flooded-rice production, CH_4 emissions arise from the availability of organic substrates in the soil as well as from stocks of inorganic N that build up from the application of chemical fertilizer under anaerobic soil conditions. With SRI management, where soils are intermittently wetted and dried rather than being kept flooded, and weeds are controlled with soil-aerating mechanical weeding, the more-aerobic soil has a lower rate of CH_4 emission because the populations of methanogens, anaerobic microorganisms that synthesize CH_4, are reduced. At the same time, SRI practice increase the numbers of methanotrophs in the soil, aerobic microbes which consume the CH_4 produced by methanogens (Rajkishore et al., 2013).

Lower CH_4 emissions have been frequently documented when SRI practices are combined, as seen below. This effect would be less for rainfed SRI than from irrigated SRI rice production, but CH_4 emissions would be reduced to some extent by not maintaining as much rainwater as possible on lowland rice paddies for as long as possible during and after rain.

It needs to be considered, however, whether SRI rice paddies with less flooding would emit more N_2O at the same time that they produce less CH_4. Compared to soils that are always saturated and thus hypoxic, aerobic soils have a greater supply of NO_3–N through the process of nitrification (Jain et al., 2014). The NO_3–N serves as a substrate for microbial denitrifiers whose activity results in N_2O emissions. Under flooded soil conditions, most of the N_2O that is formed during processes of nitrification–denitrification gets further reduced to N_2 so it has no impact on global warming. Alternate wetting and drying is itself a source of N_2O since its emission is regulated by the soil's transitioning between aerobic and anaerobic phases of rice fields with alternating water status under AWD (Xiong et al., 2007).

Of concern here is whether under SRI management there is enough increase in N_2O emissions to offset and negate the climate-change mitigation benefits that derive from reduced emission of CH_4. To date, most studies that have assessed this tradeoff have concluded that with SRI practices, there is a net reduction in GHG emissions evaluated in terms of their GWP (in CO_2 equivalence). However, GHG emissions vary considerably according to temperature, soil type, soil pH, soil moisture, nutrient and water management, crop growth stage, variety, and other parameters, so only ranges can be determined, not any one value that can be generalized across all locations.

Under the soil and climate conditions prevailing at the research site of the Indian Agricultural Research Institute in New Delhi, with the same integrated nutrient management, SRI methods were found to reduce CH_4 emissions by 62%, with a 23% increase in N_2O emissions compared with conventional irrigated rice crop management. Considered together, these effects amounted to a 28% net reduction in GWP ha^{-1} (Jain et al., 2014). In the same location, another study reported a 39% reduction in CH_4 emissions, but did not measure N_2O so the net effect of SRI on GWP was not calculated (Suryavanshi et al., 2013).

In Vietnam, an assessment of the impact that alternative rice production methods can have in the Mekong Delta included the measurement of GHG production among other effects (Dill et al., 2013). The SRI management was found to lower

Table 4. Methane and nitrous oxide emissions in Mekong Delta trials, Vietnam. Source: Dill et al. (2013).

Variable	Plot type	No. of observations	Mean	SD
Methane emissions, $mg\ h^{-1}\ m^{-2}$ CO_2 equivalent	SRI†	253	1.899‡	1.869
	Control	255	2.376‡	2.160
Nitrous oxide emissions, $mg\ h^{-1}\ m^{-2}$ CO_2 equivalent	SRI	246	1.411§	1.298
	Control	248	1.431§	1.320

† SRI, system of rice intensification.

‡ Two-sample *t* test on equality of means, $p < 0.01$.

§ Two-sample *t* test on equality of means, $p > 0.1$.

the emissions ha^{-1} of both CH_4 and N_2O, respectively by 20% (statistically significant) and 1.4% (not a statistically significant decrease) (Table 4). In this evaluation, there was no offsetting increase in N_2O with SRI practices that would reduce the value of their CH_4 reduction. This is an example of how variable and location-specific GHG emissions can be.

Researchers in Korea recorded a large reduction in methane emissions with SRI water management practices compared to standard rice-growing methods, using similar integrated nutrient management with both methods. The respective CH_4 emissions were 127 vs. 458 kg ha^{-1}, a 72% decrease. While the increase in N_2O emissions that was measured at the same time was large in relative terms (0.074 vs. 0.000028 kg ha^{-1}), these amounts were too small to have much impact in terms of CO_2 equivalence. The combined effect of SRI changes in CH_4 and N_2O emissions was reported to make a net reduction of >70% in GWP (Choi et al., 2014).

In India, a life-cycle assessment of total GHG emissions from paddy rice production compared SRI with conventional methods in Andhra Pradesh state. The researchers calculated that under SRI management, total GHG emissions on an areas bases were reduced by >25% ha^{-1}. Because SRI increased crop yield substantially, net GHG emissions kg^{-1} of rice produced were lowered by >60%. N_2O emissions ha^{-1} increased somewhat with SRI methods, as expected, but the higher SRI yields meant no significant increase in N_2O emission kg^{-1} of rice (Gathorne-Hardy et al., 2013).

To date, most of the evaluations of SRI for measuring GHG emission from rice fields have been conducted by applying similar amounts of organic and chemical fertilizers to both SRI and conventionally managed fields. The effects on GHG emission discussed above are thus mainly from keeping SRI soils in more aerobic condition. Changing water management in flooded rice paddies is one of the important strategies for controlling CH_4 efflux. Methane production and emissions are negligible in upland rice fields, while continuous flooding leads to greater CH_4 emissions as compared to the kind of alternate flooding and drying recommended for SRI (Mishra et al., 1997; Hadi et al., 2010).

Organic fertilization is an important component of SRI strategy. The addition of fresh organic sources to flooded rice soils increases the availability of methanogenic substrates, thereby enhancing CH_4 production and emissions (Neue, 1993). Also, the addition of rice straw to flooded rice paddies similarly stimulates CH_4 emission (Bossio et al., 1999). However, the use of fully decomposed organic matter such as compost is an effective means for mitigating methane emissions from rice fields (Kumaraswamy et al., 2000; Minami and Neue, 1994).

Providing decomposed organic sources of nutrients creates no superfluity of N in the soil such as results from supplying it with synthetic N fertilizer. When recommended SRI practices are followed, the microbes that synthesize N_2O do not have much substrate to work with, and there is little excess N to be volatilized into the air, and less to get leached into water systems. Also, there is a suppressive effect on N_2O emissions from having greater populations of arbuscular mycorrhizal fungi in the soil (Bender et al., 2014). These fungi inhabit plant roots under aerobic soil conditions, but not when the soil is kept flooded. The SRI practices create favorable soil conditions for maintaining larger populations of these symbiotic fungi which inhibit N_2O production.

The assessment of SRI effects on GHG emissions in Andhra Pradesh, India, summarized above, included an estimation of the effects of alternative crop management on CO_2 emissions, comparing SRI with conventional practice following guidelines of the Intergovernmental Panel on Climate Change. Reducing farmers' applications of chemical fertilizer to their fields will in itself diminish CO_2 emissions. The production of such fertilizer has been estimated to create GHG emissions equal to 5 to 10% as much GWP as from all of the agriculture sector's direct GHG emissions associated with the production of food (Vermeulen et al., 2012).

To this should be added the CO_2 emissions that derive from the far-flung distribution and on-farm application of N and P fertilizers. Reducing farmers' reliance on mineral fertilizers as well as on agrochemicals for the control of weeds, insect pests, and diseases should make a non-trivial although difficult-to-measure contribution to the mitigation of global warming. The agricultural sector as a whole contributes about 30% of anthropogenic GHG emissions, and rice is one of its major crops. However, arriving at aggregate figures on CO_2 reduction that could result from greater use of SRI methodology remains very difficult. Also, the role of various plant factors in GHG production and emission, for example, the effects of enhanced root biomass and modified rhizosphere environments, of greater root exudation and root-oxidizing capacities, of higher root activity and morphological differences observed under unflooded soil environments with SRI methods, are still not well understood.

The long-term C sequestration effects of growing rice plants with SRI methods that induce the growth of much larger root systems which remain in the soil to decompose have not been studied. Neither has the impact of expanding the soil biota through increased root exudation from larger root systems and from enhanced organic soil amendments as promoted with SRI. These should contribute to enhanced levels of C sequestration. Overall, SRI use should contribute to net reductions in GHG emissions from rice production if taken up in a major way. However, the extent and impact of this remains to be evaluated more systematically.

ORIGIN AND SPREAD OF SYSTEM OF RICE INTENSIFICATION IDEAS AND MANAGEMENT

How SRI practices improve crop management is now much better understood through research and farmer experience than was known some 30 yr ago when the practices that apply SRI principles were inductively assembled in Madagascar (Laulanié, 1993; Mishra et al., 2006; Stoop, 2011; Toriyama and Ando, 2011; Thakur et al., 2016). For example, we now know that certain soil microorganisms (rhizobia) enhance the length, branching, volume, and surface area of roots (Yanni et al., 2001). That increases in the growth of root systems and in the soil biota are synergistic, with positive feedback between them as characterized in Table 1, is important for consolidation of the theory behind SRI. Larger root systems support more photosynthesis in the canopy, while this process supports more root exudation, which benefits the soil biota around, on, and inside rice plants (Thakur et al., 2016).

