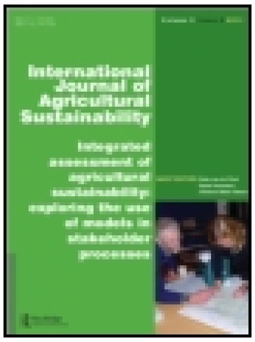

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System of crop intensification for more productive, resource-conserving, climate-resilient, and sustainable agriculture: experience with diverse crops in varying agroecologies

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ABSTRACT
With continually increasing demand for food accompanied by the constraints of climate change and the availability and quality of soil and water, the world's farmers are challenged to produce more food per hectare with less water, and with fewer agrochemical inputs if possible. The ideas and methods of the system of rice intensification which is improving irrigated rice production are now being extended/adapted to many other crops: wheat, maize, finger millet, sugarcane, tef, mustard, legumes, vegetables, and even spices. Promoting better root growth and enhancing the soil's fertility with organic materials are being found effective means for raising the yields of many crop plants with less water, less fertilizer, reduced seeds, fewer agrochemicals, and greater climate resilience. In this article, we review what is becoming known about various farmer-centred innovations for agroecological crop management that can contribute to agricultural sustainability. These changes represent the emerging system of crop intensification, which is being increasingly applied in Asian, African, and Latin American countries. More research will be needed to verify the efficacy and impact of these innovations and to clarify their conditions and limits. But as no negative effects for human or environmental health have been identified, making these agronomic options more widely known should prompt more investigation and, to the extent justified by results, utilization of these methodologies.

KEYWORDS
Agroecological management; Sustainable Sugarcane Initiative; system of crop intensification; system of rice intensification; system of wheat intensification

Introduction

During the latter half of the twentieth century, most efforts to increase food production were based on improving and increasing 'modern' agricultural inputs: new-variety seeds, irrigation water, and inorganic fertilizers and pesticides. This strategy, whose

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apotheosis was dubbed the green revolution, has raised the output of food, but with substantial and growing financial and environmental costs, and for some years it has been encountering diminishing agronomic and economic returns (Peng et al., 2010; Pingali, Hossain, & Gerpacio, 1997). At the same time, it has had some adverse impacts on soil health, water quality, and biodiversity. For the sake of agricultural sustainability – a quest complicated by constraints which emanate from climate change – there is need to develop some alternatives to the currently prevailing paradigm for agriculture so that farmers are not locked in to a single costly and vulnerable strategy for sustaining food production.

The concept and goal of 'sustainable intensification' (SI) has received growing support, although without much agreement on what this means. Some versions of SI focus on achieving more efficient use of inputs, emphasizing technologies like high-tech precision agriculture for field crops, alternative-wetting-and-drying for irrigated rice production, and integrated pest and nutrient management to reduce and optimize the use of agrochemical inputs (e.g. CSISA, 2015; Heaton et al., 2013; Montpellier Panel, 2013). These approaches do not question the desirability or viability of continuing the current input-dependence of production strategies. Other versions of SI, on the other hand, consider how could farmers become less dependent on external inputs, basing their agriculture more on making modifications in the management of their inputs, seeking to capitalize more effectively and efficiently on the natural resource base and its inherent capacities (e.g. Pretty, Toulmin, & Williams, 2011).

This alternative approach to agricultural improvement, which is broadly characterized as agroecology, aims to diminish dependence on external inputs as much as possible by mobilizing the biological processes and potentials that are available in existing plant and animal genomes and in the soil systems that support both crops and livestock (Altieri, 1995; FAO, 2014; Gliessman, 2007; Uphoff et al., 2006). To what extent can such a strategy be profitable as well as sustainable? This question is hard to answer conclusively because most agricultural R&D for the past 50 years has focused on increasing and improving inputs, giving little attention to management except to make the input-dependent approach more productive and profitable. Achieving varietal improvements has been the leading element rather than improving resource management.

Nobody can know for certain what will be sustainable in future decades. But continued and expanded agricultural production will probably be more sustainable to the extent that farmers' reliance on agrochemical, fossil fuel and other inputs is diminished. Is it possible to get more output with reductions rather than increases in these agricultural inputs?

We suggest here, based on widespread and diverse evidence, that these effects are indeed achievable through the appropriate utilization of agroecological principles and practices. Explanations for such effects with rice are given in Uphoff (2017). This paper reports on a variety of innovations by farmers and civil society organizations that have adapted to a range of other crops such as wheat, maize, finger millet, sugarcane, etc., the ideas and methods that were developed in the system of rice intensification (SRI) for rice (FAO, 2016, p. 44–47; Stoop, Uphoff, & Kassam, 2002; Uphoff, 2015). The principles and practices that improve the productivity and resilience of these varied crops are broadly referred to as the system of crop intensification (SCI), which is the focus of this article. The rubric of SCI includes versions of SRI for wheat, finger millet, sugarcane, tef, etc., each with its own acronym (e.g. SWI, SFMI, SSI, STI, …).

SCI methods are particularly relevant for resource-limited, nutritionally vulnerable households because SCI like SRI relies minimally on purchased inputs. However, as reported in this article, it is possible with appropriate mechanization to scale up these methods for commercial production. Inducing the growth of larger, better-functioning root systems and increasing and supporting more beneficial life in the soil, which can buffer the effects of drought, storm damage, extreme temperatures, pests and diseases, is feasible on large as well as small farms.

Because SCI is only about 10 years old, most of what is reported here is relatively recent. This is also why the published literature on SCI cited here is limited. We draw on as much such literature as is available; but most of what we can report is data from the field rather than from experiment stations. The results reported are remarkable enough – and important enough for agricultural sustainability – that sceptics are invited to undertake their own evaluations, preferably under the realistic and often adverse conditions that farmers must deal with. Enough has been seen and evaluated over the past decade, with consistent patterns of results, that we believe SCI phenomena should be made known to readers concerned with agricultural sustainability, not as something scientifically indisputable, but as warranting further investigation.[1]

This article draws together and presents a wide range of experience in adapting and applying the ideas and methods of SRI to sustainably improving diverse crops. It was compiled by Uphoff from written reports from and direct communication with the other authors, who have been developing SCI and documenting it in the field for five years or more. It is unfortunate that not all of the farmers who have helped to create this agroecological strategy could be included here, but they are represented by Baskaran, Fulford, and Sharif who joined in preparing this paper. We hope that readers will appreciate that SCI, a common-property, open-access innovation, is still under development.

An overview of the agronomics of SCI

Before considering the range of SCI innovations that can contribute to sustainable food and nutrition security with less vulnerability to abiotic and biotic stresses, we give an overview of it that spans its varying manifestations. SCI is an agricultural production strategy that seeks to increase and optimize the benefits that can be derived from making better use of available resources: soil, water, seeds, nutrients, solar radiation, and air. There is always need to consider agricultural options in context, taking full account of the factors and interactions of time and space so that field operations are conducted in a timely way, with land area optimally occupied by crops, and not just by a single crop. It is also important that ecosystem services be considered (Garbach et al., 2017). In this article, we look beyond cropping systems to consider also farming systems in SCI perspective.

Simply stated, SCI principles and practices build upon the productive potentials that derive from plants having larger, more efficient, longer-lived root systems and from their symbiotic relationships with a more abundant, diverse, and active soil biota. It is unfortunate that both roots and soil biota were essentially ignored by the green revolution. In the Indian state of Bihar, SCI was at first referred to as the system of root intensification (Verma, 2013). This designation does not, however, give concurrent credit to the contributions to crop productivity that beneficial soil organisms make. These are equally important and interact synergistically with root systems (Yanni et al., 2001). Through their chemical and physical impacts on soil systems, roots help to sustain an abundance of life in the soil. These organisms, in turn, provide nutrients and protection to the roots and through them to the plant itself.

The main elements of SCI include:

- *Starting with high-quality seeds or seedlings*, well-selected and carefully handled, to establish plants that have vigorous early growth, particularly of their root systems.
- *Providing optimally wide spacing of plants* to minimize competition between plants for available nutrients, water, air, and sunlight. This enables each plant to attain close to its maximum genetic potential.
- *Keeping the topsoil around the plants well-aerated* through appropriate implements or tools so that soil systems can absorb and circulate both air and water. Usually done as part of weeding operations, this practice can stimulate beneficial soil organisms, from earthworms to microbes, at the same time that it reduces weed competition.
- If irrigation facilities are available, these should be used but sparingly, *keeping the soil from becoming waterlogged and thus hypoxic*. A combination of air and water in the soil is critical for plants' growth and health, sustaining both better root systems and a larger soil biota.
- *Amending the soil with organic matter*, as much as possible, to enhance its fertility and structure and to support the soil biota. Soil with high organic content can retain and provide water in the root zone on a more continuous basis, reducing crops' need for irrigation water.
- *Reducing reliance on inorganic fertilizers and pesticides*, and to the extent possible, eliminating them. This will minimize environmental and health hazards and avoid adverse impacts on beneficial soil organisms, which are essential for SCI success.

These elements underscore the interaction between plants and their environment, unlike the green revolution technologies that regarded crops' yield as mostly a result of plants' genetic potentials plus exogenous inputs, rather than as the consequence of inputs which were mostly endogenous to the agroecosystem. The merit of an agroecological approach for achieving more productive phenotypes from given genotypes of rice has been validated through a number of well-designed agronomic studies (e.g. Lin, Zhu, Chen, Cheng, & Uphoff, 2009; Thakur, Rath, Patil, & Kumar, 2011; Thakur, Rath, Roychowdhury, & Uphoff, 2010; Thakur, Uphoff, & Antony, 2010; Zhao et al., 2009) as well as for wheat (Dhar, Barah, Vyas, & Uphoff, 2016).

Even though some of these agroecologically based processes are still not completely understood (e.g. Lehmann & Kleber, 2015; Van der Heijden, de Bruin, Luckerhoff, van Logtestijn, & Schlaeppi, 2016), it is evident that the interactions between crop plants and the soil biota with respect to water and nutrient uptake will be enhanced by having individual plants with expanded root systems and a more active and diverse soil biota (Anas, Thiyagarajan, & Uphoff, 2011; Barison & Uphoff, 2011; Lin et al., 2009; Rupela, Gowda, Wani & Bee 2006; Thakur, Rath, & Mandal, 2013). These positive interactions are complemented by the beneficial effects of symbiotic bacterial and fungal endophytes (Chi et al., 2005; Uphoff, Chi, Dazzo, & Rodriguez, 2013).

From many evaluations of rice, we know that yields from any given variety can be boosted by at least 25–50% by agroecological management, and often the increases are 100% or more. These effects are quite explainable in scientific terms (Thakur, Kassam, Stoop, & Uphoff, 2016). Crops that have better-developed root systems, for example, are less vulnerable to drought and to lodging (being knocked down by wind or rain). They are also generally more resistant to attacks and losses from pests and diseases. In addition to enabling crops to resist the stresses of climate change, there are net reductions in greenhouse gas emissions (Thakur & Uphoff, 2017; Uphoff, 2015). Fortunately, we are finding that these effects can be extended beyond rice.

The following discussion reviews how farmers in a dozen countries have applied the concepts and practices of SRI with appropriate modifications to a variety of crops. Although most such applications began less than a decade ago, they have burgeoned. Table 1 lists crops that are being improved with SCI methods, and where. These developments are widespread. The majority are in India, but also in Afghanistan, Cambodia, Nepal, and Pakistan in Asia; in Ethiopia, Kenya, Malawi, Mali, and Sierra Leone in Africa; and in Cuba in Latin America, with SCI getting started also in the United States.

