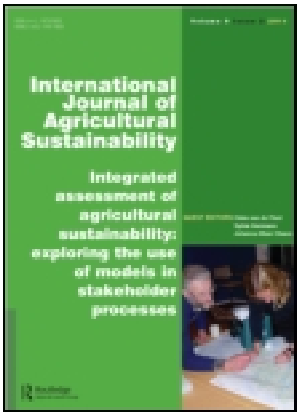

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The scientific case for system of rice intensification and its relevance for sustainable crop intensification

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The scientific case for system of rice intensification and its relevance for sustainable crop intensification

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Over the past decade, considerable empirical evidence regarding the relevance of the system of rice intensification (SRI) to pro-poor development has become available. However, concrete leads into the potential of SRI and its scientific foundations have not been adequately pursued. Instead, a few individuals, with very limited funding, have taken on the task to validate and provide a scientific basis for SRI, an approach that has been spreading at an increasing pace, particularly among smallholder farmers in India. This paper reviews the information currently available that provides the scientific, agronomic and plant physiological foundations of SRI and explores its significance for the wider future orientations of agricultural research and development in general.

Keywords: agronomic research; bio-diversity; Green Revolution; *Oryza sativa*; rice yield; sustainable agriculture; SRI

Introduction

Agricultural research, in comparison with other types of technological research, is rather unique in that it deals with *living* organisms and ecosystems (of plants, insects, animals, micro-organisms, etc.) that function in highly diverse and variable natural environments (i.e. land forms, soils, climates and weather) that together exist in delicate equilibriums (Altieri, 1999). Under real-life conditions there are thus numerous interacting factors that eventually determine the outcome of a production process, as opposed to, for instance, industrial processes. Much agricultural research – for reasons of production efficiency – has likewise adopted a largely mechanical/industrial approach and paradigm. The resulting outputs of that research tend to be relatively standardized technologies, occurring frequently in the form of best management practices (BMP). Often these prove to be unrealistic, given the agro-ecological and socio-economic diversity of the (smallholder) farming situations and the dynamic nature of agricultural production processes and constraints (see also Stoop and Hart, 2005; Carpenter *et al*., 2009).

On the other hand, research that seeks to clarify various biological and technological processes in a more integrated and holistic fashion readily encounters serious obstacles (Lynch, 2007) because it is – presumably – not problem-oriented and therefore not a priority. Such research, however, is of a longer term, evolving nature and tends to be a pre-condition for the achievement of efficiency gains at farm levels. The obstacles may range from obtaining funding, limited respectability and, consequently, barriers to having the results published, suggesting that there are risks in going against vested interests and established research doctrines and paradigms.

The negative attitude towards system of rice intensification (SRI) of the international rice research establishment is a point in case (Dobermann, 2004; Sheehy *et al*., 2004, 2005; Sinclair and Cassman, 2004). So far, formal research into SRI has been limited largely to short term, rather simplistic, comparisons with other systems, in particular the conventional, fully irrigated (flooded) rice systems. Such comparisons are subject to multiple biases, as was elaborated in a recent paper (Stoop *et al*., 2009).

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Consequently, fundamental questions regarding the dynamics of (vegetative) crop development and those of *why*, and under *what*, crop management conditions SRI type systems are able to realize their impressive yields (see Kassam *et al*., 2011; www.ciifad.cornell.edu/sri or http://srinewsandviews.blogspot.com/) have not been explored adequately.

The aim of the present paper is to elaborate and clarify the agronomic principles and mechanisms, including their plant physiological basis, that have contributed to the high grain yields obtained under SRI, for instance in India (www.sri-india.net). The implications of these results for the orientation of agricultural research and development are highlighted in the discussion.

Some basic agronomic principles of crop production

Agronomy is best viewed as an integrative science through which contributions from various specialist disciplines (breeding, genetics and crop ecology; plant and crop protection; soils and soil fertility management; soil water management, also social sciences, etc.) are brought together in an attempt to optimize crop growth conditions so that production/output can be achieved most economically and with minimal disturbance of the environment. Thus agricultural output is defined at a basic level by

$$\text{Potential biological output} = f\,[\text{weather, location, time, space}] \quad (1)$$

$$\text{Actual agricultural output} = f\,[\text{weather, location, time, space}] + f\,[\text{people : land and crop management}] \quad (2)$$

The natural biological potential (equation (1)) will be determined primarily by the *location* component consisting of topographic and soil characteristics (biological, chemical and physical properties reflected in fertility and moisture parameters) in combination with the local weather and climatic conditions (including micro level variations). In response, permanent natural vegetation and fauna, which tend to be remarkably diverse when not disturbed, will develop over time.

The actual agricultural output is in addition determined by the land and crop (=farm) management components in equation (2). The latter involves all various human interventions of land preparation, seeding, crop protection, fertilization, etc. until the harvest. Equations (1) and (2) serve to illustrate that at any location agricultural output is a function of many different and interacting factors. Moreover, several of these factors are highly variable over time and in space, up to the (micro-) field level. Thus, the outcome of any agronomic comparison made through field trials and/or demonstrations, be it in terms of different varieties, fertilizer applications or plant densities, etc., will be affected by a very wide and variable range of location-specific factors and conditions (Stoop *et al*., 2009). Comparisons between multi-component technological packages (e.g. between an irrigated rice system and an alternative such as SRI) thus become extremely complex, up to the point of being unmanageable and therefore irrelevant (see Uphoff *et al*., 2008). Likewise, the successful transfer of a new technology/technological package developed under experiment station conditions to farmer fields, or from one farmer field to another, is far less straightforward than is often assumed by scientists (not to mention policymakers and the general public).