The spread of the use of SRI principles and practices was initially quite slow because some of its ideas are so counter-intuitive. How can rice production be increased by *reducing* plant populations? Without the age-old practice of flooding of paddy fields? With less use or even no use of mineral fertilizer, which has higher nutrient concentrations kg^{-1} than compost? The idea of producing more rice with reduced rather than more inputs (Lin et al., 2009) represents a paradigm shift away from the strategy of the Green Revolution, which was based on planting new varieties at high density with more intensive irrigation and with greater use of chemical fertilizers. Producing more output with fewer inputs can only be understood when the contributions of improved root systems and plant–soil–microbial interactions which contribute to superior phenotypes are understood and enhanced.

The SRI was at first controversial in some scientific circles, for example, Dobermann (2004), Sheehy et al. (2004), Sinclair (2004), Sinclair and Cassman (2004), McDonald et al. (2006), and McDonald et al. (2008). But the controversy has receded over the past decade as there have been no further data-based critiques or dismissals, and as governments have increasingly approved SRI on the basis of their own evaluations and farmer experience. The early published critiques of SRI themselves had serious methodological limitations discussed elsewhere (Stoop and Kassam, 2005; Thakur, 2010; Uphoff et al., 2008). The negative assessments by Sheehy et al. (2004) and McDonald et al. (2006) were based on less defensible data sets and less rigorous methods than were used for a meta-analysis of published evaluations by researchers in China from eight provinces there (Wu and Uphoff, 2015). This analysis reached an opposite conclusion from extensive data that compared SRI methods with what Chinese researchers considered to be best management practices. The average SRI yield advantage in the trials evaluated was >10%; and when there was "good" use of SRI methods, not even full use, the advantage was 20%.

Based on their own researchers' evaluations and on farmers' experience, governments in China, India, Indonesia, Cambodia, and Vietnam have been promoting SRI. By 2014, almost 10 million farmers in these five countries, which produce two-thirds of the world's paddy rice, were using some or all of SRI's recommended methods on almost 3.5 million hectares. Their average paddy rice yield increase, calculated as 1.66 t ha^{-1}, was being achieved with less water input and with usually lower costs of production (Uphoff, 2016).

The advantages of SRI practices have gained increasing acceptance internationally over the past 15 yr (Yuan, 2002; MSSRF, 2004; Swaminathan, 2006; Africare/Oxfam America/WWF, 2010; CCAFS, 2013; CCAFS/CTA, 2013; UNEP, 2015; FAO, 2016; Styger and Uphoff, 2016). The efficacy of SRI principles and practices has been seen in more than 50 countries of Asia, Africa, and Latin America (SRI-Rice, 2017), and IFAD and the World Bank have websites providing information on SRI. Phenotypical benefits from SRI management have been seen in a variety of agro-ecological systems, ranging from mountain environments in Afghanistan (Thomas and Ramzi, 2011) to desert conditions in Mali (Styger et al., 2011), from the tropical environment of Panama (Turmel et al., 2011) to temperate climate in Japan (Chapagain and Yamaji, 2009). This does not mean, however, that the methods of SRI can be used productively everywhere even if the agronomic principles on which they are based have broad applicability.

CONSTRAINTS AND OPPORTUNITIES

Adaptations to climate stress, like the mitigation of forces driving climate change, are matters of degree. As the biotic and abiotic stresses of climate change become greater, nobody can know where and when tipping points may occur, and whether or where plant-microbial defenses may implode. The agricultural production systems on which individual and collective human life depend will need to be modified in many ways to sustain and increase food production to meet human needs over the next 50 yr (FAO, 2012). If we do not succeed within this period, further progress is likely to become purely hypothetical. Below we review the main constraints on the adoption of SRI methods that need to be addressed for this knowledge to be utilized more widely to improve agronomic practices in climate-smart ways, and then some directions in which this knowledge and its application can evolve.

The constraints that can limit the partial or full adoption of SRI practices will vary from country to country, region to region, and farmer to farmer, and there is no reason to expect that the practices will be effective everywhere or for everyone. Even if the underlying agronomic principles are reasonably robust, their application in practice must respond to and be suitable for specific biophysical, socio–economic and other conditions. Factorial trials have shown that best results are achieved with full application of the recommended SRI practices (Uphoff and Randriamiharisoa, 2002), but partial use of the methods can benefit farmers generally as seen from a large-scale evaluation across 13 Indian states (Palanisami et al., 2013).

The most often-mentioned constraints are adequate water control, with difficulties in water management arising both in irrigated systems and under rainfed conditions (Senthilkumar et al., 2008; Tsujimoto et al., 2009; Krupnik et al., 2012), and the need for higher labor inputs, at least initially, especially where there is limited household labor availability (Tsujimoto et al., 2009; Ly et al., 2012). Since SRI is a knowledge-based rather than an input-dependent innovation, the most crucial factor for its successful use is having sufficient attentive and motivated labor. Even as mechanization of various SRI production activities proceeds and reduces the amount of labor required, SRI will remain a management-oriented innovation that stresses adaptation and not just routinization. This means that human actors and factors are critically important.

Water Constraints

If rice paddy soils cannot be maintained in mostly aerobic condition, the positive effects from SRI practices will be limited because then rice plants' root systems will not thrive and will senesce. Also, the populations of beneficial aerobic soil biota will be less abundant and less diverse. Best results with SRI methods are achieved with careful, optimizing water control. But benefits can still be derived from increasing aeration of the soil, passively and/or actively, as a matter of degree.

Where water supply and water control present challenges, there are often ways to adapt to these constraints and thus to capitalize on the productivity potentials from following SRI principles as much as possible. Within irrigated rice production systems, farmers may have difficulty controlling the timing and amount of their water because they depend on field-to-field flows or have to work within uniform water distribution schedules. Under such circumstances, a degree of soil aeration can be attained, for example, by creating raised beds and drainage channels within paddies (Sato et al., 2011). In Bangladesh, researchers have reported that SRI required 33% more irrigation cost than practices based on flooding (Latif et al., 2009). However, they acknowledged that this higher cost was mainly due to inefficient irrigation systems where owners of shallow or deep tube-wells were basing charges on the number of irrigations, rather than on the volume of water applied or on tubewells' operating time. As mentioned above, when farmers require energy or money to pump water into their rice fields, they can save energy as well as production costs by using less water under SRI. Gathorne-Hardy et al. (2016) calculated a 60% water saving at farm level with SRI use in Andhra Pradesh, India.

Farmers practicing a rainfed version of SRI often find it difficult to have young seedlings ready for transplanting when unpredictable rainfall begins; also they will not be able to replenish in-field water applications according to their own schedule for AWD. One response can be to plant several SRI nurseries in sequence 8 to 10 d apart so that farmers will have young seedlings available from one of the nurseries whenever rain commences. Since SRI nurseries require only 10 to 20% as much seed as farmers usually use, there will still be a net saving of seed even if they plan to sacrifice several of their nurseries, a cost recouped by the higher yield from planting younger seedlings.

Getting rainfed farmers not to keep their rice fields maximally full of water during the start of the rainy season is difficult until they understand from explanations and observation that continuous flooding asphyxiates their rice plants' roots, making these plants less able to survive subsequent water stress when rainwater flooding subsides. Such modifications have been introduced by NGOs with rainfed communities in eastern India (Sinha and Talati, 2007). In the Philippines, to get the benefits of SRI methods, researchers developed an irrigation management transfer (IMT) system to assure farmers of timely water supply to their respective fields, to get the benefits of higher yields through SRI (Miyazato et al., 2010). This underscores that SRI is not a fixed set of practices, but rather expects pragmatic farmer adaptations to apply SRI principles for getting the most benefit from available resources. The SRI should vary according to conditions.

Labor Constraints

In comparison with most modern rice cultivation systems, SRI requires relatively more labor than capital, which makes it *by definition* more labor-intensive than capital intensive. However, whether SRI is more labor-intensive for farmers will depend on what methods they are using now. In Madagascar, where SRI was developed, rice production is traditionally labor *ex*tensive, meaning that farmers invest as little labor ha^{-1} as possible, with correspondingly low yields. Any effort to raise production in Madagascar must require more labor that at present. Yet even there with labor-extensive practices as the baseline, it has been found that once farmers gain skill and confidence in the new methods, SRI can reduce their labor requirements ha^{-1} within a few years (Barrett et al., 2004).

More important for farmers than labor-intensity ha^{-1} is the labor required kg^{-1} of rice produced, that is, their labor productivity. Moser and Barrett (2003:1098) report that in Madagascar "the returns to labor … far outweigh those of traditional methods." Their research pointed out the problem that very poor households there who live hand-to-mouth and depend on their income as agricultural laborers for survival may not be able to afford investing any additional labor in their own production to get the delayed productivity gains that can be achieved with SRI but which are available only at the end of the season. Given the usurious interests rates charged in rural informal credit markets, poor households in Madagascar cannot afford to reap SRI productivity gains for themselves. But this represents a market failure, not a flaw in SRI as a rice-production system.

