ELSEVIER

Agricultural Systems 71 (2002) 249–274

AGRICULTURAL SYSTEMS

www.elsevier.com/locate/agsy

A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers

Willem A. Stoop[a,*], Norman Uphoff[b], Amir Kassam[c]

[a]*West African Rice Development Association (WARDA), 01BP 2551, Bouaké 01, Côte d'Ivoire*
[b]*Cornell International Institute for Food, Agriculture and Development, Box 14, Kennedy Hall, Cornell University, Ithaca, NY USA*
[c]*Technical Advisory Committee of the CGIAR, FAO, Rome, Italy*

Received 28 August 2000; received in revised form 8 December 2000; accepted 2 April 2001

Abstract

The "system of rice intensification" (SRI) that evolved in the 1980s and 1990s in Madagascar permits resource-limited farmers to realise yields of up to 15 t of paddy/hectare on infertile soils, with greatly reduced rates of irrigation and without external inputs. This paper reviews the plant physiological and bio-ecological factors associated with agronomic practices that could explain the extraordinary yields in terms of synergies resulting from the judicious management of the major crop production factors: time, space, water, plant nutrients and labour. The findings underscore the importance of integrated and interdisciplinary research, combining strategic and adaptive (on-farm participatory) approaches that explore and link bio-physical and socio-economic factors in crop production. Such approaches would permit to unlock currently untapped production potentials of rice and other major cereal grain crops, without extra costs to farmers or to the environment.

Keywords: Sustainable farming systems; Agricultural research strategies; Interdisciplinary agricultural research; Rice cropping systems; Rice agronomy; G×E interactions

* Corresponding author. Present address: Akkerweg 13 A, 3972 AA Driebergen-R., The Netherlands. Tel.: +31-343-516311; fax: +31-343-517126.

E-mail address: nadamo@planet.nl (W.A. Stoop).

PII: S0308-521X(01)00070-1

1. Introduction

The system of rice intensification (SRI) originated in Madagascar and was first synthesized in 1983 by Father Henri de Laulanie, a French Jesuit priest. Under the drought conditions of that year, he experimented serendipitously with transplanting very young seedlings of only 15 days old. To everyone's surprise, the yields surpassed all expectations and in subsequent years reliable yields, ranging from 7 to 15 t/ha, were obtained by small farmers cultivating soils with low inherent fertility, using much reduced irrigation rates, and no mineral fertilizers or other agricultural chemicals. The average national yields remained about 2 t/ha. In the last 2 years some development-oriented organizations have successfully repeated this method in half a dozen Asian countries.

Until recently, few agricultural research scientists have shown an interest in understanding how SRI works. Scepticism is understandable, as SRI practices differ greatly from what have been understood to be the optimum conditions and techniques for rice cultivation. Moreover, SRI depends on neither of the two pillars of the crop-improvement paradigm of the Green Revolution: varietal improvement, and external inputs.

This has prompted us to make a critical review of the possible mechanisms that may be involved in SRI. Within the context of integrated crop management systems, the SRI case indicates how *synergies* may contribute to a shift in what have been considered agronomic "yield ceilings". This paper considers:

1. the growth and development processes of the rice plant, particularly the interdependence between tillering and root growth, and how this enhances grain formation;
2. how these processes may be affected by environmental factors such as temperature, light intensity, day length, humidity, soil moisture and aeration, and plant nutrient availability; and
3. how the various agronomic management practices, when taken together, can benefit the development and yield of a rice crop through synergistic effects.

The crops' microenvironment will be crucially influenced by the agronomic management practices, setting in motion important interactions. For example, the water management regime will affect soil aeration, the soil microbial communities, the organic matter mineralization process, and as a result the dynamics and availability of soil nutrients. It will also affect the build-up of various insect pests, diseases and weeds.

In view of the large diversity in the world's rice production systems, SRI first needs to be understood in terms of *a set of principles* and *a set of mostly bio-physical mechanisms* that should be tested under a range of different agro-ecological environments. On-farm participatory research following a farming-systems approach would be required to validate the practical relevance and risks of SRI practices, before any attempts are made to promote their integration into specific production systems.

This review has identified several fundamental gaps in present rice production knowledge. Subsequently, a number of research hypotheses are formulated through which SRI could be validated or discounted, and which would define the conditions under which it might be applied successfully. Resolving these issues would contribute to improved input-use efficiency and factor productivity for farmers; likewise the detrimental effects of a high external-input, "modern" agriculture on the environment and on the health of both producers and consumers could be reduced. Understanding SRI dynamics thus may provide insights into better ways of growing rice as well as other crops. As such it would contribute towards realising a future agriculture, as envisioned by Bonte-Friedheim and Kassam (1994a, b), that is more sustainable, more profitable and in greater harmony with nature than is presently the case.