Because of the over-riding concerns regarding production, agronomic research has largely focused in practice on the land and crop management elements of equation (2), while neglecting the fundamental aspects captured in equation (1). In the context of modern farming, the factor *location* has become a variable that, often at great monetary expense and environmental damage, is being altered through practices such as deforestation, irrigation, land levelling, drainage, greenhouses, etc. This is in sharp contrast to the prevailing strategy of resource-poor farmers who will have to adjust the use of a location according to its natural potential. As a result, agricultural scientists may readily lose track of the fundamentals captured by equation (1).

The cheapest and most environment-friendly way to take land into agricultural production is by choosing crops that are naturally adapted to their respective conditions. As was initially elaborated by van Staveren and Stoop (1985) and Stoop (1987) with regard to the West African savannah region, the *toposequence concept* provides a tool to link land types with land use. This concept is widely recognized and practiced by (traditional) smallholder farmers all over the world and facilitates linkages between agricultural science and (location-specific) farming. It also permits one to define land-use alternatives and adapted cropping systems, thereby identifying research priorities that are of immediate practical relevance to resource-poor farmers. Moreover, it explains the preferential occupation of specific land types by local populations and various shifts in land use and tenure arrangements as population pressures increase and/or land degradation becomes an issue (Vierich and Stoop, 1990).

With respect to cropping systems, a first essential step will be the selection of adapted crop cultivars with growth cycles – the *time* factor in equation (2) – that are dictated by seasonal weather conditions or the length of the rainy season. Next, cropping systems' combinations (e.g. intercropping systems and crop rotations) that may permit farmers to raise their overall output and/or spread the risks of total crop failure become the second step. Generally, the *time* factor is optimally exploited by matching it with the crop development cycle. This implies, in particular for photosensitive (mostly traditional) cultivars, that the vegetative phase is extended by seeding as early as possible (i.e. with the earliest instances of major rainfall, or as soon as minimum temperatures get above a critical level).

An extended vegetative phase, such as that featured by photosensitive varieties, leads to an increase in above-ground biomass production as well as that in corresponding below-ground root development. This biomass constitutes the *source* that eventually will provide the carbohydrates and proteins that will be transported and accumulated in grains: the so-called *sink* (defined as the total number of grains/plant and the weight of individual grains). For the various plant physiological processes (photosynthesis, respiration, transpiration) to perform optimally, which is essential to maximize grain formation and growth, it is therefore necessary that the plant population – the *space* factor in equation (2) – is adjusted. In practical terms, this means: the longer is the vegetative phase and, therefore, the greater is the above ground biomass per plant, the lower will be the optimum plant population. It follows also that when vegetative growth is stimulated by applications of mineral fertilizers – nitrogen in particular – further downward adjustments in plant population may be required to permit an efficient photosynthetic process during grain formation and grain-filling stages of crop development. Another implication is that the higher is the natural soil fertility of a field, the lower will be the optimum plant population, at which maximum grain yield is obtained. Consequently, there is a trade-off between production factors, *time* and *space* (see also Bell *et al*., 2008), and the required levels of external inputs (i.e. seeds and agricultural chemicals, nitrogen fertilizers in particular) and labour. In essence, the agronomic discipline has to cope with a far more dynamic crop development process than that currently recognized by the modern, industrialized type of agriculture. Moreover, these processes become particularly relevant when the farmer target group lacks financial resources (as is seen in the case of hundreds of millions smallholders/family farms in developing countries) to invest in extensive modern improvements and machinery. This perspective, therefore has implications for research direction and priorities, as will be elaborated in the discussion section.

System of rice intensification

Conventional rice research has frequently insisted on characterizing SRI as a *technology* to be implemented following certain specific and precisely defined guidelines. From the beginning, however, it has been underscored that SRI should be viewed as a *set of practices* to be followed and implemented flexibly and in response to the divers local agro-ecological and socio-economic conditions faced by farmers (Stoop *et al*., 2002; Stoop and Kassam, 2005). To realistically permit the linking of SRI research to these diverse conditions and needs of the farming environment, the subsequent sections will first briefly present the practices and their implications for SRI agronomy. The section is concluded by a summary of recent research results that largely explain the plant physiological basis for the SRI phenomenon and finally addresses some of the priority research needs that logically follow from the present state of knowledge.

The SRI practices

SRI, as initially developed by de Laulanié (1993) in Madagascar for lowland/irrigated rice, is based on the application of the following six practices so as to achieve the best results:

1. the use of very young, 8- to 12-day-old seedlings in transplantation;
2. transplanting single seedlings per hill quickly, with minimal root disturbance;
3. widely spaced hills, ranging from 20 × 20 up to 50 × 50cm;
4. an alternate wet and dry soil moisture regime (no permanent flooding) to maintain aerobic soil conditions;
5. the use of organic, rather than mineral, fertilizers;

6. frequent weeding, preferably performed using a surface rotary hoe, during early crop development stages so as to control weeds and aerate the soil.