In most of Asia, where 90% of the world's rice is produced, rice cultivation is already relatively labor-intensive. While some studies of SRI labor requirements have shown it to require more labor, for example, in Bangladesh (Latif et al., 2009), most evaluations have found SRI to be labor neutral, for example, in Cambodia (Anthofer, 2004) and Indonesia (Sato and Uphoff, 2007), or labor saving in China (Li et al., 2005) and India (Sinha and Talati, 2007).[3] In the Cambodian study, an evaluation based on random samples of 500 farmers in five provinces where rice production is mostly rainfed, adopting SRI methods raised their labor productivity by 64%, increasing the gross returns per man-day of labor from US$1.60 with conventional practices to US$2.50 with SRI crop management (Anthofer, 2004). In India, the evaluation of SRI in Andhra Pradesh state cited above reported that SRI methods substantially reduced farmers' need for hired labor as most labor operations could be handled by family members (Gathorne-Hardy et al., 2016). That SRI lowered income-earning opportunities for agricultural laborers by 50% was characterized as a social cost to be reckoned with. But the study confirmed that where rice

[3] In Bangladesh, Latif et al. (2009) reported that SRI methods required 13% more labor ha^{-1} than scientists' recommended practices, the higher SRI labor requirements being mainly for transplanting and weeding. However, in these comparison trials, weeding was done by hand, which made labor costs high compared to using mechanical weeders which are recommended for SRI and can reduce labor time by as much as three-quarters (Mrunalini and Ganesh, 2008). To minimize labor cost for weeding, various methods and techniques are being evaluated. For example, Malaysian researchers have found that mulching with a rice straw mat (2 mm thickness) for up to 40 d after transplanting controls 98.5% of weeds while conserving soil moisture in SRI fields and giving higher grain yield (Mohammed et al., 2016). Technological innovations with SRI are ongoing to address whatever bottlenecks are initially encountered.

production is presently labor-intensive, introducing SRI is more likely to decrease labor requirements than to increase them.

Evaluations of SRI labor requirements should take account of the fact that learning any new method of agricultural production will invariably involve some additional time while it is being mastered. With SRI, there are likely to be short-run increases in labor requirements, as in the Bangladesh study reported above, because of the need to re-learn rice production methods. This can be a definite constraint. But the added costs are likely to be transitory, even in a country like Madagascar with labor-extensive methods (Barrett et al., 2004). If rice production is currently labor-intensive, then labor savings with SRI can begin from the first year.

It should be added that for SRI to succeed there has to be a willingness to learn and to make changes in practices, something not always available, for example, among poorly paid agricultural laborers. Sharing with them some of the windfall gains in productivity from SRI would provide material incentives to learn and change. For adoption of SRI under labor-shortage conditions, mechanization for land leveling, weeding, and transplanting will be a significant accelerator. Innovation along these lines is starting in countries such as Pakistan and Vietnam (Sharif, 2011).

Other Constraints

Agricultural innovations commonly face constraints of climate or soil, but a meta-analysis of published research findings has indicated few limitations, although results vary depending on how favorable are the climatic and soil conditions. Factors like soil pH and soil structure as well as agro-climatic differences will affect levels of productivity. However, SRI methods have been found to raise productivity in most soil and climatic circumstances and with most rice varieties (Jagannath et al., 2013). Like other methods for producing rice, SRI yields are less successful on saline soils, although even with these, in part because of changes in the soil biota induced by soil aeration and by organic amendments, there are productivity gains to be achieved (Subardja et al., 2016). Where air and soil temperatures are low, it will not be possible to use seedlings as young as is generally recommended. This will limit the benefits from SRI crop management. But adjusting seedling age is part of the adaptation which is expected for utilization of SRI. Where temperatures are low, a seedling that is 20 d old by the calendar may have a biological (phenological) age equivalent to a typical 15-d seedling, or to a 12-d seedling that is growing in the humid tropics.

Pests and diseases are always potential constraints for crop production, but as noted above, more often than not, SRI rice crops are less affected by these hazards. The factors accounting for this remain to be studied in detail. The factors analyzed by Chaboussou (2004) could be operative with reduced or no fertilizer and agrochemical use. Chewing insects might be inhibited by greater silicon uptake in the stalks and leaves under different soil and water management (Reynolds et al., 2009). But research is needed to determine the extent and causes of SRI phenotypes' being more resistant to damage from insect pests and diseases. There are some reports from farmers of less damage from vertebrates (birds, rats) and from snails (controllable by water management practices). But all that can be said for now is that pests and diseases are not more of a constraint for SRI than for other methods.

Crop Diversification for Climate Resilience

The SRI was developed for mono-cropped rice production, but as farmers seek to intensify their farming systems and build more resilience into them, there are opportunities for crop diversification that capitalizes on synergies and complementarities among various crops. There are already concrete examples of how SRI can be used as part of integrated farming systems to adapt to climate change. This can enhance economic benefits as well as crop resilience, so these farming system opportunities should be considered in addition to direct SRI rice-cropping effects.

In Cambodia, higher yields achieved with SRI methods have enabled rainfed farmers there to take about 40% of their small landholdings out of rice production and (a) construct a pond for fish and other aquatic production on part of this redeployed area, and (b) engage in complementary fruit, vegetable, poultry, and other production on the rest of the reassigned area. This generates increased employment opportunities and year-round revenue, raising incomes by two to four times with an investment cost as low as US$300, while also making improvements in household nutrition (Lim, 2007). Such diversified production strategies give households much more scope for coping with the vagaries and adversities of climate change.

Farming systems that have some supplementary water supply, either from a well or from a catchment pond for water harvesting, are better able to withstand climate extremes. Water harvesting during the rainy season by converting part of the rice area into ponds for water storage expands farmers' production opportunities, for example, raising stocked fish, with the surrounding dikes and water catchment area planted with fruit trees or vegetables for additional income and nutrition. Two years of replicated trials under varying climatic conditions at the Indian Institute of Water Management showed that such an integrated system dependent on rainfall can be very productive. Rice yield was raised with SRI methods above what could be achieved with mono-cropping, and the net economic productivity of water (all sourced from rainfall) was increased by several orders of magnitude. This system is climate-resilient, retaining its productivity during a low-rainfall season (Thakur et al., 2015).

Evaluating a similar strategy in East Java, Indonesia, Khumairoh et al. (2012) found that an irrigated SRI rice production system can result in increased grain yield and additional revenue by adding different combinations of compost, azolla, duck, and fish. The study documented significant synergies among these components of the farming system. These examples of poly-cropping, capitalizing on SRI gains in rice productivity as a food-security platform, show the importance of thinking, investing and acting in farming-systems terms, seeking to build greater resilience into farmers' operations, rather than proceeding with one crop at a time.

Enhancement of Soil Systems' Fertility

An essential foundation for CSA is building up soil fertility. Increasing the supply of organic matter in the soil is a key component of SRI, both for providing a full complement of plant nutrients, especially micronutrients, and for improving soil systems' structure and functioning (Uphoff et al., 2006). These effects are enhanced by both active and passive soil aeration which promotes better root growth and the better functioning of soil systems. Increased stocks of soil organic C, through root growth, increased root exudation, and larger populations of soil organisms, contribute to crops' ability to adapt to climate change as well as to generate more sustainable agricultural production.

Attempts can be made through plant breeding to elicit deeper, bushier root systems that improve the soil's structure and its steady-state C, water and nutrient retention, contributing thereby to higher and sustainable plant yields (Kell, 2011). It makes sense to reorient crop breeding objectives away from simple yield-improvement criteria in response to climate pressures. However, as suggested by the foregoing discussion, plant breeding should be part of a larger strategy rather than being considered the leading strategic component. Substantial improvements in resilience as well as in productivity can presently be achieved rather quickly and at low cost by making agro-ecologically informed changes in crop management practices, with breeding efforts supporting this endeavor (Uphoff et al., 2015).

An integrated soil–crop system management approach has been proposed by Chen et al. (2011), aiming to enhance the yield of present agronomic practices without requiring additional N-fertilizer use, especially in developing countries. This should abate the negative externalities of current agricultural practices which affect the air and atmosphere through volatilization and alter water quality through the leaching of N and also P into groundwater reserves. Soil applications of P are already having adverse effects on riverine and aquatic ecosystems through eutrophication (Smith et al., 1999). Excess build-up of both N and P in soil systems affects the synergistic balance of communities of soil organisms, as some species which utilize efficiently the superfluity of nutrients expand their populations at the expense of other species whose substrates are reduced thereby. Climate-smart agriculture needs to address these dynamics by finding ways to reduce dependence on external inorganic inputs.