Initially, it was thought that the methods which succeeded with rice (*Oryza sativa*) would apply only to other crops in the broad botanical family of grasses (*Gramineae* or *Poaceae*), such as wheat, barley, millet, tef, even sugarcane, which are classified as monocotyledons. Such plants have multiple, roughly parallel stalks (or tillers) and thick, bushy root systems, rather than growing with dominant main stems and main (tap) roots from which branching canopies and root systems emerge. However, we have seen that dicotyledonous crop plants such as mustard, legumes, green leafy vegetables, and some spices also respond positively to SCI practices. Thus, the efficacy of these practices is not limited to monocots.

Crop reviews

Most examples of SCI have derived from farmers' innovations in crop-growing methods based on their own

Table 1. Summary of SCI experience and experimentation, by crops and countries.

Crop	Countries where SCI use has started
Finger millet (*Elusine coracana*)	India (Karnataka, Jharkhand, Uttarakhand), Ethiopia (Tigray), Nepal, Malawi
Wheat (*Triticum* spp.)	India (Bihar), Nepal, Afghanistan, Mali, Pakistan (Punjab), Ethiopia (Tigray, Oromia), USA (Maine), Netherlands
Maize (*Zea mays*)	India (Uttarakhand, Assam)
Sugarcane (*Saccharum officinarum*)	India (Maharashtra, Odisha, Uttar Pradesh, Andhra Pradesh), Kenya, Tanzania, Cuba
Tef (*Eragrostis tef*)	Ethiopia (Amhara, Tigray, Oromia)
Mustard (*Brassica juncea* and *B. carinata*)	India (Bihar, Gujarat)
Pulses: cowpea/black-eyed pea (*Vigna unguiculata*), chickpea/garbanzo beans (*Cicer arietinum*); mung bean/green gram (*Vigna radiata*); lentil/black gram (*Vigna mungo*); pigeon pea/red gram (*Cajanus cajun*); common/haricot/kidney bean (*Phaseolus vulgaris*), soy bean (*Glycine max*), groundnut/peanut (*Arachis hypogaea*)	India (Karnataka, Tamil Nadu, Bihar, Uttarakhand), Ethiopia
Vegetables: carrots (*Daucus carota*), eggplant (*Solanum melangina*), onions (*Allium cepa*), potatoes (*Solanum tuberosum*), mallow (*Corchorus olitorius*)	India (Bihar), Pakistan (Punjab), USA (Maine), Sierra Leone, Ethiopia
Spices: coriander (*Coriandrum sativa*), cumin (*Cuminum cyminum*), turmeric (*Curcuma longa*)	India (Gujerat, Tamil Nadu)
Fruit trees	India (Madhya Pradesh), USA (Maine)

Source: Authors' own contribution.

observations and experimentation, usually prompted by their experience with SRI ideas and methods that improve their rice production. Since SCI crops are not grown in irrigated rice paddies as is most SRI rice, the gains that result from farmers' adapting SRI practices to unirrigated crops do not derive primarily from changing soil conditions from being anaerobic (hypoxic) to being aerobic; other mechanisms are involved.

Time and again, farmers have seen improvements in yield, profitability, and resilience when they have extrapolated SRI practices to widely varying crop types, either on their own or with encouragement from civil society, government, or university partners. In this section, we survey the emergence and effects of a range of SCI applications. Full accounts cannot be offered in an article like this, but more details on the various crops and methods are available elsewhere (e.g. Abraham et al., 2014; Araya et al., 2013; Behera et al., 2013; Dash & Pal, 2011; SRI-Rice, 2014; WOTR, 2014). This article covers what is currently known, much of it from our own respective personal involvements with SCI.

*Finger millet (*Eleusine coracana*)*

SCI as a concept and strategy can be said to have begun with farmers' modifications of their usual methods for cultivating finger millet in India and Ethiopia. These farmer initiatives proceeded before SRI ideas and methods for growing rice had become known within their communities.

First initiatives

About 40 years ago, millet farmers in Haveri district of northern Karnataka state of India developed a system of cultivation that they called *guli ragi* ('hole-planted millet') This food crop, traditionally established by broadcasting seed, was giving yields of 1.25–2.5 tonnes/ha, with a maximum of 3.75 tonnes. In *guli ragi* cultivation, young millet seedlings 20–25 days old are transplanted into holes spaced 45 × 45 cm in a square grid pattern, two seedlings per hole. *Guli ragi* includes putting a handful of compost or manure into each hole along with the seedlings to boost soil fertility.

When the plants are established in a square grid, intercultivation between rows is possible in perpendicular directions, not just between rows. An ox-drawn weeding implement that farmers use for this operation functions like a stirrup hoe, breaking up, lifting, and aerating the surface soil as it cuts through the roots of weeds, burying them in the soil as a form of green manure (Uphoff, 2006a).[2]

With these methods which closely parallel SRI methods for rice, farmers have achieved yields of 4.5–5.0 tonnes/ha, and as much as 6.25 tonnes (Green Foundation, 2005). Although *guli ragi* requires more work from farmers, their labour is well repaid. Farmers report that their millet crop acquires more resistance to lodging, especially when traditional varieties are planted; and their crop is less susceptible to pests and diseases, particularly to stem borers and aphids, according to the farmers (Uphoff, 2006a).

In a parallel development, field staff of the Ethiopian non-governmental organization (NGO) Institute for Sustainable Development (ISD) have worked with farmers in Tigray province under the difficult rainfed conditions there. When they tried some experimenting with finger millet in 2003, an elderly woman farmer, Mama Yehanesu, transplanted 30-day seedlings at 25–30 cm spacing, a big departure from farmers' usual broadcasting methods for establishing finger millet which typically gave yields around 1.3 tonnes/ha. With these methods, also applying compost to her small experimental plot, she got an unprecedented yield of 7.6 tonnes/ha, almost triple the 2.8 tonnes yield that she produced that season with her usual methods (which included the application of compost – she was known to be a good and innovative farmer). Neighbouring farmers who saw this effect began using transplanting methods to establish finger millet and subsequently began obtaining usual yields of 4–5 tonnes/ha (Araya et al., 2013). In that woreda (district), about 90% of farmers are now using SCI methods for finger millet, tef, and some other field crops, finding SCI spacing and other ideas to be beneficial.

These two examples of finger millet improvement are reported to begin our review of SCI so that readers can see what large improvements in yield can be obtained from a given variety (genotype) on the same soil and with the same climate just by varying the methods of crop establishment, plant density, soil fertility management, and other practices similar to those used with SRI for rice. By the middle of this century's first decade, what is now called SCI began to emerge as a transnational, trans-crop phenomenon.

India

In 2006, the NGO PRADAN began working with farmers in Jharkhand state to extend SRI ideas and methods to their growing of finger millet. The application of SRI practices to this rainfed crop was seen to have effects similar to those observed for irrigated rice, as seen in Figure 1. The plant on the right is a local variety grown with farmers' usual broadcasting methods. In the centre is an improved variety (A404) raised with the same methods. This difference shows what having an improved genotype can accomplish. However, the plant on the left is the same improved variety when grown with adapted SRI methods: transplanting young seedlings with wide spacing, soil aeration, and enhanced soil organic matter. This contrast showed what improvement is attainable with modifications in crop management. The changes in root system growth shown in Figure 2 help to explain some of the difference in growth and yield. Of particular interest to farmers was that they found that SFMI methods their costs of production per kilogram of grain by 60% (PRADAN/SDTT, 2012).

Researchers at the state agricultural university in Andhra Pradesh (ANGRAU) had previously evaluated the effect that transplanting finger millet seedlings at a young age had on root growth. Two improved varieties were transplanted as seedlings when 10, 15, and 21 days old, respectively, and their roots were compared at 60 days after transplanting. Their results showed that finger millet plants have a root-growth response to the transplanting of young seedlings that parallels what has been observed with rice plants which are cultivated with SRI practices. These results were, however, unfortunately never published (Figure 3).

In Uttarakhand state in the Himalayan foothills, application of SRI ideas and methods to finger millet began in 2007 when the NGO People's Science Institute (PSI) worked with five farmers who transplanted seedlings just 15–20 days old @ 20 × 20 cm spacing. This raised their yield by 33% compared with the same variety grown with their usual methods. The next year, 43 farmers tried SCI finger millet on their small rainfed terraced fields. Their average yield was again 2.4 tonnes/ha, while the average conventional yield that year dropped from 1.8 tonnes/ha to 1.5 tonnes because of less favourable weather, which raised the SCI yield advantage to 60%.

Figure 1. Finger millet plants grown with different methods in Jharkhand state of India, 2006 season. On left is a plant of improved variety (A404) grown with adapted SRI methods, including transplanting of young seedlings; in the centre is a plant of the same improved variety grown with farmers' usual broadcasting methods; on right is a local variety grown with these same traditional broadcasting methods (photo courtesy of B. Abraham).

Figure 2. Comparison of the root systems of finger millet plants grown in Jharkhand state of India; SFMI methods on left, and conventional methods on right (photo courtesy of B. Abraham).

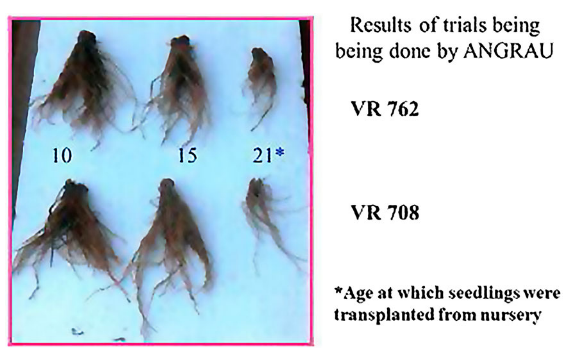

Figure 3. Comparison of root growth in finger millet plants at 60 days after sowing, in 2004–05 *rabi* season trials at Acharya N.G. Ranga Agricultural University in Hyderabad, India (photo courtesy of A. Satyanarayana).

In 2009, a low rainfall year again, the number of farmers using SCI methods grew to 340, and conventional finger millet yields dropped to 1.2 tonnes/ha. SCI yields, however, averaged 2.2 tonnes/ha, raising the yield advantage to 83%. Under drought conditions, the SCI yield declined by only 8%, while conventional millet yields fell by 20–33%, evidence of climate resilience. By 2011, more than 700 farmers in the area were using these new methods. Since 2012, PSI has left it to the farmers themselves to further adapt and upscale SCI on their farms, so no aggregate statistics are available, but the methods have continued to spread (data from PSI records).

In the state of Odisha, application of SCI practices to finger millet started in Koraput district in 2010, promoted by the NGO PRAGATI which works with mostly tribal villages. Initial SCI yields of finger millet were 2.1 tonnes/ha compared with farmers' usual yields of 1.0–1.1 tonnes/ha. By 2013, the number of farmers using the methods described in Adhikari (2016) was up to 143. In 2014, 1,215 farmers used them on 330 ha, with an average yield of 2.25 tonnes/ha. That year, Koraput farmers found that their SCI crop resisted damage from Cyclone Hudbud which hit interior districts of the state. By 2016, 2259 farmers were using finger millet SCI on 545 ha in 119 villages. Improved varieties produced 4.8 tonnes/ha under SCI management, while local varieties gave 4.2 tonnes/ha with these methods. The highest yield recorded that year was 6 tonnes/ha. On fertile soils, finger millet yields with SCI methods have been found to average 4.5–4.7 tonnes/ha, a four-fold increase over farmers' usual yields (Adhikari, 2016).