These practices evolved in direct response to biophysical conditions on the Madagascar Plateau and to the socio-economic needs of the small and poor rice-farmers in the area. Shortages of rice seeds and of (irrigation) water, required to keep the fields permanently flooded, were the major local constraints; farmers lacked the cash to buy external inputs such as mineral fertilizers and pesticides. The cumulative result of the six general practices as reported by de Laulanié (1993), subsequently confirmed in numerous tests throughout the world's rice growing areas, was seen to be the abundantly tillering rice plants that yielded many large panicles with heavy individual grains that together added up to spectacular grain yields/ha (see www.ciifad.cornell.edu/sri). This invites the question as to what lies behind the practices proposed by de Laulanié in terms of the fundamental aspects of plant growth and crop development, and which apparently are inadequately appreciated by modern mainstream rice research.

The agronomy of SRI

To appreciate the SRI agronomy, one has to go back to the agronomic principles introduced in the 'Some basic agronomic principles of crop production' section and to the features of local cropping systems, as described initially for the West African savannah (van Staveren and Stoop, 1985). Here, the major upland cereal crops (pearl millet and sorghum) and their prevailing local, photosensitive cultivars respond to early planting by developing an abundant biomass (i.e. the essential *source* required for subsequently filling the *sink*). Rice shows a similar feature, but primarily through the tillering process. In addition, however, rice's photosensitivity characteristics, as in many local rice cultivars, will further enhance biomass development, upon early planting.

The initial paper on SRI (Stoop *et al*., 2002) elaborated how the rice plant develops during the vegetative growth phase, through a tillering process. De Laulanié, on the basis of an earlier work by Katayama (1951), identified tillering to be the key feature in the development of a rice crop. Thus, during the vegetative phase:

- every tiller has the potential to develop a new tiller, which amounts to a roughly exponential increase in the number of tillers per individual plant;
- every new tiller develops adventitious roots at its base that directly support the particular tiller and lead to a very extensive overall root system per plant;
- potentially every tiller can develop a panicle.

The tillering feature becomes particularly striking during the second half of the vegetative phase, when an explosion of tillers occurs: roughly from 16 to 32 and from 32 to 64 and beyond, provided soil conditions and plant spacing are favourable (the record number of tillers/rice plant recorded so far was reported from Indonesia and amounted to 220 tillers, Uphoff *et al*., 2009). However, conventional planting methods and spacing (several rice plants per hill and a relatively close hill spacing) result in plant populations in excess of 100plants/m^2. Consequently, the tillering and rooting processes of individual plants will be obstructed seriously.

SRI agronomy seeks to exploit the tillering feature by managing two critical elements: *time* and *space* [see equations (1) and (2) above]. In more-concrete agronomic terms, this means that the age of the transplanted seedling and the spacing between transplants (i.e. plant population) are the key variables to be managed for maximum grain production (apart from proper weed control during the early vegetative phase). It follows that the younger the seedlings are at transplantation, the greater will be the total quantity of above-ground biomass developed during the vegetative growth phase, as a result of the exponential increase in tillers. Therefore, it becomes imperative to space the individual transplants relatively widely to avoid 'overcrowding' of the field at the time of flowering. When for one reason or another older seedlings have to be used for transplantation, the duration of the vegetative phase and thereby tillering are automatically cut short, as will be the root system development. Common measures by farmers to counter such situations will be to increase plant densities.

The effects described above will be compounded by two additional factors. These are:

1. the growth conditions in the nursery, and
2. the overall soil fertility condition of the main field.

Under conventional management, seeding rates in nurseries tend to be far higher (5–10 times) than those recommended for SRI. When seedlings are kept in crowded nurseries for a considerable period of time prior to transplantation (which is often the case in traditional farming and, to a lesser extent, also under conventional practices), the subsequent vegetative development is likely to be affected and, with it, the yield potential of the crop (see the 'Recent results of plant physiological and agronomic research in support of SRI' section).

Furthermore, the general soil fertility condition of the paddy field will always remain a critical factor in determining the optimum plant density. High soil fertility will enhance and accelerate a crop's vegetative development. Individual plants then require a relatively wider spacing than that seen in the case of less fertile soils, in order to utilize the solar radiation most effectively at the critical periods of flower initiation and grain formation. On the other hand, typical soil constraints such as salinity (see Menete *et al*., 2008), iron toxicity or acid sulphate (sub)soils (see Mishra and Salokhe, 2010) would interfere with the development of an extensive root system. The resulting reduction in overall above-ground biomass production (due to reduced rates of tillering) can then be compensated, to a limited extent, by increasing the plant density at transplantation, so as to increase the crop's interception of solar radiation.

Recent results of plant physiological and agronomic research in support of SRI

As was discussed in a previous paper (Stoop *et al*., 2009), the outcome of agronomic and plant physiological experiments will always be affected critically by the rice variety used, and indirectly by the agro-ecological and agronomic management conditions under which it was developed and selected initially (see also 'Implications for rice breeding and the selection of SRI specific varieties' section). Apart from this issue of varietal adaptation, there has been a number of well-focused studies on several aspects of rice crop growth and production systems that helps clarify the crop features and practices associated with the high yields recorded under SRI conditions.