We noted above that SRI builds on the same agroecological principles as conservation agriculture. Some successful initial efforts have begun in Pakistan and China to integrate a CA rice-based cropping system with SRI practices for enhanced irrigated rice production with soil fertility enhancement (Sharif, 2011; Lu et al., 2013). These efforts are just beginning, however. We expect there to be more convergence in the decades ahead for SRI and CA in both irrigated and rainfed production systems.

CONCLUSIONS

There is now substantial scientific evidence to support a conclusion that altering crop, soil, water, and nutrient management methods can produce more robust as well as more productive crop phenotypes. In particular for irrigated rice production, there can be substantial reductions in water use and enhanced water productivity with SRI management compared to current practices. As crops grown under SRI methods help farmers adapt their operations to the biotic and abiotic stresses of climate change while reducing rice paddies' contribution to global warming, this qualifies SRI as CSA.

The efficacy of SRI management methods is increasingly accepted by the policymakers and farmers in diverse countries in Africa, Asia, and Latin America. However, SRI should not be regarded as single remedy or as a replacement for all current production methods. Indeed, SRI is not a technology so much as a set of ideas and insights for realizing more fully the productive and sustainable potentials existing in rice and other crops. The science and practice of SRI are still evolving as it is a work in progress. Its concepts and methods warrant further evaluation and experimentation to take advantage of whatever benefits they can confer, with further innovation also needed.

As rice paddies are one of the major anthropogenic sources of GHGs, there is reason to study carefully the source strength of emissions from agroecosystems modified under SRI management, evaluating this and other effects of the soil, water, and crop management practices associated with SRI methods of rice cultivation. From this review, it has been seen that these methods make for more productive use of water, which is becoming scarcer for agriculture and an increasing constraint on food production. This is seen at both the field level and the plant level, though how much saving can be achieved at scheme or landscape level depends on decision-making beyond the agronomic domain.

Information presently available is insufficient to understand all of the effects of SRI practices, particularly on the dynamics of microbial communities and their relation to GHG production and emission from rice paddy soils under SRI management. Experience with and research on SRI is pointing to positive, symbiotic roles of microorganisms around, on and inside plants, even inside their cells, in more intimate and complex relationships than has been apprehended previously. Microbes, the longest-surviving lifeforms on earth, may hold the key to the survival of our crop plants under increasingly adverse climatic conditions, and in turn, the survival of our own species.

REFERENCES

Abraham, B., O.O. AdeOluwa, H. Araya, T. Berhe, Y. Bhatt, S. Edwards et al. 2014. The system of crop iIntensification (SCI): Reports from the field on improving agricultural production, food security, and resilience to climate change for multiple crops. Agric. Food Security 3:4. doi:10.1186/2048-7010-3-4

Adak, A., R. Prasanna, S. Babu, N. Bidyarani, S. Verma, M. Pal, Y.S. Shivay, and L. Nain. 2016. Micronutrient enrichment mediated by plant-microbe interactions and rice cultivation practices. J. Plant Nutr. 39(9):1216–1232. doi:10.1080/01904167.2016.1148723

Africare/Oxfam America/WWF. 2010. Farmers leading the way from crisis to resilience: Global farmer perspectives on the system of rice intensification. Africare, Washington, DC; Oxfam America, Boston, MA; WWF-ICRISAT Dialogue Program, Hyderabad, India.

Altieri, M. 1995. Agroecology: The science of sustainable agriculture. Westview, Boulder, CO.

Anas, I., O.P. Rupela, T.M. Thiyagarajan, and N. Uphoff. 2011. A review of studies on SRI effects on beneficial organisms in rice soil rhizospheres. Paddy Water Environ. 9:53–64. doi:10.1007/s10333-011-0260-8

Anthofer, J. 2004. Potential of system of rice Intensification (SRI) in Cambodia. Consultancy report to Food Security and Nutrition Policy Support Program, GTZ, Phnom Penh.

Araya, H., S. Edwards, A. Asmelash, H. Legesse, G.H. Zibelo, T. Assefa, E. Mohammed, and S. Misgina. 2013. SCI: Planting with space. Agroecology case study. Alliance for Food Sovereignty in Africa (AFSA), Addis Ababa, Ethiopia.

Barah, B.C. 2009. Economic and ecological benefits of System of Rice Intensification (SRI) in Tamil Nadu. Agric. Econ. Res. Rev. 22:209–214.

Barison, J., and N. Uphoff. 2011. Rice yield and its relation to root growth and nutrient-use efficiency under SRI and conventional cultivation: An evaluation in Madagascar. Paddy Water Environ. 9:65–78. doi:10.1007/s10333-010-0229-z

Barrett, C.B., C. Moser, J. Barison, and O.V. McHugh. 2004. Better technology, better plots or better farmers? Identifying changes in productivity and risk among Malagasy rice farmers. Am. J. Agric. Econ. 86:869–888. doi:10.1111/j.0002-9092.2004.00640.x

Behera, D., A. Chaudhury, V.K. Vutukutu, A. Gupta, S. Machiraju, and P. Shah. 2013. Enhancing agricultural livelihoods through communityinstitutions in Bihar, India. World Bank, New Delhi.

Bender, S.F., F. Plantenga, A. Neftel, M. Jochen, H.R. Oberholzer, L. Kohl et al. 2014. Symbiotic relationships between soil fungi and plants reduce N_2O emissions from soil. ISME J. 8(6):1336–1345. doi:10.1038/ismej.2013.224

Bossio, D.A., W.R. Horwath, R.G. Mutters, and C. van Kessel. 1999. Methane pool and flux dynamics in a rice field following straw incorporation. Soil Biol. Biochem. 31:1313–1322. doi:10.1016/S0038-0717(99)00050-4

Bouman, B.A.M., R.M. Lampayan, and T.P. Tuong. 2007. Water management in irrigated rice production: Coping with water scarcity. Int. Rice Res. Inst., Los Baños, Philippines.

Cannon, W.A., and E.E. Free. 1917. The ecological significance of soil aeration. Science (Washington, DC) 45(1156):178–180. doi:10.1126/science.45.1156.178

CCAFS. 2013. Large-scale implementation of adaptation and mitigation actions in agriculture. Working Paper no. 50. CGIAR Research Program on Climate Change, Agriculture, and Food Security, Copenhagen. p. 71–75.

CCAFS/CTA. 2013. Climate-smart agriculture: Success stories from farming communities around the world. CGIAR Res. Program on Climate Change, Agric., and Food Security, Copenhagen, and Technical Centre for Agric. and Rural Coop., Wageningen, the Netherlands. p. 11–13.

Chaboussou, F. 2004. Healthy crops: A new agricultural revolution. Jon Anderson, Charnley, UK.

Chang, Y.-C., N. Uphoff, and E. Yamaji. 2016. A conceptual framework for eco-friendly paddy farming in Taiwan, based on experimentation with System of Rice Intensification (SRI) methodology. Paddy Water Environ. 14(1):169–183. doi:10.1007/s10333-015-0488-9

Chapagain, T., A. Riseman, and E. Yamaji. 2011. Assessment of system of rice intensification (SRI) and conventional practices under organic and inorganic management in Japan. Rice Sci. 18:311–320. doi:10.1016/S1672-6308(12)60010-9

Chapagain, T., and E. Yamaji. 2009. The effects of irrigation method, age of seedling and spacing on crop performance productivity and water-wise rice production in Japan. Paddy Water Environ. 8(1):81–90. doi:10.1007/s10333-009-0187-5

Chen, X.P., Z.-L. Cui, P.M. Vitousek, K.G. Cassman, P.A. Matson, J.-S. Bai et al. 2011. Integrated soil–crop system management for food security. Proc. Natl. Acad. Sci. USA 108:6399–6404. doi:10.1073/pnas.1101419108

Chi, F., S.H. Shen, H.P. Cheng, Y.X. Jing, Y.G. Yanni, and F.B. Dazzo. 2005. Ascending migration of endophytic rhizobia, from roots to leaves, inside rice plants and assessment of benefits to rice growth physiology. Appl. Environ. Microbiol. 71:7271–7278. doi:10.1128/AEM.71.11.7271-7278.2005

Chi, F., P.F. Yang, F. Han, Y.X. Jiing, and S.H. Shen. 2010. Proteomic analysis of rice seedlings infected by *Sinorhizobium meliloti* 1021. Proteomics 10:1861–1874. doi:10.1002/pmic.200900694

Choi, J.D., G.Y. Kim, W.J. Park, M.H. Shin, Y.H. Choi, S. Lee et al. 2014. Effect of SRI methods on water use, NPS pollution discharge, and greenhouse gas emissions in Korean trials. Paddy Water Environ. 13:205–213. doi:10.1007/s10333-014-0422-6

Dass, A., S. Chandra, N. Uphoff, A.K. Choudhury, R. Bhattacharya, and K.S. Rana. 2017. Agronomic fortification of rice grains with secondary and micronutrients under differing crop management and soil moisture regimes in the north Indian plains. Paddy Water Environ. (in press.) doi: 10.1007/s10333-017-0588-9

Dazzo, F.B., and Y. Yanni. 2006. The natural rhizobium-cereal crop association as an example of plant-bacteria interaction. In: N. Uphoff, et al., editors, Biological approaches to sustainable soil systems. CRC Press, Boca Raton, FL. p. 109–127. doi:10.1201/9781420017113.ch8

de Fraiture, C., and D. Wichelns. 2010. Satisfying future water demands for agriculture. Agric. Water Manage. 97:502–511. doi:10.1016/j.agwat.2009.08.008

Dhar, S., B. Barah, A.K. Vyas, and N. Uphoff. 2016. Evaluation of system of wheat intensification (SWI) practices as compared to other methods of improved wheat cultivation in the north-western plain zone of India. Arch. Agron. Soil Sci. 62:7, 994–1006. doi:10.1080/03650340.2015.1101518

Dill, J., G. Deichert, and T.N.T. Le, editors. 2013. Promoting the system of rice intensification: Lessons learned from Trà Vinh Province, Vietnam. German Agency for International Cooperation (GIZ) and International Fund for Agricultural Development, Hanoi.