Nepal

A recent study by researchers at the Institute of Agriculture and Animal Science in Rampur reported the results of controlled trials that evaluated SCI methods for finger millet relative to standard direct-seeded cultivation of this crop and conventional transplanting methods using seedlings 30 days old, rather than 15 days as used in the SCI trials. SCI grain yield was 82% higher than with direct-seeding, and 25% more than transplanting with older seedlings (Bhatta, Subedi, Joshi, & Gurung, 2017).

Malawi

It is reported that in 2015, smallholders here started growing SCI finger millet with encouragement from researchers and NGO support (Ngwira & Banda, 2015). However, we do not have current information on this initiative.

Wheat (Triticum *spp.)*

The system of wheat intensification (SWI) which adapts SRI ideas and methods for rice to the production of wheat has been developed mostly in India, although SWI has been started also in Nepal, Pakistan, Afghanistan, Ethiopia, and Mali with farmer involvement. Yields vary considerably between and within countries because of differences in growing conditions (soil, climate, etc.) as well as seasonal variations; however, this is normal for all crop production.

India

The first SWI results reported were from the Himalayan foothills. In 2006, the PSI based in Dehradun conducted the first trials with modified SRI methods for wheat on its own land. These trials land showed increases of 35–67% in grain yield along with 10–30% more straw biomass. Successful trials were conducted by farmers on their own fields in Uttarakhand and Himachal Pradesh states the next year (Prasad, 2008). Subsequently, PSI extended SWI use also to farmers in Madhya Pradesh. By 2010, about 13,000 farmers were taking advantage of the new methods (Chopra & Sen, 2013). Among the new adopters, SWI yields averaged 3.4 tonnes/ha (range: 2.1–5.6 tonnes), 27% more than their previous yields. In the 2016 *rabi* season, the number of farmers using SWI methods was double that of 2013, and their area under SWI was tripled, which indicated growing confidence in the methods (data from PSI records).

In the state of Bihar, PRADAN started evaluations of SWI in the 2008–2009 season with 415 farmers on trial plots in Gaya and Nalanda districts, with support from the Bihar Rural Livelihood Promotion Society (Jeevika). Landholdings there are very small, just 0.3 ha on average. Initial average yields with SWI methods were 3.6 tonnes/ha, double the yield of 1.6 tonnes/ha that farmers got with their usual methods. The next year, with the support of Jeevika, a World Bank-assisted programme, the number of SWI farmers increased to 25,235, and then to 48,521 in 2010–2011, with SWI yields averaging 4 tonnes/ha (data from PRADAN records; Bhalla, 2010).

SWI practices raised farmers' cost of production per hectare, but their costs per kilogram of grain produced were lower by 28% due to the higher yield. Farmers working with NGO rather than government staff

Figure 4. Adjacent wheat fields planted at the same time in Chandrapura village, Khagaria district, Bihar state, India, in 2012. The SWI wheat field on left matured earlier than the traditionally-managed field on right. SWI crop panicles had already emerged while the crop grown with standard methods was still in its vegetative stage (photo by E. Styger).

guidance made further increases in yield, averaging 4.6 tonnes/ha instead of 2 tonnes/ha (PRADAN, 2012a). Beneficial crop responses to the new methods were easily seen (Figure 4). The Jeevika programme reported that average SWI yield increases in 2012 were 72%, with households' net income/ha from wheat production raised by 86% under SWI (Behera et al., 2013). By 2016, an estimated 500,000 farmers were using SWI methods in Bihar covering about 300,000 ha, with yields of 4–5 tonnes/ha representing an average increase of 60–80%.

In Madhya Pradesh, that state government's rural livelihood mission began introducing SWI to farmers in tribal areas in 2008–2009, starting in Shahdol district. Farmers there traditionally sowed their wheat crop quite densely, using about 175 kg of seed per hectare. With wider plant spacing, the seed rate under SWI was reduced by 95%, to just 7.5 kg/ha while giving a much higher yield. Farmers' usual cultivation methods which required more seeds, inputs, and water gave an average yield of 3.75 tonnes/ha. With SWI methods, yield was roughly doubled, in the range of 6.25–7.5 tonnes/ha. The National Rural Livelihood Program (Govt. of India) New Delhi has subsequently taken up SWI promotion in the states of Chhattisgarh, Gujarat, Jharkhand, Maharashtra, Odisha, and West Bengal in addition to Bihar and Madhya Pradesh, working through the respective state rural livelihood programmes.

Nepal

SWI began to be used here in the terai region bordering India after SRI methods had been successfully introduced there for rice. The first systematic evaluations were conducted on farmers' fields in Kailali and Dadeldhura districts in 2010 (Khadka & Raut, 2012), followed by on-farm and on-station trials in other parts of the country. For SWI in Nepal, instead of broadcasting seeds or line-sowing them, just one or two germinated seeds were planted (dibbled) in each hill with the hills spaced at 20 × 20 cm. Two or three mechanical weedings were done during the season to control weeds and break up the soil. Trials showed that wheat yield was increased by 91–100% with SWI methods.

Experiments carried out in 2014 at the Agricultural Research Station at Dailekh showed that SWI methods resulted in better plant architecture with significantly greater root length, and also more leaf area, higher grain weight, and more filled grains per spike compared to wheat plants grown with either line-sowing or broadcasting. Also, SWI plants were judged to be greener with less senescence and better able to tolerate temperature stress. This was attributed by researchers to the plants' having deeper, better-distributed root systems (Ghimire, 2015).

Afghanistan

In 2011, the UN Food and Agriculture Organization (FAO) included wheat, the main staple of Afghanistan, as part of a national strategy to improve agricultural sector performance. SWI practices were adapted to local conditions, planting wheat in rows using locally made rakes that made parallel furrows, followed by drum seeders that dropped wheat seeds into the furrows with wide spacing. Subsequently, a rotary weeder, made locally, was used to remove weeds and break up the soil surface. Water was provided as necessary, usually just two or three times during the growing season (Baryalai, 2013).

By 2015, over 7000 Afghan farmers from all the major wheat-growing provinces of the country had been trained in these methods using farmer field school methods. Compared with conventional cultivation practices, SWI provides average yield increases of 42%, with farmers' net income/ha increased by 83% because of their lower costs of production. The training methodologies and tools developed by FAO for adapting SWI in Afghanistan are being promoted in a number of other projects in the country. Case studies give details of the impact that SWI can have on the ground in Afghanistan (FAO/IPM, 2014a, 2014b).

Mali

Farmers in the Timbuktu region started trying to improve their production of irrigated rice with SRI methods in 2007, assisted by the international NGO Africare. The next year, at farmers' initiative, trials extrapolating SRI methods to wheat were begun. These trials indicated that direct-seeded SWI gave higher yields than either conventional methods or SWI starting with transplanted seedlings. Further farmer trials in 2009 tested direct-seeding vs. transplanting, the best number of grains per hill when direct-seeding, and different spacings between hills. Other aspects that farmers evaluated included applying organic manure instead of using termite-mound soils as had been done traditionally, and the use of SRI weeders that aerate the soil around plants (Styger & Ibrahim, 2009).

Based on their results from these trials, farmers settled on the practices of direct-seeding with 2 grains/hill spaced at 15×15 cm. This allowed farmers to reduce their seed requirement per ha by 90%, from 100 to 150 kg with traditional broadcasting to 10–12 kg with direct-sown SWI methods. This innovation rewarded farmers with wheat yields often doubled and sometimes even tripled. Over a period of 7 years, while traditional wheat yields in the region have ranged between 1 and 2 tonnes/ha, and 2.4 tonnes/ha was the best yield reached, the *lowest* SWI yields have been 3 tonnes/ha, with some fields producing 5.5 tonnes/ha.

Today, farmers in the pioneer villages are planting all of their wheat area with SWI methods, and neighbouring villages have started to adopt SWI in their own fields. In the 2016/2017 season, it is estimated that about half of the wheat area within a 12-village area was planted with SWI. The spread is probably underestimated because there has been no institutional support or follow-up. Despite considerable security problems and Jihadist occupation of the Timbuktu region in 2012, farmers have persevered with SWI methods to improve their wheat production and food security.

On-station evaluation of SWI methods

SWI was evaluated at the Indian Agricultural Research Institute (IARI) in New Delhi with replicated, controlled trials over two *rabi* (winter) seasons, 2011/2012 and 2012/2013 (Dhar et al., 2016). IARI wheat scientists compared their standard recommended practices (SRPs) with SWI practices based on farmer experience in Bihar state. The trials also evaluated treatments in which the SRP methods were modified by using either SWI water management or SWI spacing, and also evaluating growing wheat on furrow-irrigated raised beds.

On all of the criteria, direct-seeded SWI gave the best performance among the treatments evaluated. (Researchers determined in their first season of trials that transplanted SWI was not as successful as direct-seeding as Malian farmer trials also showed.) In the first season, which had reasonably normal weather conditions, the direct-seeded SWI plots achieved 30% higher yield than the SRP plots. The next season, the weather conditions were adverse with high average temperatures in the first months and then heavy rains during the flowering and grain-filling stages. These conditions contributed to lower wheat yields across much of northern India that year, but SWI's yield advantage increased, to 46%. This showed not only the new methods' superior productivity, but also their greater climate resilience (Dhar et al., 2016).

An economic evaluation of results showed SWI methods giving 35% higher net returns than did the currently promoted SRP. Of particular interest for sustainable agriculture were the differential effects of the practices on soil nutrient levels. Soil testing of the plots before and after each cropping season showed that in SRP plots, the levels of N, P, and K were generally diminished, even though they had been well-supplied with fertilizer during the trials. Conversely, levels of these nutrients were increased in the SWI plots, which received compost, although not all of the respective differences in nutrient levels were significant statistically (Dhar et al., 2016). Still more systematic evaluations like this with controls and replications should done for SWI and other versions of SCI, but it is evident that such research should be undertaken.

Maize (*Zea mays*)

Together with rice and wheat, maize is the third major cereal crop in the world, with about one-third more maize produced and consumed than either rice or wheat. Unfortunately, there have been fewer efforts to apply SRI ideas to improving the production of maize than of rice or wheat.

India

The People's Science Institute in Dehradun has worked with smallholders in Himachal Pradesh, Uttarakhand, and Madhya Pradesh states to improve maize output using adaptations of SCI practice. In the first trials in Himachal Pradesh in 2009, farmers direct-seeded 1–2 seeds per hill, adding compost and other organic matter to the soil, and doing three soil-aerating weedings. Their average yield of 3.5 tonnes/ha was 75% more than is produced with conventional methods, which average 2 tonnes/ha. Trials were laid out to measure the effects of having different spacings between hills. These trials showed best results being obtained by sowing seeds in a grid pattern with 40 × 40 cm spacing. In subsequent years, however, different spacings have been recommended regarding what spacing is optimal because this depends upon soil conditions and upon the maize variety. In Assam state, where maize yields are usually 3.75–4.5 tonnes/ha, farmers' versions of SCI have given yields of 6.0–7.5 tonnes, with spacing as wide as 30 × 60 cm and with their seed rate reduced by 50% (SeSTA, 2015).

Undertaking further adaptations and evaluations of SCI methods to improve maize production, particularly to benefit food-insecure, climate-stressed households, should be a priority for SCI development, given the many millions of households in dozens of countries who depend on this crop for their sustenance and often also for income. Increases in yield have not been as dramatic with maize as with some other crops under SCI management. However, the aggregate impact for people's well-being could probably be greater from making SCI improvements with maize than with any other crop.