First, San-oh *et al*. (2006) showed that tillering and root development were enhanced by transplanting seedlings as single plants/hill instead of the usual three plants/hill. This result was recorded under flooded conditions. Subsequent studies by Pasuquin *et al*. (2008) reemphasized that rapid crop establishment and the avoidance of transplanting shock, achieved by using young seedlings (about 10-day-old), are advantageous in raising grain yields. In addition, Mishra and Salokhe (2008) studied the effects of the seedbed moisture condition (moist-aerobic vs. wet-anaerobic), seeding rates and N fertilizer on early seedling establishment and on the development of above- and below-ground parts in the nursery. Next, they transplanted 12-day- and 30-day-old seedlings from their respective seedbed treatments as single plants into moist or wet/flooded conditions to study early plant development (plant dry weight, plant height and tillering). Their results showed patterns of early plant growth that were far more intricate than anticipated:

- seedbed moisture conditions distinctly affected early root growth and the proportions between above- and below-ground plant development in favour of humid, rather than wet, nurseries;
- young vigorous seedlings (12 days old) from a moist seedbed seeded at a low seed rate upon transplantation into a moist soil gave significantly heavier rice plants that tillered far more profusely after 45 days than did plants derived from wet seedbeds transplanted into either moist or wet conditions;
- when transplanting 30-day seedlings, these never managed to catch up with the 12-day-old seedlings.

One could postulate that the *older* the seedlings were at transplantation the *smaller* the plants would be 45 days later. This mainly reflects the increased transplantation shock suffered by old seedlings, which then become unable to catch up with young seedlings irrespective of any subsequent field measures (fertilizer applications, weeding and irrigation).

In an earlier and comprehensive review of plant physiological processes, Mishra *et al*. (2006) had elaborated on the various interactions between roots and leaves (mainly for hormones like auxins and cytokinins) and their subsequent effects on root development and root activity, as well as on those delaying the senescence of plants. On the basis of that review it was postulated that there are interdependent processes between roots and leaves (especially the older, lower leaves) that affect source–sink relationships and that contribute to grain formation and grain-filling in widely spaced plants. Under those conditions, shading of the lower, older leaves is reduced and consequently their senescence was delayed. In subsequent field experiments in Thailand (near Bangkok), Mishra and Salokhe (2010) confirmed the intricate interaction effects between plant spacing and density, on one hand, and the soil moisture/irrigation regime, on the other. Minimizing intra-hill plant competition was one way to increase grain yield under continuous flooded conditions, but this effect was enhanced by following an intermittent irrigation regime during the vegetative phase. Simultaneously, the latter practice significantly delayed root degeneration and the decrease in leaf chlorophyll contents during the crop ripening phase.

Thus, single rice plants at a 20 × 20cm spacing and under an alternate wet and dry (AWD) soil water regime resulted in deeper, more profuse and more active root systems, as well as higher leaf chlorophyll contents at later growth stages, thereby prolonging the photosynthetic and grain-filling processes. Together, these translated into increased grain yields as compared with continuously flooded conditions and with more-crowded plant stands. Mishra and Salokhe (2010) postulate correctly that under soil conditions that are more favourable than those of the acid sulphate soils at their experiment station the optimum plant spacing would have shifted to higher values (e.g. 30 × 30cm or even more). More generally they concluded that spacing is a factor to be optimized, depending on soil and varietal characteristics.

These findings have been complemented by Thakur *et al*. (2009a, b, 2010a, b) in Orissa (India) through a series of field experiments. They established that widely spaced, individual plants under AWD water regimes significantly affected plant architecture and canopy structure, with significant effects on leaf area index measurements as well as on the interception rates of solar radiation. Moreover, a shallow depth of planting contributed to a plant architecture, upon tillering, that was responsible for a greater coverage of the ground and greater interception of light. In closely spaced systems (i.e. several plants/hill and/or a hill spacings closer than 20 × 20cm, as seen in conventional practices) the older and lower leaves die prematurely. This also affected the vitality of the root system during the late vegetative and the on-set of the reproductive phase.

As Thakur *et al*. (2010a) show, the excessive competition between plants for solar radiation during this critical phase of plant development is reflected in significantly reduced growth rates under the conventional system as compared with SRI, which subsequently also affects the grain-filling process. Plant spacing significantly affected foliar structure (plant architecture, leaf thickness and size) and properties (in terms of chlorophyll and leaf nitrogen contents and its evolution with leaf aging for different types of leaves; see also Mishra and Salokhe, 2010). A wider spacing, than that used conventionally, contributed to an increased efficiency of the photosynthetic and respiratory processes during the reproductive phases of panicle initiation, grain development and grain-filling. Thus, although the total biomass of the SRI as compared with the conventional flooded system was similar, the former yielded significantly more grain than did the latter, as reflected through an increased harvest index and increases in panicle size, the number of grains/panicle and the weight of individual grains (Thakur *et al*., 2009a). Moreover, recorded changes in leaf structure (larger, thicker and generally tougher leaves) may provide an explanation for the lower incidences of pests and diseases that have been observed for SRI-type cropping systems.