Dobermann, A. 2004. A critical assessment of the system of rice intensification (SRI). Agric. Syst. 79:261–281. doi:10.1016/S0308-521X(03)00087-8

Doni, F., C.R.C.M. Zain, A. Isahak, F. Fathurrahman, N. Sulaiman, N. Uphoff, and W.A.W. Yusoff. 2016. Relationships observed between Trichoderma inoculation and characteristics of rice grown under system of rice intensification (SRI) vs. conventional methods of cultivation. Symbiosis. doi:10.1007/s13199-016-0438-3

Dung, N.T. 2007. SRI Application in rice production in northern ecological areas of Vietnam. Report of National IPM Program to Ministry of Agriculture and Rural Development, Hanoi.

Ezhil Rani, K. 2004. Relative abundance of insects in SRI and conventional rice. M. Sc. thesis. Tamil Nadu Agric. Univ., Coimbatore, TN, India. http://tnau.egranth.ac.in/cgi-bin/koha/opac-detail.pl?biblionumber=61732 (accessed 20 Nov. 2016).

Falkenmark, M., and J. Rockström. 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management. J. Water Resour. Plan. Manage. 132(3):129–132. doi:10.1061/(ASCE)0733-9496(2006)132:3(129)

FAO. 2010. 'Climate-smart' agriculture: Policies, practices and financing for food security, adaptation and mitigation. UN Food and Agriculture Organization, Rome.

FAO. 2012. Coping with water scarcity: An action framework for agriculture and food security. UN Food and Agriculture Organization, Rome.

FAO. 2013. Climate-smart agriculture: Sourcebook. UN Food and Agriculture Organization, Rome.

FAO. 2014. Final report for the international symposium on agroecology for food security and nutrition. UN Food and Agriculture Organization, Rome. 18–19 Sept. 2014.

FAO. 2016. Save and grow: Maize, rice and wheat– A guide to sustainable crop production. UN Food and Agriculture Organization, Rome. p. 44–47.

Fasoula, D.A., and V.A. Fasoula. 1997. Competitive ability and plant breeding. Plant Breed. Rev. 14:89–138.

Fedoroff, N.V., D.S. Battisti, R.N. Beachy, P.J.M. Cooper, D.A. Fischhoff, C.N. Hodges et al. 2010. Radically rethinking agriculture for the 21st century. Science (Washington, DC) 327:833–834. doi:10.1126/science.1186834

Frankenberger, W., and M. Arshad. 1995. Phytohormones in soils: Microbial production and function. Marcel Dekker, New York.

Gathorne-Hardy, A., D. Narasimha Reddy, M. Venkatanarayana, and B. Harriss-White. 2013. A life cycle assessment (LCA) of greenhouse gas emissions from SRI and flooded rice production in SE India. Taiwan Water Conserv. 61:110–125.

Gathorne-Hardy, A., D. Narasimha Reddy, M. Venkatanarayana, and B. Harriss-White. 2016. System of rice intensification provides environmental and economic gains but at the expense of social sustainability- A multidisciplinary analysis in India. Agric. Syst. 143:159–168. doi:10.1016/j.agsy.2015.12.012

Gbenou, P., A.M. Mitchell, A.B. Sedami, and P.N. Agossou. 2016. Farmer evaluations of the system of rice intensification (SRI) compared with conventional rice production in Benin. Eur. Scientific J. 12:280–296. doi:10.19044/esj.2016.v12n30p280

Gliessman, S.R. 2007. Agroecology: The ecology of sustainable food systems. 2nd ed. CRC Press, Boca Raton, FL.

Gopalakrishnan, S., R. Mahender Kumar, P. Humayun, V. Srinivas, B.R. Kumari, R. Vijayabharati et al. 2013. Assessment of different methods of rice (*Oryza sativa* L.) cultivation affecting growth parameters, soil chemical, biological and microbiological properties, water saving, and grain yield in rice-rice system. Paddy Water Environ. 12:79–87. doi:10.1007/s10333-013-0362-6

Hadi, A., K. Inubushi, and K. Yagi. 2010. Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. Paddy Water Environ. 8:319–324. doi:10.1007/s10333-010-0210-x

Hameed, K.A., A.K.J. Mosa, and F.A. Jaber. 2011. Irrigation water reductions using system of rice intensification compared with conventional cultivation methods in Iraq. Paddy Water Environ. 9:121–127. doi:10.1007/s10333-010-0243-1

IATP. 2015. What's wrong with 'climate-smart agriculture? Inst. for Agriculture and Trade Policy, Washington, DC.

Ilag, L.L., A.M. Ilag, M. Rosales, F.A. Elazegui, and T.M. Mew. 1987. Changes in the population of infective endomycorrhizal fungi in a rice-based cropping system. Plant Soil 103:67–73. doi:10.1007/BF02370669

Jagannath, P., H. Pullabhotla, and N. Uphoff. 2013. Meta-analysis evaluating water use, water saving, and water productivity in irrigated production of rice with SRI vs. standard management methods. Taiwan Water Conserv. 61:14–49.

Jain, N., R. Dubey, D.S. Dubey, J. Singh, M. Khanna, H. Pathak, and A. Bhatia. 2014. Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic Plains. Paddy Water Environ. 12:355–363. doi:10.1007/s10333-013-0390-2

Kabir, H., and N. Uphoff. 2007. Results of disseminating the system of rice intensification (SRI) with farmer field school methods in northern Myanmar. Exp. Agric. 43:463–476. doi:10.1017/S0014479707005340

Kar, S., S.B. Varade, T.K. Subramanyam, and B.P. Ghildyal. 1974. Nature and growth pattern of rice root system under submerged and unsaturated conditions. Il Riso 23:173–179.

Karthikeyan, K., J. Sosamma, and S.M. Purushothaman. 2010. Incidence of insect pests and natural enemies under SRI method of cultivation. Oryza 47:154–157.

Kell, D.B. 2011. Breeding crop plants with deep roots: Their role in sustainable carbon, nutrient and water sequestration. Ann. Bot. (Lond.) 108:407–418. doi:10.1093/aob/mcr175

Khakwani, A.A., M. Shiraishi, M. Zubair, M.S. Baloch, K. Naveed, and I. Awan. 2005. Effect of seedling age and water depth on morphological and physiological aspects of transplanted rice under high temperature. J. Zhejiang Univ. Sci. 6B:389–395. doi:10.1631/jzus.2005.B0389

Khumairoh, U., J.C.J. Groot, and E.A. Lantinga. 2012. Complex agro-ecosystems for food security in a changing climate. Ecol. Evol. 2:1696–1704. doi:10.1002/ece3.271

Krupnik, T.J., C. Shennan, and J. Rodenburg. 2012. Yield, water productivity and nutrient balances under the system of rice intensification and recommended management practices in the Sahel. Field Crops Res. 130:155–167. doi:10.1016/j.fcr.2012.02.003

Kumaraswamy, S., A.K. Rath, B. Ramakrishnan, and N. Sethunathan. 2000. Wetland rice soils as sources and sinks of methane: A review and prospects for research. Biol. Fertil. Soils 31:449–461. doi:10.1007/s003740000214

Lal, R. 2009. Soil degradation as a reason for inadequate human health. Food Secur. 1:45–57. doi:10.1007/s12571-009-0009-z

Lal, R. 2015. Restoring soil quality to mitigate soil degradation. Sustainability 7:5875–5895. doi:10.3390/su7055875

Latif, M.A., M.Y. Ali, M.R. Islam, M.A. Badshah, and M.S. Hasan. 2009. Evaluation of management principles and performance of the System of Rice Intensification (SRI) in Bangladesh. Field Crops Res. 114:255–262. doi:10.1016/j.fcr.2009.08.006

Laulanié, H., 1993. Le système de riziculture intensive malgache. Tropicultura 11:110–114; republished in English in 2013 in Tropicultura 29:183–187.