Sugarcane (*Saccharum officinarum*)

This crop is not often considered as a major food crop, but in 2015, the total world production of sugarcane, in tons, was 84% higher than that of wheat, 150% more than that of rice, and 163% more than that of wheat (FAO, 2015). When produced with intensified 'modern' management, it is a major consumer of irrigation water and chemical fertilizers. So increasing the productivity of resources devoted to sugarcane production with fewer external inputs and lower cost is important.

India

A Sustainable Sugarcane Initiative (SSI) was launched in 2009 by a joint WWF-ICRISAT programme that was already promoting SRI for rice (Gujja, Loganandhan, Goud, Agarwal, & Dalai, 2009). However, SSI had significant antecedents in the work of Indian researchers in the sugarcane industry over the preceding decades. Their experimentation with propagating sugarcane seedlings from bud chips (small amounts of primordial tissue cut out of the cane) made possible devising a methodology that could scale up SCI applications to large-scale production of this crop. The idea of germinating cane seedlings vegetatively from bud chips for transplanting into main fields, instead of resprouting cane plants from whole lengths of cane laid in the soil, goes back as far as the 1950s. However, this method for crop establishment had been used only experimentally or in demonstrations, not being expanded into widespread practice.

Fortuitously, when Andhra Pradesh farmers who were using SRI methods to grow their rice crop in the mid-2000s started adapting SRI practices for their sugarcane production as well, these initiatives came to the attention of researchers who could assist them in improving the process. Some pioneering farmers had already found that they could boost their output from 40 to 100 tonnes/ha by adapting SRI ideas and methods to their sugarcane production (Uphoff, 2005). Researchers with the Andhra Pradesh state agricultural university (ANGRAU) began working with these farmers to refine this innovation (Bhushan, Uphoff, Suresh, & Reddy, 2009).

The WWF–ICRISAT programme took an interest in improving sugarcane production because prevailing methods using large amounts of water and fertilizer had adverse impacts on water supply and quality as well as on soil health. The programme began experimenting with growing seedlings from bud chips and then transplanting them. This left most of the seed cane available to be crushed to make sugar, greatly cutting farmers' costs of crop establishment. The chips were placed into small cups filled with planting material to grow roots and shoots; after 25 days, healthy seedlings were then transplanted from nurseries into the main field. This SSI technology was well-suited for smallholder operations, but it could also be scaled up for larger, commercial-scale operations.

Most of the elements of SSI are similar to SRI, although the age of seedlings differs because sugarcane plants have different growth dynamics from rice (Gujja, Natarajan, & Uphoff, 2017). Reducing the number of plants/ha by 90% greatly lowers the mortality of the plants, which are no longer overcrowded. This results in more efficient use of the water and nutrients available in the soil. With SSI, there is no flooding of the field, and organic matter is applied as mulch or compost. The resulting canes are heavier and have a somewhat higher content of sugar when crushed, in one analysis calculated to be 2.5% more, a windfall increase.

With SSI, farmers' costs of production/ha are cut by about 30% because there is less need for water and fertilizer as well as for agrochemical protection, since the incidence of pests and diseases in SSI cane fields is less. Systematic evaluation of SSI began in four states of India in 2011 and 2012, documenting yield increases generally about 40%. A major unanticipated benefit was that SSI cane plants because of their larger root systems had higher ratoon yields (the harvest from a second cutting of the canes with no re-planting). This production was often even greater than obtained from the first (planted) crop, with lower production costs. Under conventional management, ratoon-crop yields are usually *lower* than from the first harvest (Gujja et al., 2017). Since 2010, a social-entrepreneurial consulting firm based in Hyderabad, India, AgSRI (http://www.agsri.com/), has been disseminating SSI knowledge among sugarcane producers outside as well as within India.

East Africa

SSI was introduced in Kakamega county of Kenya by AgSri in 2015 in collabouration with West Kenya Sugar Factory Ltd. Cane yields in this region have been somewhat low, averaging 70 tonnes/ha, because the county lies at 1500 m above sea level, and low temperatures at this high altitude slow the growth of cane. In the 2016–2017 season, SSI management boosted yields to 90–100 tonnes/ha on demonstration plots, an increase of 40–50% over traditional methods. SSI methods are also being introduced in neighbouring Tanzania.

Caribbean

The new methods have been introduced in several Cuban sugar cooperatives having learned about Indian and African SSI experience through AgSri. The first coop, in the western end of the island, which planted an experimental plot of 0.9 ha in 2012 using 40-day-old transplanted, single-bud seedlings, got a cane yield of 150 tonnes/ha compared to its usual yield of 60 tonnes/ha. A second cooperative, in the easternmost, dryer part of the country, has planted 600 of its 1114 ha of cane land with wider SSI spacing. The advantages it reports are: being able to incorporate more female workers in the planting operation because the workload is lighter when seedlings are used rather than having to handle long, heavy seed cane; a shortening of the planting period; higher yield, 85–100 tonnes/ha compared to previous yields of 60–75 tonnes; and major reductions in planting material, needing only 2–3 tonnes/ha instead of 8–10 tonnes. Despite such demonstrated advantages, there has not been much evident interest in SSI thus far at the national level in Cuba. AgSri has also done some SSI training in Belize.

*Tef (***Eragrostis tef***)*

Ethiopia

This indigenous crop is the country's most popular grain. By the year 2000, farmers' production of tef lagged so far behind national demand that the high market price for tef put it beyond the reach of many consumers. Sadly, many smallholding producers could not afford to consume their own crop, selling it off for a good price to buy cheaper coarse grains for home consumption. In 2006, the government banned the export of tef flour to curb the further rise of tef prices. The upward price pressure was fuelled in part by tef's becoming regarded as a health food in the US and Europe because of its many desirable nutritional qualities.

In 2008/2009, after learning how SRI ideas and methods were being successfully extrapolated to raise the production of finger millet in India, exploratory trials applying SRI practices and principles to tef showed that SRI methods could be adapted to this crop even though it is extremely fine-grained (Berhe, Gebretsadik, & Uphoff, 2017). Traditionally, the crop has been established by broadcasting with very high plant density, which gives a low yield, just 0.5–1.2 tonnes/ha. When the seeds are sown so densely, the plant roots do not get well-established, making the crop susceptible to lodging, which lowers both the quantity and the quality of the harvest.

First-year trials showed that by transplanting tef seedlings about 25 days old with 20 × 20 cm spacing and enhanced soil organic matter, yields of 3–5 tonnes/ha could be obtained. When certain soil micronutrients (Fe, Zn, and Cu) were applied in addition to N, P, and K, even higher yields could be obtained, 6–8 tonnes/ha (Berhe & Zena, 2009). Further evaluation the next year supported by Oxfam America through a grant to the ISD confirmed these results, and the government of Ethiopia began to take an interest in this methodology, starting its own trials and evaluations in 2010/2011.

Because the government wanted and needed to raise the production of tef quickly and on a very large scale, experiments were undertaken to develop a less labour-intensive version of the system of tef intensification (STI), drilling seeds in rows with wide spacing between them, instead of growing seedlings and transplanting them. This methodology, christened TIRR (**T**ef with **I**mproved seed, **R**educed seed rate, and **R**ow planting), raised tef grain yields by about 70% over usual production levels, with a 90% reduction in seed, needing only 3–5 kg of seed/ha instead of 30–50 kg, and without the increased labour needed for growing seedlings and transplanting them.

TIRR methods like those of STI have induced more vigorous tillering, grain-filling, and grain production as shown in Figure 5. In 2011/2012, the government's Agricultural Transformation Agency (ATA) set a target of having 70,000 farmers start using these new tef methods. But there was a large overshoot as 160,000 farmers used TIRR practices, while 7000 used the more labour-intensive but more productive methods of STI. Trials conducted again the next year showed that large gains in productivity can be achieved when shifting from broadcasting to direct-seeding to transplanting as seen in Figure 6. When seed requirements were reduced by two orders of magnitude, there was almost a tripling of yield.

ATA reported that in 2014/2015, 2.2 million farmers were using TIRR methods, one-third of the total number of tef farmers in Ethiopia, on 1.1 million ha. The average TIRR yields of 2.8 tonnes/ha were 75% higher than produced with traditional methods,

Figure 5. Comparison of tef panicles growing from a single plant: the top panicle was grown with TIRR methods, and the bottom panicle with standard broadcasting methods (photo courtesy of Z. Gebretsadik).

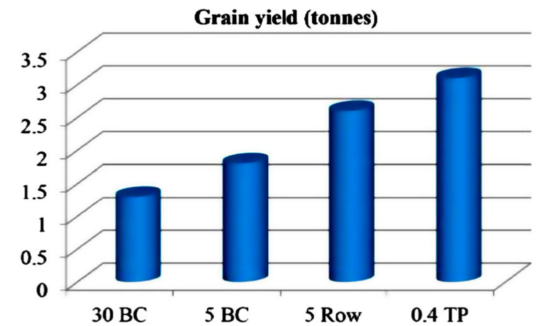

Figure 6. Average tef yields (t/ha) with different planting methods and different seed rates, ranging from 30 kg to 0.4 kg seed/ha, in 2012/2013 season. (a) Broadcasting at 30 kg seed/ha; (b) broadcasting at 5 kg seed/ha; (c) row planting (direct-seeding) at 5 kg seed/ha; and (d) transplanting young seedlings at 0.4 kg seed/ha

(Source: Berhe, 2014).

1.6 tonnes. ATA also found that the yields from traditional methods were rising nationally, at least in part because Ethiopian farmers were coming to understand that they could get more production by lowering their seeding rates. Nationally, the production of tef grain has risen from 3 million tonnes in 2008/2009 when SCI experimentation started to 4.7 million tonnes in 2014/2015 (ATA, 2016). In 2015/2016, most farmers' planting of tef was constrained by a serious drought resulting from El Niño, but the spread and performance of TIRR and STI have continued. Over time, Ethiopian farmers may use the more labour-intensive methods of STI because they raise both land and labour productivity; but for now, the less labour-demanding methods of TIRR are preferred (Abraha, Shimelis, Laing, & Assefa, 2017).

*Mustard (***Brassica juncea** *and* **B. carinata***)*

This crop has tiny seeds much like tef, but it is used as an oilseed rather than as a cereal (or it can be processed to extract an essential oil for cosmetic or other uses). Mustard is an important crop in many parts of South Asia where mustard oil is a preferred cooking oil, on a par with soya oil and peanut oil. That mustard plants can be grown with low rainfall and on poor soils makes this an important crop for many smallholders.

India

The oilseed yields from mustard plants grown here by broadcasting methods are usually only about 1 tonne/ha, or less. Since production is less than market demand, imports impose a substantial drain on foreign exchange. With SCI management, farmers find that their mustard yields average 3 tonnes/ha and can even reach 5 tonnes or more (Times of India, 2017). Young seedlings when just 8–12 days old are transplanted into pits dug about 20–25 cm deep and 15 cm in diameter, which are refilled with soil that has been made loose for good root growth. The recommended spacing of hills depends on the duration of the variety planted. Varieties that mature in <100 days are best spaced 30 × 30 cm, using about 600 g of seed/ha, while mustard varieties that mature in 130–150 days should be spaced 75 × 75 cm, which requires less than 200 g of seed/ha (PRADAN, 2012b).