The results reported by Mishra, Thakur and their co-workers take on additional relevance against the recent findings by Chinese scientists. Yang and Zhang (2010) report for two high-yielding varieties that moderate soil drying (rather than flooded) resulted in an increased harvest index, whereas Zhang *et al*. (2010) found that such a soil moisture regime, when maintained during the reproductive phase, enhanced the grain-filling process. The latter investigated the bio-chemical mechanisms involving plant hormones (e.g. various cytokinins) that regulate the grain-filling process.

Intermittent irrigation and a moist, aerobic soil condition thus appear to affect also a wide range of plant physiological processes, apart from enhancing tillering and root-system development (Yang *et al*., 2004; Stoop, 2005; Thakur *et al*. 2009a). A logical consequence of more extensive and active root systems is increased drought-tolerance, as well as greater efficiency in nutrient uptake (and in fertilizer use). The former has been reported repeatedly by farmers in India who were confronted recently by serious droughts; the latter has been well illustrated in studies by Zhao *et al*. (2009) in China. Here the optimum for N fertilization under SRI was reached at levels around 80kg N/ha, whereas under flooded conditions the N response continued to increase up to 240kg N/ha, and yet the grain yields always remained inferior to those obtained under SRI conditions. Moreover, this low optimum N rate was also associated with a reduced level of nitrogen losses through ammonia volatilization, a process enhanced by AWD soil moisture regimes. In spite of such losses the overall N-use efficiency was still much increased as compared with the flooded system (Zhao *et al*., 2010).

Meanwhile, Thakur (personal communication) recorded similar results from Orissa (India), showing an optimum N application rate of around 90kg N/ha. Even more important, they emphasized the interdependence between below- and above-ground activity of roots and leaves. As elaborated initially by Samejima *et al*. (2004), root exudation rates measured during the reproductive phase provide a useful index of root activity; similarly, the chlorophyll and N contents of flag leaves and fourth leaves during the early and late maturity stages of the crop serve this purpose for the plant's photosynthetic activity. Each of these parameters showed significant increases under SRI conditions as compared with the continuous flooded system. These results confirm that the delayed senescence of the leaves involved a continued photosynthetic activity that led to the increased grain weights observed under SRI.

Interrelationships between soil (micro-) biology, crop rooting and growth

The extensiveness of root systems will be important with regard to the rate and efficiency with which moisture and nutrients can be absorbed by the plant from the soil. Recent contributions by Birkhofer *et al*. (2008) and Uphoff *et al*. (2009) have reviewed the various possible interactions between roots and soil (micro-)organisms, such as nematodes, bacteria, fungi, mycorrhriza, etc., and their possible impacts on plant growth, including above-ground pest and disease incidence. The tremendous numbers (millions) of these micro-organisms per cm^3 of soil indicate the need to view soils as *living* rather than merely physical platforms for plant stability and nutrient/water reservoirs; a switch from anaerobic flooded to aerobic drained soil conditions – as seen under SRI – will have significant impacts on the soil microbial community structure (Unger *et al*., 2009). Obviously, soil biota will become more important as root systems become more extensive and also as the number of micro-organisms in the soil increases. Under moist, aerobic soil conditions, rather than in the anaerobic flooded situation, the diversity in soil micro-organisms will be at its greatest and will lead to increased nitrification rates, as shown by Sooksa-nguan *et al*. (2009). These authors postulate that, in addition, changes in the dominant ammonia-oxidizing bacterial populations have the potential to change the N dynamics in the SRI system and thereby improve yields. In a subsequent study (Sooksa-nguan *et al*., 2010), it was confirmed that early water management under SRI (i.e. during the vegetative phase) had a lasting effect on soil bacterial communities.

As the principal source of energy/nutrition, soil organic matter (including through applications of organic materials such as manure, compost, mulch, green manure, etc.) at increased levels will enhance the total number of micro-organisms. Liu *et al*. (2007) recorded that the resulting improved soil health was also reflected in reduced levels of diseases, which is in line with the observations made by Thakur *et al*. (2009a) on plant and leaf structures. Thus, the growth of the soil micro-organism population, and thereby its various contributions to above-ground plant growth, has effects that go far beyond mere plant nutrition. The rhizosphere population of an SRI plant may thus significantly affect plant development, through hormone production, and induce the biological control of pathogens, but further research is needed to assess this proposition.

However, under wet, flooded (i.e. anaerobic) soil conditions, the application of organic manures will have remarkably different effects, as the break-down of the organic materials will lead to the accumulation of toxic organic components as well as to that of ferrous iron, sulphide and manganese, all highly toxic to rice roots (Yoshida, 1981). These results provide further justification to combine the use of compost and alternate wet-and-dry, aerobic, soil moisture regimes, such as those as employed in the SRI practices (see the 'The SRI practices' section). Thus rice crop responses to various organic and inorganic fertilizers and the effectiveness of these nutrient sources will always be affected distinctly by the particular soil water regime (Yang *et al*., 2004). It is likely that a larger and more bio-diverse soil microbe population under SRI conditions will lead to a faster rate of mineralization of the soil organic matter and thereby to an enhanced nutrient supply. Yet, under flooded conditions the build-up of wide-C:N-ratio organic matter will result in a decrease in the nitrogen available to plants from either fertilizer or mineralization.