Li, X.Y., X.L. Xu, and H. Li. 2005. A socio-economic assessment of the system of rice intensification (SRI): A case study of Xinsheng Village, Jianyang County, Sichuan Province. Report for College of Humanities and Development, China Agric. Univ., Beijing. (In Chinese.) Chinese Rural Economy, 2006, p. 13–22.

Lim, S. 2007. Experiences in multi-purpose farm development: Raising household incomes in Cambodia by utilizing productivity gains from the system of rice intensification. Cambodian Center for Study and Development of Agriculture (CEDAC), Phnom Penh.

Lin, X.Q., D.F. Zhu, H.A. Chen, S.H. Cheng, and N. Uphoff. 2009. Effect of plant density and nitrogen fertilizer rates on grain yield and nitrogen uptake of hybrid rice (*Oryza sativa* L.). J. Agric. Biotech. Sustain. Dev. 1:44–53.

Lin, X.Q., D.F. Zhu, and X.J. Lin. 2011. Effects of water management and organic fertilization with SRI crop practices on hybrid rice performance and rhizosphere dynamics. Paddy Water Environ. 9:33–39. doi:10.1007/s10333-010-0238-y

Lu, S.H., Y.J. Dong, J. Yuan, H. Lee, and H. Padilla. 2013. A high-yielding, water-saving innovation combining SRI with plastic cover on no-till raised beds in Sichuan, China. Taiwan Water Conserv. 61:94–109.

Ly, P., L.S. Jensen, T.B. Bruun, D. Rutz, and A. de Neergaard. 2012. The system of rice intensification: Adapted practices, reported outcomes and their relevance in Cambodia. Agric. Syst. 113:16–27. doi:10.1016/j.agsy.2012.07.005

Mahinder Kumar, R., Ch. Padmavathi, K. Surekha, P.C. Latha, P. Krishnamurthy, and S.P. Singh. 2007. Influence of organic nutrient sources on insect pests and economics of rice production in India. Indian J. Plant Path. 35:264–267.

McDonald, A.J., P.R. Hobbs, and S.J. Riha. 2006. Does the system of rice intensification outperform conventional best management? A synopsis of the empirical record. Field Crops Res. 96:31–36. doi:10.1016/j.fcr.2005.05.003

McDonald, A.J., P.R. Hobbs, and S.J. Riha. 2008. Stubborn facts: Still no evidence that the system of rice intensification out-yields best management practices (BMPs) beyond Madagascar. Field Crops Res. 108:188–191. doi:10.1016/j.fcr.2008.06.002

Mendes, R., P. Garbeva, and J.M. Raaijmakers. 2013. The rhizosphere microbiome: Significance of plant beneficial, plant pathogenic and human pathogenic organisms. FEMS Microbiol. Rev. 37:634–663. doi:10.1111/1574-6976.12028

Minami, K., and H.U. Neue. 1994. Rice paddies as a methane source. Clim. Change 27:13–26. doi:10.1007/BF01098470

Mishra, S., A.K. Rath, T.K. Adhya, V.R. Rao, and N. Sethunathan. 1997. Effect of continuous and alternate water regimes on methane efflux from rice under greenhouse conditions. Biol. Fertil. Soils 24:399–405. doi:10.1007/s003740050264

Mishra, A., and V.M. Salokhe. 2008. Seedling characteristics and the early growth of transplanted rice under different water regimes. Exp. Agric. 44:365–383. doi:10.1017/S0014479708006388

Mishra, A., and N. Uphoff. 2013. Morphological and physiological responses of rice roots and shoots to varying water regimes and microbial densities. Arch. Agron. Soil Sci. 59:705–731. doi:10.1080/03650340.2012.669474

Mishra, A., M. Whitten, J.W. Ketelaar, and V.M. Salokhe. 2006. The system of rice intensification (SRI): A challenge for science, and an opportunity for farmer empowerment towards sustainable agriculture. Int. J. Agric. Sustain. 4:193–212.

Miyazato, T., R.A. Mohammed, and R.C. Lazaro. 2010. Irrigation management transfer (IMT) and system of rice intensification (SRI) practice in the Philippines. Paddy Water Environ. 8:91–97. doi:10.1007/s10333-009-0188-4

Mohammed, U., W. Aimrun, M.S.M. Amin, A. Khalina, and U.B. Zubairu. 2016. Influence of soil cover on moisture content and weed suppression under system of rice intensification (SRI). Paddy Water Environ. 14:159–167. doi:10.1007/s10333-015-0487-x

Moser, C.M., and C.B. Barrett. 2003. The disappointing adoption dynamics of a yield-increasing low external-input technology: The case of SRI in Madagascar. Agric. Syst. 76:1085–1100. doi:10.1016/S0308-521X(02)00041-0

Mrunalini, A., and M. Ganesh. 2008. Work load on women using cono weeder in SRI method of paddy cultivation. Oryza 5:58–61.

MSSRF. 2004. Fourteenth annual report, 2003–2004. M.S. Swaminathan Research Foundation, Chennai, Tamil Nadu, India. p. 71.

Namara, R., D. Bossio, P. Weligamage, and I. Herath. 2008. The practice and effects of System of Rice Intensification (SRI) in Sri Lanka. Qtrly. J. Intl. Agric. 47:5–23.

Ndiiri, J.A., B.M. Mati, and N. Uphoff. 2013. Water productivity under the System of Rice Intensification from experimental plots and farm surveys in Mwea, Kenya. Taiwan Water Conserv. 61:63–75.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu et al. 2009. Climate change: Impact on agriculture and costs of adaptation. Int. Food Policy Research Inst., Washington, DC.

Nemoto, K., S. Morita, and T. Baba. 1995. Shoot and root development in rice related to the phyllochron. Crop Sci. 35:24–29. doi:10.2135/cropsci1995.0011183X003500010005x

Neue, H.U. 1993. Methane emission from rice fields. Bioscience 43:466–474. doi:10.2307/1311906

Padmavathi, Ch., R. Mahinder Kumar, L.V. Subba Rao, K. Surekha, M.S. Prasad, and V.R. Babu. 2009. Influence of SRI method of rice cultivation on insect pest incidence and arthropod diversity. Oryza 46:227–230.

Palanisami, K., K.R. Karunakaran, U. Amarasinghe, and C.R. Rangamuthu. 2013. Doing different things or doing it differently? Rice intensification practices in 13 states of India. Econ. Polit. Wkly. 48:51–58.

Pandey, S. 2009. Effects of weed control methods on rice cultivars under the system of rice intensification (SRI). M.S. thesis. Inst. of Agriculture and Animal Sciences, Rampur, Nepal.

Pasuquin, E., T. Lafarge, and B. Tubana. 2008. Transplanting young seedlings in irrigated rice fields: Early and high tiller production enhanced grain yield. Field Crops Res. 105:141–155. doi:10.1016/j.fcr.2007.09.001

Pathak, M., R.C. Shakywar, D. Sah, and S. Singh. 2012. Prevalence of insect pests, natural enemies and diseases in SRI (system of rice intensification) of rice cultivation in North East region. Annals. Plant Prot. Sci. 20:375–379.

Pinton, R., Z. Varnanini, and P. Nannipieri, editors. 2007. The rhizosphere: Biochemistry and organic substances at the soil-plant interface. 2nd ed. CRC Press, Boca Raton, FL. doi:10.1201/9781420005585

Prasad, A., 2008. Going against the grain: The system of rice intensification is now being adapted to wheat–with similar good results. Outlook Business, Oct. 18, p. 54–55.

Rajkishore, S.K., P. Doraisamy, K.S. Subramanian, and M. Maheswari. 2013. Methane emission patterns and their associated soil microflora with SRI and conventional systems of rice cultivation in Tamil Nadu, India. Taiwan Water Conserv. 61:126–134.

Rama Rao, I.V.Y. 2011. Estimation of efficiency, sustainability and constraints of SRI (system of rice intensification) vis-a-vis traditional methods in north coastal zone of Andhra Pradesh. Agric. Econ. Res. Rev. 24:325–331.