As with tef, seed rates reduced by >95% give farmers much higher yields. The soil in the pits is enriched with compost, preferably vermicompost, and yields can be boosted by applying also some biofertilizer, e.g. Trichoderma, and small amounts of inorganic fertilizer. At ~60 days after transplanting, the soil around the plants is broken up with a hoe or spade while also eliminating weeds. While such intensification of crop management increases the costs of production, the higher yield cuts by half farmers' costs per kilogram of mustard seed produced, which makes their additional labour profitable.

SCI introduction with mustard began in 2009–2010 in Gaya district of Bihar state with seven women farmers. Within two years, their number had expanded to 1600, and a manual was prepared on the agronomic practices and economics of SMI (PRADAN, 2012b). Farmers working with the PSI in Uttarakhand and Madhya Pradesh states have had average yield increases of 40% with reduced cost of production per kilogram. In 2015, 23 farmers in Madhya Pradesh tried grid-spacing mustard with very wide distance between rows (1 m). With an improved variety of mustard (RP09, *Brassica carinata*), their average yield was 2.73 tonnes/ha (range: 1.8–3.3 tonnes/ha). In the 2016 *rabi* season, the number of farmers in these villages who were using SCI methods for mustard tripled, with more than a 10× increase in area, showing farmers' interest in the new methods. There has been experimentation with SCI mustard and area expansion in other Indian states as well (Times of India, 2017).

Pulses

The productivity of pulses, also referred to as legumes, has been demonstrably improved by promoting the vigorous early growth of plants, starting with properly selected seed, and making special efforts to stimulate the growth of plants' roots. The density of plant populations is greatly reduced through wider spacing between plants, while the organic matter in the soil is enhanced. Efforts are made to keep the soil (at least its surface) well-aerated while controlling weeds. These practices encourage both root growth and more active soil biota. Specific pulse crops whose performance has been improved with SCI methods were listed in Table 1. Here, we give some reported results from India as examples.

India

Work with SCI ideas to improve pulse production in this country started in Uttarakhand state in 2007 at the initiative of the PSI. The basic approach for pulse SCI has been to plant just one or two seeds in hills that are spaced widely in a square or rectangular grid pattern. Soil fertility is enhanced by amendments of organic matter, and there is active soil aeration to promote root growth and stimulate the life in the soil. Direct-seeding has usually proved better than transplanting, but the method of crop establishment should be tested to see which is more suitable for a given legume in a certain location.

PSI has found that SCI yield increases across seven kinds of pulses average about 45%, with much lower seed requirements and, perhaps more important, with less loss from either water stress or water excess. The seeds are often treated before sowing with some combination of cow urine, jaggery (unrefined sugar), trichoderma, phosphate-solubilizing bacteria, and rhizobium culture to inhibit plant diseases and to promote more biological activity in the seed, plant, and soil.

There have been no resources or institutional support for concerted promotion of SCI for pulse crops in India, so the spread has been mostly opportunistic, often rapid locally but slow overall. Demonstrating the advantages of SCI practices with pulses has usually started with farmer or NGO initiative (e.g. AMEF, 2012; Bhatt, 2014; Shankar, 2014), although SCI modifications in pulse-growing are also being accepted by some government agencies (e.g. Ganesan, 2013; KVK 2014).

The Bihar state poverty-reduction programme reported that in 2012, SCI methods were raising pulse yields there on average by 56% for 41,645 resource-limited households which used the methods on 15,590 ha that year. Because of their lower costs of production, households' net incomes from pulse-growing increased by 67% (Behera et al., 2013). While the application of SCI ideas and methods for improving pulse production is not as advanced as SRI for rice or SWI for wheat, these methods are spreading, whether or not designated as 'SCI'.

Vegetables

The extrapolation of SCI ideas and methods to vegetables has been more diffuse than other kinds of SCI because vegetables are such a diverse category. Here are reports from several countries.

India

The Bihar poverty-reduction programme cited in the preceding section on pulse SCI reported that also in 2012, over 60,000 households were using SCI methods to improve their growing of tomatoes, eggplants (also known as aubergine or *brinjal*), and other vegetable crops on 5244 ha. (Poor households in Bihar have very small areas for growing vegetables.) Their average increase in yield was 20%, but their net income/hectare was 47% greater given their lower costs of production (Behera et al., 2013).

In the state of Odisha, an NGO which started introducing SRI methods for rice in that state, Udayama, has reported that farmers got doubled yield of eggplant when they adapted SRI concepts and methods for this vegetable. The top SCI yields are 50% higher than the previously reported maximum for eggplant. Wider spacing, organic fertilization, and other management changes resulted in plants that have many more blossoms and more and bigger fruits (Dash & Pal, 2011). This publication reported on SCI for several other vegetables in addition to eggplants (pp. 24–27).

Pakistan

At the other end of the spectrum from smallholder farming, SCI ideas have been adapted for use in highly mechanized vegetable production under large-scale operations in the Punjab province (Sharif, 2011; SRI-Rice, 2014, pp. 52–57). Similar kinds of productivity and income gains are reported for potatoes, onions, and other crops using this capital-intensive production system. Data are reported in Table 2 below in the section on broader adaptations of SCI.

USA

An organic farmer in the state of Maine who has taken up SCI methods for his diversified cropping has found them quite versatile. Along with other crops, carrot production has responded well to SCI methods. From a 25-m long raised bed (38 m^2) that was cultivated using SCI ideas and methods adapted to vegetable production, there was a harvest of 109.5 kg of Grade A carrots, seen in Figure 7 (Fulford, 2014). This yield was equivalent to 73 tonnes/ha, 3.3 times more than a typical yield from this variety (Cordoba). All but 12% of the harvest could be marketed as Grade A as there was little damage from rodents or deer, and no wireworms or carrot fly maggots. The crop also had virtually no disease and could be sold for what would be $170,000 on a per-hectare basis. The 2016 season carrot crop gave similar results, but with a different variety having better flavour and uniformity. These methods have been adapted also to beets, parsnips, turnips, and daikon (winter radish).

Sierra Leone

A very different kind of vegetable production can make use of SCI ideas and methods to improve the output of a green leafy vegetable in West Africa known locally as *krain krain*. This vegetable, more generally known as mallow (with the scientific name *Corchorus olitorius*), is widely grown and consumed in Sierra Leone and other countries in the region.

This adaptation of SCI practices starts with the transplanting of young seedlings (8–15 days old) rather than by broadcasting, greatly reducing seed requirements. Plants are widely spaced at 20 × 20 cm, and farmers enhance their soil with organic matter. Weeding that earths up around the plants and actively aerates the soil between the plants is done every 7 days to promote better growth (Aruna, 2016).

Krain krain plants grown this way can give two harvests instead of just one because their larger root systems enable them to produce a significant ratoon (regrowth) crop. Moreover, by harvesting seed from their second crop, farmers no longer need to buy seeds. Purchasing seeds is necessary when *krain krain* is grown conventionally because such plants are harvested by removing them from the garden before there is any seed-set.

While intensified SKKI management requires about 40% more labour per hectare, the greater yield that is attained from a single transplanting more than repays the increased effort. With their usual practices, farmers collect about 300 g of *krain krain* leaves from the 250 to 350 plants that grow unevenly and densely on a

(a) (b)

Figure 7. SCI carrot bed, on left, and harvest, on right, at Teltane Farm, Monroe, Maine, USA, 2014 (Source: Fulford, 2014).

broadcasted square metre of land. This is a yield equivalent to 3 tonnes/ha.

Under SKKI management, on the other hand, farmers can gather 700 g of leaves from their first harvesting of the 25 plants that grow on a square metre, which is equivalent to a 7 tonnes/ha yield. Then, because these plants have larger, deeper root systems and continue to put out more leaves, farmers can harvest another 3 kg per square metre. This represents an additional yield of 30 tonnes/ha, quite unprecedented.

Although a third harvesting period would be possible from SKKI plants, collecting seed after a second period of leaf collection is more valuable to farmers and thus preferred. The seeds harvested from these plants are more robust and have a 90% germination rate, a benefit not included in financial calculations of yield.

Farmers find that plants grown with SKKI methods are more resistance to pest damage, even from grasshoppers, as leaf damage is quickly repaired by plants that have good root systems. Also, when an SKKI crop was grown during the season between the rains, it showed reasonable drought-resistance. Harvesting could be done twice, and the seeds harvested during the dry season needed little additional water.

This productive potential has always existed within *krain krain* plants. But it was not realized due to the conditions under which they were being cultivated, particularly with dense sowing. It was knowledge of SRI and SCI practices that encouraged this experimentation with *krain krain*. These examples of horticultural improvement on three continents should encourage SCI applications and extrapolations for more cost-effective vegetable production in many other countries and with diverse crops.

Spices

That SCI ideas and methods have been extrapolated to spice crops helps us understand the mechanisms and the potentials of this strategy for dealing with food and nutrition insecurity, with farmers in a leading role. Similar to the SCI experience with vegetable cultivation, farmers in several states of India, once they became acquainted with SRI ideas and methods through their rice cropping, have begun adapting these to their spice crops.

Turmeric

The first initiative that we know of was in Tamil Nadu state of India, where members of the Thumbal SRI Farmers Association in Salem district developed an SCI methodology for growing turmeric (*Cucurma longa*) starting in 2009. This has been presented in a manual prepared by the Association's founder and president (Baskaran, 2012).

The methods employed are similar to those developed for sugarcane. Instead of planting whole rhizomes or parts of rhizomes in the field, turmeric plants are grown from seedlings that were started in nurseries from small cuttings of rhizome. These are grown in cups filled with planting material and vermicompost, with some biofertilizer enhancement added. This method reduces by 80% the amount of planting material needed to grow turmeric, which gave farmers an immediate saving.

The seedlings were transplanted into the field at 40–45 days, preferably onto raised beds with furrow irrigation, at wide spacing of 30 × 40 cm. Irrigation can be reduced by about two-thirds. The rhizomes that result from such cultivation have more primary and secondary fingers. While the yield increase is only 25%, farmers' costs of production are reduced by USD 825/ha, even taking their additional labour into account. The resulting increase in farmers' net income is almost USD 1000/ha (Baskaran, 2012).

Cumin

In Gujarat state of India, farmers working with the Aga Khan Rural Support Project have adapted SCI concepts and methods to their production of spices. In an initial trial where cumin seeds were planted with wide and regular spacing, instead of being broadcasted, farmers' seed cost was reduced by 95%, with higher yield. A traditional organic fertilizer concoction made from diverse local materials was sprayed on the crop in the field every 15 days. Even with the much wider spacing between plants (30 × 30 cm), plant biomass per square meter was increased by 40% (Singh, 2015a). Seeds per plant were increased by 125%, while seed weight went up by as much as 50%. The yield of cumin seed under SCI management was 65% higher than from the farmer's control plot, and 83% above India's national average yield for cumin seed. With total costs of production cut by 80% compared to current practice which is heavily dependent on purchased inputs, farmers' resulting net income per unit area is increased by 150% (Singh, 2015a).

Coriander

The gains from SCI management of this spice when first tried in Gujarat were not as great as with cumin, but still non-trivial. Coriander seeds, instead of being broadcast, were sown in rows widely spaced, 50 cm. During the season, within-row spacing between plants was progressively increased by uprooting and removing some of the plants within the rows as they grew, thereby giving the remaining plants more room to grow. The young green leaves harvested by this thinning operation were sold for a good price in local markets, adding to the farmer's income from the crop.