Together, these issues underscore that earlier efforts to explain/predict crop growth, nutrient uptake and the sustainability of soil fertility, in terms of relatively simple input–output nutrient budgets (e.g. Smaling, 1998), are incomplete. They also leave unexplained the considerably beneficial effects of organic matter application (manure, compost, crop residues, cover crops, etc.), which go beyond that which can be explained by their relatively low N, P and K contents. But also the soil moisture regime (drained or flooded) will critically affect the dynamics and availability of soil nutrients. The diversity of soil micro-organisms and the delicate equilibriums between species/strains, as well as the effect of soil type and the complexity of their various interactions with plant roots, make this an extremely complicated research subject. It is hoped that new molecular techniques can help elucidate this biodiversity.

Implications for rice breeding and the selection of SRI specific varieties

So far all formal and informal testing of SRI has been done using any locally-available rice variety (traditional, as well as improved varieties). SRI's features have been recorded irrespective of the rice variety employed, which underscores the general validity of the approach. It also indicates that were one to use improved rice varieties specifically selected under SRI conditions of wide spacing and aerobic soil conditions, substantial further yield gains could be expected.

Apart from the physiological functioning of the rice plant, as presented above, Thakur *et al*. (2009b) also provide information on how the optimum plant spacing under SRI should be adjusted in response to rice varieties of different maturity types (early, intermediate and late) and of different heights (i.e. overall biomass production). For the full-season cultivar, the optimum plant spacing was reached at 25 × 25cm, while for the early and intermediate materials this was 20 × 20cm. In earlier studies by Stoop (2005) a similar result was recorded, whereas Mishra and Salokhe (2008) also pointed to the need to adjust plant spacing in response to varieties and their maturity cycles.

These results provide important leads for identifying the most desirable plant characteristics to be aimed at in rice cultivars that are specifically selected for their adaptation to SRI type systems. These characteristics would be, first and foremost, a high tillering ability and adaptation to moist, aerobic soil conditions. Depending on the local agro-ecological conditions, intermediate- to long-duration varieties would be preferable to prolong the tillering phase and process. It is interesting to note, therefore, that the Chinese breeding programme towards a super-hybrid (Zhang *et al*., 2009), and IRRI's work towards ideotype breeding, including its efforts towards the *new plant type*, emphasize plant characteristics that are rather different. The plant characteristics emphasized by IRRI resulted from plant and crop physiology and morphology knowledge in combination with simulation modelling to define a *theoretically efficient* plant (Virk *et al*., 2004; Peng *et al*., 2008). On this basis, a reduced tillering capacity, large panicle size and improved lodging resistance were identified to be critical. The specifically shaped top three leaves and flag leaf, strong stems, reduced plant height and large individual grains were additional selection parameters, contributing to an increased harvest index. Moreover, a general aim has been to select short- to intermediate- growth-cycles, with a preference for the former.

Neither the Chinese super-hybrid nor IRRI's new plant-type breeding programmes appear to have paid adequate attention to rooting characteristics and root systems, or to possible interrelationships between root health and leaf quality/survival. Yet, in his review paper, Lynch (2007) draws attention to the different types of roots and their roles in accessing moisture and nutrients from different soil horizons. He also emphasized the genetic variability that exists in root systems and the architecture that can be exploited through modern plant breeding and selection techniques in developing varieties particularly suited to marginal soil conditions. Likewise, Samejima *et al*. (2004) emphasized the genetic aspects of the root–shoot interdependence that affect the productivity of new rice lines. Earlier, Soejima *et al*. (1995) had linked this interdependence to higher cytokinin synthesis by active root systems and its transport in root exudates to above-ground shoots (see the 'Recent results of plant physiological and agronomic research in support of SRI' section).

Mishra and Salokhe (2010) and Thakur *et al*. (2010a, b) subsequently confirmed that the development of the rice root system, in the nursery seedbed as well as in the field after transplanting, is greatly affected by the agronomic management of soil moisture and of plant spacing/population (see the 'Recent results of plant physiological and agronomic research in support of SRI' section). Under the moist, aerobic soil conditions of SRI, the early root development becomes much more extensive than it does under wet soil conditions (Mishra and Salokhe, 2008), and a larger, deeper, more active root system and vigorous plant is produced by the time the reproductive phase is reached (Mishra and Salokhe, 2010; Thakur *et al*., 2010a, b). The development of extensive root systems therefore appears to be determined partly by genetic factors and – to an even larger extent – by complex interrelationships between the below-(roots) and above-(canopy) ground plant organs. If one were to look at the development over time of the ratio *below-ground : above-ground* plant dry weights for SRI compared with the conventional fully irrigated system, distinct differences could be expected. The considerations by Uphoff *et al*. (2009) about plant–microbial interactions (see the 'Interrelationships between soil (micro-) biology, crop rooting and growth' section) would only increase the significance of root systems with regard to overall plant development.