Redman, R.S., Y.O. Kim, C.J.D.A. Woodward, C. Greer, L. Espino, S.L. Doty, and R.J. Rodriguez. 2011. Increased fitness and adaptation of rice plants to cold, drought and salt stress via habitat adapted symbiosis: A strategy for mitigating impacts of climate change. PLoS One 6(7):e14823. doi:10.1371/journal.pone.0014823

Reynolds, O.L., M.G. Keeping, and J.H. Meyer 2009. Silicon-augmented resistance of plants to herbivorous insects: A review. Ann. Appl. Biol. 155:171–186. doi:10.1111/j.1744-7348.2009.00348.x.00348.x

Rodriguez, R.J., D.C. Freeman, E.D. McArthur, Y.O. Kim, and R.S. Redman. 2009. Symbiotic regulation of plant growth, development, and reproduction. Commun. Integr. Biol. 2:141–143. doi:10.4161/cib.7821

San-oh, Y., Y. Mano, T. Ookawa, and T. Hirasawa. 2004. Comparison of dry matter production and associated characteristics between direct-sown and transplanted rice plants in a submerged paddy field and relationships to planting patterns. Field Crops Res. 87:43–58. doi:10.1016/j.fcr.2003.09.004

San-oh, Y., T. Sugiyama, D. Yoshita, T. Ookawa, and T. Hirasawa. 2006. The effect of planting pattern on the rate of photosynthesis and related processes during ripening in rice plants. Field Crops Res. 96:113–124. doi:10.1016/j.fcr.2005.06.002

Sarwar, N., H. Ali, H. Maqsood, A. Ahmad, E. Ulllah, T. Khaliq, and J.E. Hill. 2014. Influence of nursery management and seedling age on growth and economic performance of fine rice. J. Plant Nutr. 37:1287–1303. doi:10.1080/01904167.2014.881490

Sato, S., and N. Uphoff. 2007. A review of on-farm evaluations of system of rice intensification in eastern Indonesia. CAB Rev. 2:54 Commonwealth. Agric. Bur. Int., Wallingford, UK. doi:10.1079/PAVSNNR20072054

Sato, S., E. Yamaji, and T. Kuroda. 2011. Strategies and engineering adaptations to disseminate SRI methods in eastern Indonesia. Paddy Water Environ. 9:79–88. doi:10.1007/s10333-010-0242-2

Satyanarayana, A., T.M. Thiyagarajan, and N. Uphoff. 2007. Opportunities for water saving with higher yield from the system of rice intensification. Irrig. Sci. 25:99–115. doi:10.1007/s00271-006-0038-8

Schlaeppi, K., and D. Bulgarelli. 2015. The plant microbiome at work. Mol. Plant Microbe Interact. 28:212–217. doi:10.1094/MPMI-10-14-0334-FI

Senthilkumar, K., P.S. Bindraban, T.M. Thiyagarajan, N. de Ridder, and K.E. Giller. 2008. Modified rice cultivation in Tamil Nadu, India: Yield gains and farmers' (lack of) acceptance. Agric. Syst. 98:82–94. doi:10.1016/j.agsy.2008.04.002

Sharif, A. 2011. Technical adaptations for mechanized SRI production to achieve water saving and increased profitability in Punjab, Pakistan. Paddy Water Environ. 9:111–119. doi:10.1007/s10333-010-0223-5

Sheehy, J.E., P.L. Mitchell, and B. Hardy. 2007. Charting new pathways: C4 rice. Int. Rice Res. Inst., Los Baños, Philippines.

Sheehy, J.E., S. Peng, A. Dobermann, P.L. Mitchell, A. Ferrer, J. Yang, Y. Zou, X. Zhong, and J. Huang. 2004. Fantastic yields in the system of rice intensification: Fact or fallacy? Field Crops Res. 88:1–8. doi:10.1016/j.fcr.2003.12.006

Sinclair, T.R. 2004. Agronomic UFOs waste valuable scientific resources. Rice Today 3:43 Int. Rice Res. Inst., Los Baños, Philippines.

Sinclair, T.R., and K.G. Cassman. 2004. Agronomic UFOs. Field Crops Res. 88:9–10. doi:10.1016/j.fcr.2004.01.001

Sinha, S.K., and J. Talati. 2007. The impact of system of rice intensification (SRI) on paddy productivity: Results of a study in Purulia District, West Bengal, India. Agric. Water Manage. 87:55–60. doi:10.1016/j.agwat.2006.06.009

Smith, V.H., G.D. Tilman, and J.C. Nekola. 1999. Eutrophication: Impacts of excessive nutrient inputs on freshwater, marine and terrestrial ecosystems. Environ. Pollut. 100:179–196. doi:10.1016/S0269-7491(99)00091-3

SRI-Rice. 2014. The system of crop intensification (SCI): Agroecological Innovations for improving agricultural production, food security, and resilience to climate change. SRI-Rice, Cornell Univ., Ithaca, NY, and Technical Center for Agricultural and Rural Cooperation, Wageningen, the Netherlands.

SRI-Rice. 2017. Website of the SRI International Network and Resources Center, Cornell Univ., Ithaca, NY. http://sri.cals.cornell.edu; listing of over 800 journal articles published on SRI: http://sri.cals.cornell.edu/research/JournalArticles.html (accessed 5 Jan. 2017).

Stoop, W.A. 2011. The scientific case for the system of rice intensification and its relevance for sustainable crop intensification. Int. J. Agric. Sustain. 9:443–455. doi:10.1080/14735903.2011.583483

Stoop, W.A., and A.H. Kassam. 2005. The SRI controversy: A response. Field Crops Res. 91:357–360. doi:10.1016/j.fcr.2004.07.023

Stoop, W.A., N. Uphoff, and A.H. Kassam. 2002. Research issues raised for the agricultural sciences by the System of Rice Intensification (SRI) from Madagascar: Opportunities for improving farming systems for resource-limited farmers. Agric. Syst. 71:249–274. doi:10.1016/S0308-521X(01)00070-1

Styger, E., M.A. Attaher, H. Guindo, H. Ibrahim, M. Diaty, I. Abba, and M. Traoré. 2011. Application of SRI practices in the arid environment of the Timbuktu region in Mali. Paddy Water Environ. 9:137–144. doi:10.1007/s10333-010-0237-z

Styger, E., and N. Uphoff. 2016. The System of Rice Intensification: Revisiting Agronomy for a Changing Climate. GACSA Practice Brief. Global Alliance for Climate-Smart Agriculture, FAO, Rome.

Subardja, V.O., I. Anas, and R. Widyastuti. 2016. Utilization of organic fertilizer to increase paddy growth and productivity using System of Rice Intensification (SRI) methods in saline soil. J. of Degraded and Mining Lands Manage. 3:543–549. doi:10.15243/jdmlm.2016.032.543

Sudhakar, T.R., and P.N. Reddy. 2007. Influence of system of rice intensification (SRI) on the incidence of insect pests. Presentation at 2nd National SRI Symposium, Agartala, Tripura, India. 3–5 Oct. http://www.slideshare.net/SRI.CORNELL/0729-influence-of-sri-on-the-incidence-of-insect-pests (accessed 10 Dec. 2009).

Suresh, A., M. Ramesh, and S. Ram Reddy. 2014. Fluorescence pseudomonads contribute to the enhanced growth and yield under system of rice intensification (SRI). Indian J. Agric. Res. 48:287–293. doi:10.5958/0976-058X.2014.00662.3

Suryavanshi, P., Y.V. Singh, R. Prasanna, A. Bhatia, and Y.S. Shivay. 2013. Pattern of methane emission and water productivity under different methods of rice crop establishment. Paddy Water Environ. 11:321–329. doi:10.1007/s10333-012-0323-5

Swaminathan, M.S. 2006. Report of the sub-committee on more crop and income per drop of water. M.S. Swaminathan, Chair, Ministry of Water Resources, New Delhi. p. 20–22

Swaminathan, M.S. 2007. Can science and technology feed the world in 2025? Field Crops Res. 104:3–9. doi:10.1016/j.fcr.2007.02.004

Tao, L.X., X. Wang, and S.K. Min. (2002). Physiological effects of SRI methods on the rice plant. In: N. Uphoff et al., editors, Assessments of the system of rice intensification (SRI). CIIFAD, Ithaca, NY. p. 132–136.

Thakur, A.K. 2010. Critiquing SRI criticism: Beyond skepticism with empiricism. Curr. Sci. 98:1294–1299.

Thakur, A.K., R.K. Mohanty, D.U. Patil, and A. Kumar. 2014. Impact of water management on yield and water productivity with system of rice intensification (SRI) and conventional transplanting system in rice. Paddy Water Environ. 12:413–424. doi:10.1007/s10333-013-0397-8

Thakur, A.K., R.K. Mohanty, R. Singh, and D.U. Patil. 2015. Enhancing water and cropping productivity through Integrated System of Rice Intensification (ISRI) with aquaculture and horticulture under rainfed conditions. Agric. Water Manage. 161:65–76. doi:10.1016/j.agwat.2015.07.008

Thakur, A.K., S. Rath, and A. Kumar. 2011. Performance evaluation of rice varieties under system of rice intensification (SRI) compared with conventional transplanting system. Arch. Agron. Soil Sci. 57:223–238. doi:10.1080/03650340903302302

Thakur, A.K., S. Rath, and K.G. Mandal. 2013. Differential responses of system of rice intensification (SRI) and conventional flooded-rice management methods to applications of nitrogen fertilizer. Plant Soil 370:59–71. doi:10.1007/s11104-013-1612-5

Thakur, A.K., S. Rath, S. Roychowdhury, and N. Uphoff. 2010b. Comparative performance of rice with system of rice intensification (SRI) and conventional management using different plant spacings. J. Agron. Crop Sci. 196:146–159. doi:10.1111/j.1439-037X.2009.00406.x

Thakur, A.K., N. Uphoff, and E. Antony. 2010a. An assessment of physiological effects of system of rice intensification (SRI) practices compared to recommended rice cultivation practices in India. Exp. Agric. 46:77–98. doi:10.1017/S0014479709990548