This methodology, with a 50% reduction in the seed rate, gave a 10% increase in yield and a 16% increase in seed weight. The increase in net income justified the additional management effort invested (Singh, 2015b). This was a first attempt to adapt SCI methods to coriander, which may or may not be amenable to making greater gains in production by introducing further SCI modifications of conventional practice.

Spices are not as central to food security objectives as are cereals and many other crops, but they are a more important source of income for households than is often recognized. Spice growing and marketing tend to be handled by women. Cultivating spices can add to the incomes of food-insecure households, especially female-headed ones, and enhanced climate resilience will be important for maintaining household incomes. We anticipate that further SCI experimentation and adaptation will be seen for spice crops.

Fruit crops

It was not initially considered that SRI methods could be extrapolated from annual crops to perennials. But there have been experiments made by farmers in the United States and India extrapolating SCI principles to orchard production. The productivity of fruit trees is greatly affected by soil qualities beyond those that are measured in conventional soil testing, and also by factors of timing and spacing of operations such as fertilization, planting, and pruning. Colleagues have found their synchronization of orchard operations with critical stages of tree growth to have analogues in SCI theory and practice.

USA

Experience with organic orchard management has underscored that fruit trees' performance is greatly affected by biological factors such as the ratio of fungal-to-bacterial microbes and the extent of mycorrhizal-fungal biomass associated with tree roots. Biological activity has effects that go beyond the direct supply of nutrients in the soil, affecting also the availability and uptake of nutrients. Close spacing, for example, leads to the loss of lower limbs of trees that are placed in competition with each other. Also, various disease problems are aggravated by close spacing. Cutting out half of the trees in an orchard that has been planted too densely can lead to gains in tree health with no loss of production. Moreover, when trees grow so that their limbs touch, there is a plateauing of production as this proximity hampers both photosynthesis and airflow, and their respective root systems become intermeshed.

Application of inorganic N fertilizer leads to rapid, unstable vegetative growth in perennial plants much as with annuals. 'Forced-feeding' of trees to increase their production beyond the trees' growth and maintenance needs does not lead to higher yield or better fruit quality. Also, pruning in orchards more than once during the year, during the dormant and early fruit-sizing stages, is quite beneficial as it facilitates sunlight penetration while diverting energy reserves from vegetative growth into already-developing fruit production as well as into future fruit-bud formation.

Maintaining plant diversity on the orchard floor supports larger, more diverse populations of insect pollinators and beneficial predators that help to keep tree pests in check. This whole set of practices reduces the need for spraying of crop-protection products, thereby reducing labour and input costs. These observations, based inductively on orchard management experience, became more comprehensible once becoming acquainted with the principles of SRI and SCI (Mark Fulford, personal communication).

Extrapolating SCI methods to perennial crops, emphasizing root growth, nurturing symbiotic associations with non-plant organisms, and appreciating the ecological interactions of diverse species, means that external inputs of water and nutrients can be reduced. This makes for less cost and less effort. Dry weather has now less adverse effects on production than previously. In the 2016 season when there was a prolonged drought in Maine, the Fulford orchard surpassed its previous yields and quality by wide margins. A single Hudson Golden Gem tree produced 340 kg of top-quality fruit, bringing in almost USD 2000 in income, by itself enough to pay the farm's local taxes.

Unsaleable fruit was converted into juice; the leftover pulp was used as animal feed, and prunings were chipped and composted, thereby achieving zero-waste orchard economics. Even as weather conditions have become harsher, tree crops are measurably more resilient to drought, frost, downpours and wind, and there is no soil erosion. Shelf-life and lasting flavour of these perishable crops has been enhanced, with a cull rate for discarding poor-quality fruit lower than in previous seasons. These factors all affect a farmer's 'bottom line' and enhance operations' profitability.

India

In Madhya Pradesh, that state's poverty-reduction programme which promotes SRI and SWI has also experimented with SCI ideas to improve fruit production in poor villages. One focus has been tree-planting in Shahdol district. SCI ideas that inform the planting and management of these trees include careful attention to seedling roots, wide spacing, enhancement of root zones with organic matter (compost), and surface mulching to conserve soil moisture and keep soil temperatures from rising in the hot summer sun. Within fields where SRI rice and SWI wheat are grown in the summer and winter seasons, respectively, farmers are establishing and maintaining fruit crops – mango, guava, pomegranate, banana, and papaya – in conjunction with their cereal cropping, to intensify their farming systems.

Farmers with SCI experience avoid crowding of trees and enrich the soil around trees' roots organically to promote root growth. With traditional methods of fruit cropping in Sagar district of Madhya Pradesh, farmers' yields of mango are usually 3.7–4.3 tonnes/ha, for example. About 45 villages in this district have now established one-acre demonstration plots for fruit-tree SCI. Their yields are already about 50% higher than they were previously, adding USD 15 per month to their income. This monthly increase is expected to become USD 45–50 when the trees become more mature (Anoop Tiwari, personal communication).

Promotion of root growth and building up the soil biota is thus proving positive for the husbandry of fruit trees as well as of crops. This represents an evolution beyond SCI as a *cropping system* to more integrated resource management which intensifies *farming systems* and makes them more productive and sustainable, as discussed in the following section.

These reports on SCI applications to orchard crops are necessarily more tentative than reports in the preceding sections about applications to field and garden crops. We offer these emerging ideas and experience with the hope that they will stimulate others' imagination and practice to move orchard management in more agroecological directions for greater production, food security, and climate resilience. As we have said already, many of the data sets that we

Table 2. Effects of SCI practices on yield across eight crops in seven countries.

Crop	Country (state, province or district)	Comparison yield (t/ha)	SCI yield (t/ha)	Comments	Source
Finger millet	India (Karnataka)	1.25–2.5 (3.75 max)	4.5–5.0 (6.25 max)	Indigenous farmer-developed system of cultivation (*Guli Ragi*)	Farmer information (Uphoff, 2006a)
	Ethiopia (Tigray)	1.3	4.0–5.0	SCI methods developed before any knowledge of SCI	ISD data (Araya et al., 2013)
	India (Uttarakhand)	1.5–1.8	2.4	Evidence of climate resilience	PSI data
	India (Odisha)	1.0–1.1	2.1–2.25	Evidence of climate resilience; 2013: 143 farmers; 2016: 2259	PRAGATI data (Adhikari, 2016)
Wheat	India (Bihar)	2.0	4.6	2008/09: 278 farmers; 2015/2016: ~500,00 farmers (300,000 ha)	PRADAN/PRAN data (Verma, 2013)
		2.25	3.87	86% increase in income/ha	Jeevika data (Behera et al., 2013)
	Nepal (Khailali and Dadeldhura)	3.4	6.5	Replicated trials, average for upland and lowland yields	Khadka and Raut (2012)
	Afghanistan	3.0	4.2	Farmer results under national FAO programme	FAO IPM programme data (Kabir communication)
	Mali (Timbuktu)	1.0–2.0	3.0–5.0	Farmer trials under Africare	Styger and Ibrahim (2009)
	India (IARI research)	5.42 (SRP)	7.44	Two years of experimental results at IARI, New Delhi	Dhar et al. (2016)
Maize	India (Him. Pradesh)	2.8	3.5	On-farm trials	PSI data
	India (Assam)	3.75–4.0	6.0–7.5	On-farm trials	SeSTA (2015)
Sugarcane	India (Telangana)	80	99.5	On-farm trials	AgSri data (Gujja et al., 2017)
	India (Odisha)	60–70	119	On-farm trials	
	India (Maharashtra)	70	96	On-farm trials	
	India (Uttar Pradesh)	61 [59]	68 [71]	On-farm trials [ratoon harvest]	
	Kenya (Kakamega)	70	90–100	On-farm trials	AgSri data (Gujja et al., 2017)
	Cuba	60–75	85–100	Modified SSI on-farm trials	R. Perez (personal communication)
Tef	Ethiopia	1.6	2.8 (TIRR) 3.0–5.0 (STI)	Estimated TIRR area in 2016 was 1.1 million ha	ATA (2016)
Mustard	India (Bihar)	1.0	3.0 4.0 (full use)	On-farm production	PRADAN (2012b)
	India (Mad. Pradesh)	1.2	2.73 (1.8–3.3)	On-farm trials	PSI data
Pulses	India (HP/UKD/MP)	46% average increase across seven pulses			PSI data
	India (Bihar)	56% increase across different pulses (15,590 households)			Behera et al. (2013)
Vegetables	India (Bihar)	20% average increase in yield; 47% increase in net income/ha			Behera et al. (2013)

are able to report at this stage are not very large, indeed often not very deep in time. But they show impacts substantial enough that we think they warrant investigation and initial field trials.

To give an overview of the yield effects of these changes in management, we have summarized in Table 2 the data reported above that we think are supported with methods and measurements solid and extensive enough that they should be taken seriously even by sceptical readers. Time and further assessments will determine how broadly applicable these modifications in crop management can be for meeting the conditions and needs of twenty-first century sustainable agriculture.

Broader integrative adaptations

The preceding section has reported on modifications made in agronomic management which raise the productivity of the respective crops reviewed. These changes offer specific opportunities to raise food production in ways that are relatively more resilient to the adverse impacts of climate change. But food and nutrition security depends on more than on the growing of particular crops. It is affected by whole farming systems, including multiple crops and livestock as well as possibly aquaculture and forest products. As knowledge has spread of the productivity gains accessible from SCI's agroecological adaptations, there have been also farming-system innovations to be considered.

Multiple cropping and intercropping

Ethiopia

As noted in the section above on finger millet, some of the first SCI stirrings occurred in this country where the ISD was working with smallholder farmers in unreliably rainfed areas. Starting crops from seedlings, rather than from seed, and planting them with wider spacing in soil that has been enhanced with compost were promoted by ISD staff among farmers and local extension officers in Tigray province and other parts of Ethiopia. This was before they had any knowledge of the SCI experiences that were beginning also in India about the same time. As knowledge has been shared back and forth, a concerted effort was made to extend these ideas and methods to a variety of crops, cereals, legumes, and vegetables. Ethiopian farmers themselves have named this new methodology for crop management as 'planting with space', a concept easier to grasp and communicate than is the more abstract term 'intensification' (Araya et al., 2013).

A key element of agroecological thinking and practice is to consider the effects of complementarities between and among different crops, e.g. their various heights and above-ground architecture as well as their differing rooting depths and conformations underground. Farmers working with ISD have experimented with different combinations and layouts of cereal, legume, and vegetable crops to capitalize more fully upon sunlight and upon both water and nutrients in the soil. With more space, individual plants grow better, but also farmers find that intercropping several plant species together helps all perform better if they complement each other.

Intercropping can benefit crop plants in several ways, by covering the ground between them, inhibiting weeds, and helping to retain soil moisture. The latter is especially important in water-stressed areas and seasons. Furthermore, intercropping helps families with limited landholdings to generate more income and to have a better distribution of food, nutrition, and income throughout the year, particularly through relay cropping in which crops are grown in overlapping sequences. So long as organic matter is returned to the soil through crop residues and by applications of manure and compost, and provided that the soil is kept well-protected by mulching, repeated and continuous use of soil seldom degrades its quality.[3]

Recall that bringing in intercropping to intensify farming systems has been an important feature of the SSI discussed above. The wider spacing which raises sugarcane crops' productivity also creates more space between rows and plants which can be utilized for shorter-duration crops that provide both nutritional and income benefits. Intercropping with legumes has the added benefit of improving soil fertility through nitrogen fixation in the soil. Given that much sugarcane in Asia and Africa is grown under monocultural outgrower schemes, the introduction of wider spacing between sugarcane plants and rows has particular relevance for the food security and nutritional intake of farming households in such schemes. Intercropping is also a practical strategy for adapting to climate change by diversifying income and nutrition.