Discussion and conclusions

The very substantial successes of the *Green Revolution* based on irrigated rice and wheat have been instrumental in creating an input-based *intensification* paradigm among agriculturists, in which *more* plants/ha and *more* mineral fertilizer should lead to *more* grain yield. To the majority of scientists operating on the basis of this paradigm, the responses recorded under SRI, as described and analysed in this paper, have become counter-intuitive, because modern agriculture has lost track of certain fundamental agronomic interrelationships. For instance, the introduction of photo-*in*sensitive (i.e. a fixed growth cycle) short-straw cultivars, a major contribution of the *Green Revolution*, and of the associated rather standardized agronomic practices raises an intricate question (also from production and environmental viewpoints): should crop systems in which every individual plant has to grow and produce much below its potential – as is seen in the case of modern farming – be considered the most efficient in terms of grain production and resource use?

The preceding analyses tend to confirm that this will *not* be the case. The analyses provide ample evidence of specific synergistic effects of AWD soil moisture regimes on root and plant development and on the beneficial effects of organic fertilizers in the absence of continuous flooding. Furthermore, these effects are enhanced by reduced plant populations that permit unrestrained tillering during the second half of the vegetative plant development phase.

Yet, SRI still faces several, rather fundamental, agronomic research questions, such as:

- the identification/development of rice varieties adapted to aerobic soil conditions and that have a suitable growth cycle and plant architecture;
- its long term impact on soil fertility/soil health maintenance and sustainability;
- the optimum soil moisture regime over the vegetative *and* reproductive growth phases of the crop (see Zhang and Yang, 2010);
- the optimum plant spacing to maximize the interception of solar radiation at the time of panicle initiation and flowering, instead of aiming for *early* canopy closure that would minimize weeding expenditures, and its interdependence with;
- the frequency of weeding, its role in aerating the soil and its significance with regard to soil micro-organisms.

The research issues mentioned above mainly aim at optimizing the system and improving the scientist's understanding of this novel, and environmentally promising, way of growing rice. The presented results and analyses make it plausible that the increased SRI rice yields originate, on the one hand, from a greater efficiency in the use of the natural resources (soil, water, nutrients, solar radiation) and external inputs, and, on the other hand, from a greater internal, plant physiological efficiency than that seen in permanently flooded systems (see the 'Recent results of plant physiological and agronomic research in support of SRI' section). Potentially, these increased efficiencies have major ramifications into savings in production costs and also into reducing the harmful effects of agricultural chemicals on the natural environment. There are other strong indications that the SRI practices lead to more resilient systems in terms of their tolerance to droughts (and flooding), as well as to infestations by pests and diseases.

Over the past half century, international agricultural research has been focused to a large extent on plant breeding and the introduction of new seeds of modern, photo-*in*sensitive cultivars. The common objectives of many breeding and selection programmes have been to shorten the growth cycle and plant height of selected cultivars as compared with local varieties. A drastically shortened growth cycle, such as of irrigated rice, permits further intensification, because two or even three consecutive crops per year can be grown; as for rainfed (upland) crops, say in semi-arid areas of Africa and India, a shortened growth cycle has been considered to be desirable to facilitate a delay in the seeding operation, thereby avoiding the common drought risks faced at the start of the rainy season. A reduced plant height permits increased plant populations and higher rates of (nitrogen) fertilizer, without lodging becoming a problem.

Although these arguments sound rational, there have been serious side-effects of these generalized strategies.

With the widespread introduction of modern cultivars for all of the major cereal staple crops also came relatively standardized packages of agronomic practices (plant spacings and various agricultural chemicals). This has led to the progressive replacement of a wide range of traditional cultivars that had been selected by generations of local farmers. This process was accelerated by the large-scale, essentially top-down, extension campaigns, through the Training and Visit approach, conducted all over Asia and Sub-Saharan Africa during the 1980s and 1990s. As a result, not only is the asset of location-specific adaptation of local varieties (the genotype × environment [G × E] interaction) vanishing, but knowledge of how these varieties are to be managed agronomically is also being lost.

Gujja and Thiyagarajan (personal communication) were able to illustrate this process by tracing several recommendations from around 1910, made by the colonial agricultural services, that advised wide spacing for rice (up to 45 × 30cm). Likewise, the well-known Indian farmer, Narayana Reddy (personal communication), cites local proverbs that refer to spacing between rice plants that should be sufficiently large *for a lamb to lie down.*

The preceding analyses of the SRI phenomenon tend to underscore that rather than focus on production increases per sé, as under the *Green Revolution*, one needs to shift emphasis towards forms of sustainable intensification. An essential element of such approach would be the location- and farmer-specificity of agriculture in general, which permits farmers to capitalize on the sizeable assets of G × E interactions of (local) varieties while safeguarding bio-diversity. As the SRI case illustrates, this has to involve a considerable degree of flexibility in presenting various crop technologies, not as fixed recommendations, but as *sets of principles and practices* to be understood and adapted/fine-tuned by farmers.

Much of international and national agricultural research has been focused, however, on developing and introducing generalized solutions through combinations of breeding widely adapted modern varieties/improved seeds, along with an increased use of agricultural chemicals. Scientists, through their research methods and approaches, have largely ignored the agro-ecological and socio-economic diversity and variability that is inherent in every farming environment. Thus, the dichotomy between the limited supply of research-based technologies (often presented as BMPs or *best bet practices*) and the large diversity in farmers and on-farm conditions (see also the 'Some basic agronomic principles of crop production' section: the *toposequence* concept) has remained largely unaddressed. For instance, the results of the multi-location testing of varieties and technologies are commonly analysed through standardized statistical methods that calculate treatment means, standard deviations and statistical significance routinely. Non-representative results (i.e. numbers that fall outside a predetermined range around a mean value) are in essence eliminated in the analysis. Unfortunately, in the absence of regular field monitoring, this may include also the scientifically most interesting data: the negative and positive outliers.