Thakur, A.K., N. Uphoff, and W.A. Stoop. 2016. Scientific underpinnings of the system of rice intensification (SRI): What is known so far? Adv. Agron. 135:147–179. doi:10.1016/bs.agron.2015.09.004

Thies, J.E., and J.M. Grossman. 2006. The soil habitat and soil ecology. In: N. Uphoff et al., editors, Biological approaches to sustainable soil systems. CRC Press, Boca Raton, FL. p. 59–78. doi:10.1201/9781420017113.ch5

Thomas, V., and A.M. Ramzi. 2011. SRI contributions to rice production dealing with water management constraints in northeastern Afghanistan. Paddy Water Environ. 9:101–109. doi:10.1007/s10333-010-0228-0

Toriyama, K., and H. Ando. 2011. Towards an understanding of the high productivity of rice with system of rice intensification (SRI) management from the perspectives of soil and plant physiological processes. Soil Sci. Plant Nutr. 57:636–649. doi:10.1080/00380768.2011.602627

Tsujimoto, Y., T. Horie, H. Randriamihary, T. Shiraiwa, and K. Homma. 2009. Soil management: The key factors for higher productivity in the fields utilizing the system of rice intensification (SRI) in the central highland of Madagascar. Agric. Syst. 100:61–71. doi:10.1016/j.agsy.2009.01.001

Turmel, M.-S., J. Espinosa, L. Franco, C. Perez, H. Hernandez, E. Gonzalez et al. 2011. On-farm evaluation of a low-input rice production system in Panama. Paddy Water Environ. 9:155–161. doi:10.1007/s10333-010-0227-1

Turner, T.R., E.K. James, and P.S. Poole. 2013. The plant microbiome. Genome Biol. 14:209. doi:10.1186/gb-2013-14-6-209

UNEP. 2015. TEEB Agriculture and Food: An Interim Report. The Economics of Ecosystems and Biodiversity Program, U.N. Environmental Program, Geneva.

Uphoff, N. 1999. Agroecological implications of the System of Rice Intensification (SRI) in Madagascar. Environ. Dev. Sustain. 1:297–313. doi:10.1023/A:1010043325776

Uphoff, N. 2011. Agroecological approaches to 'climate-proofing' agriculture while raising productivity in the 21st century. In: T. Sauer, J. Norman, and M. Sivakumar, editors, Sustaining soil productivity in response to global climate change. Wiley-Blackwell, Hoboken, NJ. p. 87–102. doi:10.1002/9780470960257.ch7

Uphoff, N. 2015. The system of rice intensification: Responses to frequently asked questions. http://www.amazon.com/The-System-Rice-Intensification-Frequently/dp/1515022056 (accessed 4 Feb. 2016).

Uphoff, N. 2016. Developments in the system of rice intensification (SRI). In: T. Sasaki, editor, Achieving sustainable rice cultivation, Vol. 2. Burleigh-Dodds, Cambridge, UK.

Uphoff, N., A. Ball, E. Fernandes, H. Herren, O. Husson, M. Laing et al., editors. 2006. Biological approaches to sustainable soil systems. CRC Press, Boca Raton, FL. doi:10.1201/9781420017113

Uphoff, N., F. Chi, F.B. Dazzo, and R.J. Rodriguez. 2013. Soil fertility as a contingent rather than inherent characteristic: Considering the contributions of crop-symbiotic soil microbiota. In: R. Lal and B. Stewart, editors, Principles of sustainable soil management in agroecosystems. CRC Press, Boca Raton, FL. p. 141–166.

Uphoff, N., V. Fasoula, I. Anas, A. Kassam, and A.K. Thakur. 2015. Improving the phenotypic expression of rice genotypes: Rethinking 'intensification' for production systems and selection practices for rice breeding. Crop J. 3:174–189. doi:10.1016/j.cj.2015.04.001

Uphoff, N., A. Kassam, and W. Stoop. 2008. A critical assessment of a desk study comparing crop production systems: The example of the 'system of rice intensification' versus 'best management practice'. Field Crops Res. 108:109–114. doi:10.1016/j.fcr.2007.12.016

Uphoff, N., and R. Randriamiharisoa. 2002. Reducing water use in irrigated rice production with the Madagascar system of rice intensification. In: B.A.M. Bouman et al., editors, Water-Wise Rice Production: Proceedings of the International Workshop. 8–11 Apr. 2002. Int. Rice Res. Inst., Los Baños, Philippines. p. 71–88.

Uzzaman, T., R.K. Sikder, M.I. Asif, H. Mehraj, and A.F.M. Jamal Uddin. 2015. Growth and yield trial of sixteen rice varieties under System of Rice Intensification. Sci. Agric. 11:81–89. doi:10.15192/PSCP.SA.2015.11.2.8189

Vermeulen, S.J., B.M. Campbell, and J.S.I. Ingram. 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37:195–222. doi:10.1146/annurev-environ-020411-130608

Visalakshmi, V., P.R.M. Rao, and N.H. Satyanarayana. 2014. Impact of paddy cultivation systems on insect pest incidence. J. Crop Weed 10:139–142.

WARREC. 2015. Application to JKUAT Innovation Fund, Sept. 15, 2015. Water Research and Resources Center, Jomo Kenyatta University of Agriculture and Technology, Nairobi.

Watanarojanaporn, N., N. Boonkerd, P. Tittabutr, A. Longtonglang, J.P.W. Young, and N. Teaumroong. 2013. Effect of rice cultivation systems on indigenous arbuscular mycorrhizal fungal community structure. Microbes Environ. 28:316–324. doi:10.1264/jsme2.ME13011

Watts, C.W., and A.R. Dexter. 1998. Soil friability: Theory, measurement and the effects of management and organic carbon content. Eur. J. Soil Sci. 49:73–84. doi:10.1046/j.1365-2389.1998.00129.x

Wheeler, T., and J.V. Braun. 2013. Climate change impacts on global food security. Science (Washington, DC) 341:508–513. doi:10.1126/science.1239402

Wu, W., and N. Uphoff. 2015. A review of system of rice intensification in China. Plant Soil 393:361–381 [erratum:393:383]. doi:10.1007/s11104-015-2440-6

Xiong, Z.Q., G.X. Xing, and Z.L. Zhu. 2007. Nitrous oxide and methane emission as affected by water soil and nitrogen. Pedosphere 17:146–155. doi:10.1016/S1002-0160(07)60020-4

Xu, F.Y., J. Ma, H.Z. Wang, H.Y. Liu, Q.L. Huang, and W.B. Ma. 2005. Rice quality under the cultivation of SRI. (In Chinese.) Acta Agron. Sin. 31:577–582.

Yang, C., L. Yang, Y. Yang, and Z. Ouyang. 2004. Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. Agric. Water Manage. 70:67–81. doi:10.1016/j.agwat.2004.05.003

Yanni, Y.G., R.Y. Rizk, F. Abd El-Fattah, A. Squartini, V. Corich, A. Giacomini et al. 2001. The beneficial plant growth promoting association of *Rhizobium leguminosarum* bv. *trifolii* with rice roots. Aust. J. Plant Physiol. 28:845–870.

Yuan, L.P. 2002. A scientist's perspective on experience with SRI in China for raising the yields of super hybrid rice. In: N. Uphoff et al., eds., Assessments of the system of rice intensification (SRI), 23-25, CIIFAD. Ithaca, NY.

Zhang, H., Y. Xue, Z. Wang, J. Yang, and J. Zhang. 2009. An alternate wetting and moderate soil drying regime improves root and shoot growth in rice. Crop Sci. 49:2246–2260. doi:10.2135/cropsci2009.02.0099

Zhao, L.M., L.H. Wu, Y.S. Li, S. Animesh, D.F. Zhu, and N. Uphoff. 2010. Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the system of rice intensification. Commun. Soil Sci. Plant Anal. 41:1–12. doi:10.1080/00103620903360247

Zhao, L.M., L.H. Wu, Y.S. Li, X.H. Lu, D.F. Zhu, and N. Uphoff. 2009. Influence of the system of rice intensification on rice yield and nitrogen and water use efficiency with different N application rates. Exp. Agric. 45:275–286. doi:10.1017/S0014479709007583

Zheng, J.G., Z.Z. Chi, X.Y. Li, and X.L. Jiang. 2013. Agricultural water savings possible through SRI for water management in Sichuan China. Taiwan Water Conserv. 61:50–62.

Zhong, X.H., and N.R. Huang. 2005. Rice grain chalkiness is negatively correlated with root activity during grain filling. Rice Sci. 12(3):192–196.

Zhu, D.F., S.H. Cheng, Y.P. Zhang, and X.Q. Lin. 2002. Tillering patterns and the contribution of tillers to grain yield with hybrid rice and wide spacing. In: N. Uphoff et al., editors, Assessments of the system of rice intensification (SRI). CIIFAD, Ithaca, NY. p. 125–131.