India

Farmers working with the PSI in northern India have pioneered SCI innovation with various crops as seen in the sections above on finger millet, wheat, maize, pulses, and vegetables. At the same time, they have been trying to optimize their use of land, labour, seed, water, and capital by making various modifications in their farming systems. Although the per-hectare costs of SCI usually exceed those of conventional practice because of the need for additional labour for careful seeding and doing regular weeding, the benefit–cost ratio with SCI still works out to be about 50% higher because of increases in total yield (calculated from PSI data). This is often accompanied by improved quality of the product.

In 2013, some trials with intercropping were undertaken by farmers of Uttarakhand state who sowed wheat seeds at 20×20 cm spacing, and in part of the same plot, every third row of wheat was replaced by a row of mustard, sown after the wheat plants had gotten established, maintaining the same plant-to-plant spacing (20 cm). Monocropped SWI gave an average wheat yield of 5.15 tonnes/ha (range 4.3–6.0 tonnes), while SCI intercropping of wheat and mustard gave respective average yields of 4.63 and 0.32 tonnes/ha. The value of produce from the SWI alone amounted to USD 790/ha; SCI wheat-mustard intercropping gave a combined value of USD 850/ha, raising farmers' income by 7%. The additional labour required was not valued in this calculation as this was unpaid household labour, so the economics of this might not be commercially profitable. However, for households with very limited land availability and with urgent nutritional needs, this increment was worth the extra labour invested.

Additional trials undertaken with SCI intercropping have included combining long- and short- duration pulses in Madhya Pradesh, and mixing maize with ground crops such as ginger in Himachal Pradesh. These trials have indicated that intercropping with adapted SCI methods can not only achieve greater value of produce per unit of land, but also gives more resilience to climate vagaries such as droughts, early withdrawal of rains, and excessive rain, which increases farmers' capacity to cope with risks. Much more experimentation and evaluation remain to be done, but a next step for SCI development is to move beyond monocropping.

Diversification integrated with pond culture

Some of the farmers and organizations working with SRI and SCI have found that they can increase their land and water productivity as well as the profitability and nutritional value of their farming operations by bringing in aquaculture along with their horticultural and grain production.

Cambodia

Hundreds of farmers here, once they learned how to raise the productivity of their rainfed rice area through SRI practices, have begun redeploying a portion of their land and labour to growing crops other than rice. This diversification of farming systems has raised total food production as well as income. In what is being called 'multi-purpose farming' (MPF), pioneered by the NGO CEDAC, Cambodian farmers have found it advantageous to take about 40% of the rainfed land area out of rice production in order to construct a catchment pond on about 15% of their farm area (Lim, 2007). This has similarities to the '5% model' developed in eastern India by the NGO PRADAN for the same purposes (Pangare, 2003).

The ponds that farmers build capture rainwater during the rainy season for use after the rains stop. On the land taken out of rice production and reassigned to other activities, they grow fruits, vegetables, and spices and raise small livestock such as pigs, chickens, and ducks. Their ponds are stocked with fish, and sometimes also with frogs and eels for additional income. These aquatic crops thrive in association with the agrochemical-free rice cropping which SRI farmers follow and are quite profitable. The ponds contribute to higher rice yields because they drain water off the rice paddies during rainy-season flooding, and then provide the rice crop with supplemental water during the subsequent dryer months.

Since these farmers have only about 1 ha of cultivable land, their production has to be intensive to support their households. Within four years of CEDAC's starting MPF, about 400 farmers in five provinces had redesigned their farming operations to capitalize on the higher land and water productivity that SRI was giving them. This enabled them to meet their staple food needs while diversifying their production. Economic and spatial details of five MPF farming systems are reported and analysed in Lim (2007). These farms, whose average size is 0.66 ha, were already generating added annual net income flows of USD350 with an average investment of USD305. Recouping the cost of such investment in a year makes this a very attractive investment.[4]

A study by Tong and Diepart (2015) reported on how 2400 households have taken up this kind of intensification in half a dozen provinces once other NGOs in addition to CEDAC began promoting MPF. By raising rice yields, SRI methods make it feasible for households to redeploy some of the rice area. The study showed that households could increase their net income from the same land area by about two-thirds. The investment cost of about USD 830 for a 1-ha farm can be recouped within 2–3 years, a very high rate of return. Since most of the changes can be made incrementally, households by stretching their investment over several years do not need to take out loans and incur indebtedness.

At first, the farmers were satisfied to continue growing fruits, vegetables, and spices with their familiar methods; but the same principles that boosted their rice productivity can be adapted in SCI ways to raise also the productivity of their other crops. The water stored in the pond can support their horticultural crops as well as their rice crop in the event of drought stress. By generating more value-added, this intensification also creates employment opportunities at the local level while improving the diversity and nutritional quality of family diets.

On-station evaluation of this farming system in India

This kind of intensified multi-crop farming system combined with pond culture has been evaluated with two years of replicated on-station trials at the ICAR-Indian Institute for Water Management in Bhubaneswar. Details are given in Thakur, Mohanty, Singh, and Patil (2015). It was found that simply using rainfed SRI vs. conventional rainfed rice production methods improved rice yield by 53%, with documentation of significant phenotypical changes in the rice plants. Both economic profitability and water productivity were increased by even more when using SRI methods for producing rice. However, still greater agronomic, economic, and hydrological benefits resulted from converting 13% of the rainfed paddy area into a catchment pond, stocked with carp, and using an equal amount of land area to create sloping bunds around the pond for the harvesting of rainwater. This catchment area was planted with fruit crops (bananas and papayas).

On an area basis, the per-hectare cost of managing this more intensified farming system with rice, aquaculture, and horticulture was four times greater than for conventional rainfed rice production. However, this intensified system magnified the productivity of water (the main constraining resource in the region), i.e. it multiplied the net income per unit of rainfall, by more than 50-fold (Thakur et al., 2015).

The Cambodian farming systems reported on above were more complex and more integrated than these trials evaluated in India, and therefore are more difficult to evaluate in rigorous, replicated trials. But these Indian trials, meeting rigorous scientific criteria, confirmed the greater productivity of such farming systems.

Moreover, because the second year's trials had to be conducted during a water-stressed season, this Indian evaluation also showed that the crops raised with SRI/SCI methods were more resilient and relatively more productive under adverse climatic conditions than were crops conventionally grown (Thakur et al., 2015). This gave evidence of climate resilience which is becoming a more important consideration. Some of the ecological synergies that are involved in such systems' productivity have been analysed in Indonesian trials reported by Khumairoh, Groot, and Lantinga (2012).

Mechanized, large-scale SCI

Probably, the main constraint on using SCI methods has been that they generally require more labour per hectare because in SCI implementation, plants are handled and managed more carefully and proactively. Also, soil, water, and nutrient resources are utilized with more precision. Requiring more labour can be a barrier to adoption of SCI, e.g. in greatly labour-constrained areas such as those affected by HIV. But even when labour is a constraint, it should be considered whether or not SCI can increase the productivity of farmers' labour, and whether SCI methods can enable farmers to produce more output per hour or day of work invested.

SCI has been found almost always to raise the productivity of farmers' labour. But a further consideration is: whether farmers' labour requirements under SCI can be reduced by mechanizing certain operations, using implements and machines that are appropriate for SCI. There can be a considerable degree of mechanization if farmers can afford this. What is most required for this, apart from capital, is the availability of appropriately designed machinery and implements.

Pakistan

In Punjab province, labour is a serious constraint for most agricultural production due to outmigration from rural areas. The high cost and limited availability of labour which presented an obstacle to the utilization of SRI practices for growing rice led to devising a highly mechanized version of SRI for rice production (Sharif, 2011). By combining the ideas of SRI with those of organic agriculture and conservation agriculture (CA), discussed in the next section, a hybrid technology was forged which is being called 'Paradoxical Agriculture' (PA). Why this designation? Because the methodology enables farmers to get *more output with reduced inputs*, including less labour.[5]

Initially, this mechanized version of SRI was applied just to rice production, but it is now being used for many other crops grown on permanent raised beds with no-till cultivation, mulch covering, and furrow irrigation. The machinery, principles, and practices have been adapted for successfully growing wheat, maize, potatoes, sugarcane, mung bean, carrots, onions, garlic, melons, cucumber, tomatoes, chillies, and sunflower, preferably in some rotation as is advised for CA.

At present, mechanized versions of SCI use some inorganic fertilization, seeking to transition over time to fully organic crop management. It is understood that where soils have been plied with inorganic fertilizers for many years, it takes some time to restore and build up the beneficial soil biota which contribute to SCI success. Depending on the crop, SCI establishes plants by transplanting young seedlings or by direct-seeding, all with optimally wide spacing. Machinery has been especially designed or modified to carry out the requisite operations (http://www.pedaver.com/) (Figure 8).

This particular methodology for mechanized production of cereals, pulses, and vegetables using the principles of SCI is most suited for larger farmers because it is quite capital-intensive and thus expensive. However, the services of the machinery required for forming raised beds mechanically, for planting,

(a)

(b)

Figure 8. On left, mechanized making of raised beds and furrows on laser-leveled field in Punjab province of Pakistan; on right, SCI carrots being grown on raised beds (photos by A. Sharif).

and for weeding can all be hired out to small farmers on an economical basis. Forming permanent beds by tractor on laser-leveled fields can be done in a few hours, for example, and once formed they will improve agriculture operations and productivity for many years. With appropriate institutional arrangements such as custom service companies, mechanized SCI can be made profitable for farming at different scales of operation, although not for very small holdings where using tractors is not practical.

PA focuses on optimizing the productivity of a given land area with efficient use of seed, water, labour, nutrient, and other inputs, paying attention to improving the land's inherent productivity over time. Plants' response to the various inputs is a function not just of the quantity of these inputs but also of their timing and their methods of application. For example, it is seen that foliar application of certain nutrients is much more effective than their application to the soil. This is especially true for crops like potato, which can be sprayed with small amounts throughout their life cycle to gain large increments in yield. Even when the yield response is not particularly large, profitability can be increased because of large reductions in input costs. It is conservatively calculated that with PA management, the net economic returns/ha can generally be increased by at least 50%.

Mechanization of SCI practices so that they can be applied on a large scale is still in early stages of development, but already the numbers are encouraging. Table 3 gives some summary figures for wheat, maize, sugarcane, potatoes, and carrots, calculated from farmers' adaptations of SCI methodology in Punjab province, e.g. from 144 ha now under SCI potato production. For these five crops, the average PA/SCI increase in yield/ha has been 62%, with an average 38% reduction in costs per kilogram produced. Some of the increases in net income/ha are so large that reporting an average number from Table 3 is not very meaningful.[6]

The spread of SCI methods within Pakistan has occurred mostly within Punjab province, where there are probably 200 ha of SCI wheat, 1000 ha of SCI sugarcane, and 100 ha of SCI carrots. Many if not all of the ideas and methods of SCI cultivation are now spreading with other crops, however. About 80% of the 1.2 million ha on which maize is grown for grain now has wider spacing and some other SCI practices; and most of the 500,000 ha under potato production are moving to SCI spacing. Additionally, many vegetables such as melons and watermelons are being grown on permanent raised beds, using SCI practices to various degrees. About half of the cotton-growing area, 3.5 million ha, is now being influenced and improved by SCI principles which are taking hold fast for this non-food crop.