Major research and development efforts thus tend to deviate from the field realities faced by a vast majority of farmers (i.e. smallholders) and those expressed in equation (2), presented in the 'Some basic agronomic principles of crop production' section. First, most of these efforts largely bypass the vagaries of the local weather and rainfall, which is an integral factor of nearly all modes of farming, and certainly for the world's dominant form (i.e. rainfed systems). Thus, mainstream agricultural research tends to focus increasingly on a *virtual* agriculture and *virtual* plant types, as illustrated also by the widespread popularity of modelling approaches. Second, the plant characteristics targeted by the major (rice) breeding programmes, in their efforts to break the presumed yield ceiling (as discussed in the 'Implications for rice breeding and the selection of SRI specific varieties' section), are another indication of this trend.

The preceding sections, however, tend to illustrate that there exists an enormous – yet untapped – scope in terms of complementary interdisciplinary research that combines genetics with physiological and agronomic (including on-farm) insights in breaking the present yield ceilings for rice and other crops. This ambitious goal is likely to require that certain biological factors such as the plant's root system and its interdependence on soil biota and on above-ground plant development are being included in the crop improvement equation. The high yields (regularly even above 10tons/ha) under SRI and in farmer fields were achieved through simple adjustments in agronomic management practices, irrespective of rice varieties. Therefore, one can hypothesize that if specifically selected, SRI-adapted varieties are made available from rice-breeding programmes, spectacularly increased yields – way above present yield ceilings – could become a widespread reality even for smallholders.

It is the inflexibility in the mainstream agricultural research (national as well as international) to cope realistically with these strategic issues that has led to the proposal of standardized technological packages to diverse groups of farmers and farming conditions (Bell *et al*., 2008). While obviously these *blue print* solutions for major and common agricultural problems have an important role to play, researchers should, in addition, ask themselves how to best exploit the well-known heterogeneity/diversity of the natural resource base and the associated bio-diversity. It is here that small local farms have a particular advantage over large-scale industrial farms in adapting/fine-tuning various cultural practices to meet location- and farmer-specific conditions and needs (Whitten and Settle, 1998; Stoop and Hart, 2005). In the case of SRI, small farmers are seen to adopt readily the more flexible and less costly approaches (in terms of external inputs) that are proposed for SRI-type systems. Both in coping with land variability and unpredictable weather variations, the greater flexibility in SRI practices therefore appears an asset rather than a liability as compared with the conventional recommendations that have mostly guided extension operations in the past.

SRI farmers are encouraged to experiment with the proposed practices and adapt these to their needs and conditions, to achieve a greatly increased efficiency in local resource use. Simultaneously, this establishes a form of ownership over the technology. As underscored by Whitten and Settle (1998) and also by Bachmann *et al*. (2009), extension approaches that enhance this process, such as for instance properly guided Farmer Field Schools and Farmer-to-Farmer approaches, have much to contribute in successfully coping with location-specific heterogeneity and variability.

The preceding sections indirectly reveal several concerns regarding the major orientation of much agricultural research over the past decades. Increased global pressures for economic efficiency and profitability have led research to evolve in directions where short-term and mechanistic types of operation start to outweigh critical judgements on the unavoidable gaps/limitations in our knowledge (Carpenter *et al*., 2009). The present paper illustrates, for instance, that in the case of rice (and most likely for other major crops as well) breeding programmes have been bypassing a whole set of critical and intricate processes, as related to the interdependency between below- and above-ground plant parts, that is, between roots and canopy. Likewise, agronomic research has largely bypassed the (micro-) biological and dynamic aspects of the soil and its various interactions with plant roots. It is incomprehensible that the multitude of organisms present in the soil would function in total isolation of plant roots and would not significantly affect their functioning in terms of growth, water- and nutrient uptake processes. Thus, soil biology, the Cinderella of agricultural sciences, is likely to become the next research frontier for food security, especially now that new molecular techniques can address the effect of crop management systems and soil types on soil microbial biodiversity (P. Dart, personal communication).

Under the presently predominant modernization and intensification paradigm, agricultural research has been developing and promoting technologies (including modern varieties) that are suboptimal for the majority of farmers (i.e. the resource-poor smallholders) that can ill-afford the additional costs and risks associated with them. From that angle, the rapid spread of SRI type practices that rely on greatly reduced levels of external inputs (seeds as well as agricultural chemicals) among smallholders in India and other Asian countries should not come as a surprise. For similar fundamental reasons the past and ongoing efforts to bring the South Asian *Green Revolution* type of (irrigated) agriculture to Sub-Saharan Africa will have limited chances of success. The SRI case illustrates that even in this age of *high-tech* research, civil society stakeholders have fundamental contributions to make. Relatively simple crop management adjustments of a mostly non-monetary nature were found to have profound effects on plant physiological processes. Therefore, a rather radical re-think of major (international) agricultural research and development programmes that claim to operate in support of resource-poor farmers appears fully justified in making research more relevant to development.

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