These are still mostly partial adoptions of SRI ideas and methods. From the smaller-scale, more-thorough utilization of SCI principles and practices, it is evident that greater agronomic, environmental, and economic benefits could be achieved with fuller use. As stated repeatedly with regard to SRI, SCI is not a set *technology* but rather a set of *ideas* to be adapted and utilized to meet local needs and conditions. There is usually

Table 3. Summary results to date from applications of 'PA' in Punjab province, Pakistan, by crop.

	Yield (t/ha) (% increase)		Cost of production (USD/kg) (% reduction)		Net income (USD/ha) (% increase)	
	Current	PA	Current	PA	Current	PA
Wheat	3 (+ 60%)	5	0.35 (−43%)	0.20	$242 (+ 43%)	$345[a]
Maize	9 (+ 22%)	11	0.18 (−28%)	0.13	$484 (+ 145%)	$1184
Sugarcane[b]	70 (+ 57%)	110	1.26 (−21%)	0.99	$75 (+ 433%)	$400
Potatoes	30 (+ 40%)	42[c]	0.09 (−32%)	0.06	$2008 (+ 102%)	$4063
Carrots	15 (+ 133%)	35	0.10 (−67%)	0.03	$475 (+ 615%)	$3398

[a]This is 1st year net income for SWI; net income in 2nd year is $550, and in 3rd year $620.
[b]These figures are an average for February and September plantings.
[c]After PA has been used enough to improve the soil, potato yields of 50 t/ha are obtained.
Source: Data collected by Asif Sharif, Pedaver, Lahore, Pakistan

some initial resistance to making changes in familiar practices, but we look to empirical results to gain wider acceptance. In Netherlands, a farmer engaged in large-scale mechanized wheat farming has been using SCI ideas in a Dutch version of SWI for several years, starting with carefully selected high-quality seeds and greatly reduced seeding rates. Using GPS-steered equipment for precision seeding that spaces the plants widely, plus organic soil and crop management, has been found very suitable for winter wheat (Titonell, 2015).

CA convergence with SCI

Given that SCI, like SRI, is based on agroecological principles, it is quite compatible with the allied agroecological system known as CA. This makes a convergence between these production strategies reasonable in many if not all circumstances. Both SCI and CA aim to build up the fertility and sustainability of soil systems, melding crop, soil, water, and nutrient management methods into a synergistic set of practices that enhance crop productivity and profitability while conserving environmental quality. There have been in recent decades some important changes in thinking and practice regarding tillage after millennia of farming when breaking up the soil by plough, shovel, or hoe was seen as a defining and essential characteristic of agriculture (Fernandes, Pell, & Uphoff, 2002). This age-old conviction is now being altered by diverse farmers' initiatives and experience, well supported by research findings (Kassam, Friedrich, Shaxson, & Pretty, 2009).

Growing understanding and acceptance of CA has reoriented agricultural production strategies in the following three main ways. CA consists of: (a) *no or minimum soil disturbance*, which in practice means no-till planting and weeding (for wetland rice, this means not puddling rice paddies instead growing rice on permanent raised beds), (b) *maintenance of a layer of organic matter as ground cover*, using mulch from crop residues or green-manure cover crops, particularly legumes, and (c) *species diversification within the farming system* through associations, sequences and rotations of annual and perennial crops (FAO, 2017).

We have already begun seeing a convergence of CA practices and those of SRI, the precursor of SCI. SRI ideas and methods for irrigated rice have been combined with no-till and raised-bed cultivation in Punjab province of Pakistan as seen above (Sharif, 2011) and in Sichuan province of China (Lu, Dong, Yuan, Lee, & Padilla, 2013). Neither has yet applied the full CA strategy, however. In the first instance, there is still mechanical intercultivation for weed control rather than mulching; and in the second, instead of organic mulch, plastic-film cover is used to control weeds. But in both situations there is crop rotation. In the Sichuan case, rice is alternatively cropped with mustard (rapeseed) in the summer and winter seasons, with crop residues from both rice and mustard used as part of an organic soil management strategy.

In the Punjab applications, as seen in the preceding section, a wide variety of crops are being alternated in this mechanized version of SCI. In most countries, farmers are predisposed to focus on single crops with their cropping decisions guided by influences of the market and of familiarity. Fortunately, the greater productivity that results from cropping system diversification can create incentives for fuller adoption of CA principles because mulching with natural biomass is more favourable for promoting soil biodiversity than is mechanical weeding or plastic mulch.

Investing labour and capital to aerate the soil by mechanical means is not necessary if equivalent or better aeration can result from biological activity in the soil, as is promoted by CA systems. For example, with mulch soil cover and no-till soil management, the improvements in soil structure and fertility that are currently achieved through SRI's active soil aeration using mechanical weeders can be realized by promoting more abundant and active life in the soil, particularly earthworms and mycorrhizal fungi. Among other things, aerobic soil conditions favour the presence of fungi that produce the glycoprotein glomalin, which improves the aggregation and stability of soil particles, increasing the soil's porosity and lowering its bulk density. Also, CA systems can reduce crops' water requirements by making the soil itself more absorptive and retentive of water from rainfall and irrigation, and further by reducing soil evaporation (Kassam et al., 2013).

SCI and CA practices together, by promoting larger root systems in plants and more soil biota, can each contribute to producing 'more from less' (Uphoff, 2017). The convergence of SCI and CA practices is a logical next step for both, growing SCI crops on untilled soil or transplanting without puddling the soil as is now widely done for growing rice, in either case covering the undisturbed soil with mulch (Jat, Kanwar, & Kassam, 2014, 2016; Kassam et al., 2009, 2013).

While specific adaptations must always be made for each crop and local situation, the principles that guide these adaptations are broadly relevant. When integrated by mobilizing biological processes and potentials that exist within crop and soil systems, CA and SCI together can create a situation that is ultimately less dependent on external inputs, better able to minimize soil degradation, improving productivity and profitability, harnessing and augmenting the flows of ecosystem services (Garbach et al., 2017), and adapting more successfully to climate change.

Conclusions

In this discussion, we have focused on technological innovations that can advance food and nutrition security under conditions of a changing climate rather than on policy innovations, and we have not addressed broader societal impacts or implications. Most SCI efforts have come from the bottom up, often originated by farmers, so there is not the usual challenge of tailoring technical innovations from experiment stations or test plots to suit local socio-cultural conditions so as to gain social acceptance. SCI innovations developed so far have been well-suited to rural communities and producers because they stem from and are adapted for local needs and capacities. Rapid acceptance and spread of most SCI initiatives have been seen in the reviews of various crops.

There has been slower response from policymakers in most countries, imbued as they are with the suppositions and preferences of green-revolution agricultural technology. Most policies still focus on developing, and then getting farmers to adopt, 'improved' varieties which require commercial inputs for fertilization and more protection against pests and diseases. That SCI does not require new varieties, being suitable for both modern and traditional cultivars, and that it does not depend much upon purchased inputs is seen in policy (and agribusiness) circles as aberrant, maybe even threatening. Most of the push for SCI's spread has come from farmers and from civil society, although supporters within government agencies and in the business community are increasing as SCI's opportunities for greater productivity and profitability become appreciated. In India, for example, the government's National Rural Livelihood Mission and the National Bank for Agriculture and Rural Development have become influential supporters of SCI to reduce poverty and hunger there.

In the latter decades of the twentieth century, the green revolution contributed to improving food and nutritional security for many although not all households around the world. Unfortunately, its technology is very 'thirsty', requiring more water rather than less, and its input requirements limit its accessibility for those households that are most in need of food and nutrition security. As SCI is a relatively young innovation, most versions being less than a decade old, there is still much that is not known about its potentials and its boundaries, but its strategy diverges in major ways from that of the green revolution, not depending on changes in varieties, on increased water use, or on purchased fertilizers and agrochemicals.

So far, we have not found any drawbacks or disadvantages that would warrant hesitation about informing farmers about SCI experiences and opportunities. Farmers are normally cautious about new approaches anyway and will test them under local conditions before undertaking any large-scale utilization unless coerced or bribed by governmental policies. Rather than propose the immediate and widespread adoption of SCI methods, our intent here has been to urge institutions and individuals to take an interest in these new possibilities that we have been seeing in the field, in many countries, and for many crops, and to undertake systematic evaluations of them, involving farmers in these evaluation and in further evolution and improvement of the ideas and methods.

Notes

1. As this is a review article rather than a research article, we do not provide much detail here on the conditions and methodologies for all of the reported data. Such information is given in the references cited, or comes from records of the organizations conducting the evaluations and making the measurements. What the results lack in precision and statistical analysis is, we think, compensated for by their realism. Comparisons were assessed as accurately as possible under the conditions, with no intent or incentive to exaggerate because doing so would be to the disadvantage of those whom the innovations are supposed to benefit. Most of the unpublished reports have been posted on the internet with links given in the References so that readers can have direct access to the reporting on methods and results and can make their own assessments of how much credence to give to the data reported.
2. Exactly when this cultivation system was started is not really known. Field inquiries did not determine just how many years ago this innovation was developed (Uphoff, 2006a).
3. As this article is focused on cropping, it has not considered livestock within an SCI framework. However, we note that many millions of households in Ethiopia and elsewhere who are resource-limited, and thus food/nutrition-insecure, rely heavily on the rearing of animals to complement their field and garden production. The benefits from animal husbandry support the enrichment and maintenance of soil fertility through its supply of manure (see e.g. Basu & Scholten, 2012). One form of mixed-farming-system intensification is the 'cut-and-carry' system with animals confined in pens or corrals. This makes the collection and use of manure and urine more efficient, and it facilitates the optimal utilization of crop residues. While this intensification requires more expenditure of labour and some capital investment, the interaction effects among plants, animals, and microbes can raise the productivity of land, labour, capital, and water. This animal dimension of broader integrative adaptations should be kept in mind even though it is not considered here within our focus on cropping.
4. See Tables 3 and 4 in Lim (2007). One of these five farmers, Ros Mao, when visited in 2006, reported that his net cash household income had increased by five times with this strategy of diversification, enumerating his sources of expanded earning. With this additional income and greater need for labor, two of his five children had remained at home instead of migrating to Phnom Penh for wage employment, where they would have less desirable, less healthy living conditions (Uphoff, 2006b).
5. The first trial to evaluate growing irrigated rice with SRI methods and a high degree of mechanization was conducted in 2009 on a large test plot (17.5 ha) that had been laser-leveled with machine-made permanent raised beds and furrow irrigation (see Figure 8). The average paddy yield achieved was 12 tonnes/ha, with a 70% reduction in water use compared to usual practice, and with a 70% reduction in the usual amount of labour needed (Sharif, 2011).
6. The large increase in income from carrot production can be explained as follows, for example. Conventionally, after the seed bed has been prepared, carrot seed is broadcasted on it; ridges are made so that water for the crop is supplied to it in furrows. The seeds sprout densely on the top of the ridge with very little space for proper growth. Although the growth looks profuse, almost 80% of the carrots that result have to be graded B, C, or D. With PA cultivation, in contrast, five rows are seeded on raised beds 105-cm-wide with uniform spacing between plants. The target is a harvest of 700,000 mature carrots/ha. PA's bed-planting methods actually increase the growing area for each carrot, and almost 80% are marketable as grade A, which commands a much higher price. See Figure 7 for the same SCI effect in USA. This greatly increased profitability results from the introduction of a suite of complementary practices, plus their timely application, to create ideal growing environments for each respective crop.

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No potential conflict of interest was reported by the authors.

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