2. Background on the Madagascar SRI development context

2.1. The agro-ecological conditions

Table 1 summarizes average rainfall per month and per year, as well as the mean monthly temperatures for three regions, ranging from 600 to 1500 m above sea level, in Madagascar. SRI is being practised in each of these regions. The soils around Ranomafana are extremely poor, with soil pH ranging from 3.8 to 4.2, very low cation-exchange capacities, high concentrations of soluble Fe and Al, and P availability of only 3–4 ppm in most locations (Johnson, 1994).

In spite of the poor soil fertility, small farmers using SRI methods on plots that range from 100 to 5000 m^2 have obtained average yields of 8–9 t paddy/ha (Hirsch, 2000). Similar results have been obtained in the last 2 years in China, Indonesia, Bangladesh, Sri Lanka, The Philippines and Cambodia from test plots or on farmers' fields, confirming the potential of SRI for a diverse range of agro-ecological conditions.

Table 1
Mean monthly and annual rainfall (mm) and mean monthly temperatures (°C) for three zones in Madagascar where SRI has been practised; means are calculated on basis of 30 years of observations (1965–1995)

Zone	Altitude (m)	Temperature (T: °C) and rainfall (R: mm/month)													
			J	F	M	A	M	J	J	A	S	O	N	D	Total
Antsirabé	1500	R	214	189	207	81	28	20	27	26	28	65	169	289	1343
		T	19	20	19	18	15	13	13	13	15	17	19	19	
Antanarivo	1300	R	278	214	165	46	27	19	22	22	23	55	130	247	1250
		T	22	22	21	20	18	15	15	15	17	19	21	21	
Ranomafana	600	R	288	204	234	66	32	38	44	47	21	45	180	284	1483
		T	25	25	25	23	19	18	16	16	18	20	22	23	

2.2. The origins and major principles of SRI

In 1983, after two decades of experimenting with various farmer practices and his own innovations, Father Henri de Laulanié synthesized the "*système de riziculture intensive*" (SRI). At his small agricultural school near Antsirabe (1500 m elevation), he transplanted very young rice seedlings of just 15 days old along with 30-days seedlings; local farmers routinely use older seedlings of even up to 60 days. The school was already using a fairly wide spacing (25×25 cm) of single seedlings in a square pattern to facilitate mechanised weeding. Moreover, the rice was not grown in flooded paddies, but rather in moist soil, with intermittent irrigation.

Laulanié observed tremendous increases in tillering, rooting and the subsequent number of grains. Only after learning about the findings of Katayama (cited by Moreau, 1987), who did his research in Japan before World War II, could he explain these results. Katayama (1951) analysed the pattern of tiller growth in rice and other gramineae crop species in terms of *phyllochrons*, a regular growth interval described in Section 4.1. Rice plants, it appears, only achieve their full tillering and production potential when transplanted before entering their fourth phyllochron of growth and when grown under favourable soil, water and plant nutrient conditions.

In 1990, Laulanié helped to establish a Malagasy NGO called Association Tefy Saina (ATS) and became its technical advisor. ATS began introducing SRI with farmers in a number of communities around the country. In 1994, the Cornell International Institute for Food, Agriculture and Development (CIIFAD) started working with ATS to introduce SRI in the peripheral zone around Ranomafana National Park as an alternative to the local slash-and-burn upland cultivation.

The major elements of the SRI strategy (Laulanie, 1993a, b), can be summarized as follows: (1) raising seedlings in a carefully managed, garden-like nursery; (2) early transplanting of eight to 15 days old seedlings; (3) single, widely spaced transplants; (4) early and regular weeding; (5) carefully controlled water management; and (6) application of compost to the extent possible.

Laulanié emphasized the need to handle the young seedlings very carefully when removing them from the nursery, not separating the seed still attached to the root. The time between uprooting and transplanting should be minimal (15–30 min), and seedling roots should be kept moist during this time. Seedlings should be transplanted only 1–2 cm deep in the mud, ensuring that the roots are laid in a horizontal position so that the root tips can easily resume their downward growth. Weeds need to be controlled regularly, starting about 10 days after transplanting. Mechanical rotary weeding, which ensures a churning action and thereby soil aeration, appears to be an important factor.

External inputs, such as mineral fertilizers and other agricultural chemicals, have not been part of SRI for reasons of their high costs and limited availability. Instead, locally available sources of organic nutrients—compost in particular—are used. Careful water management is required to avoid flooding the land, and to ensure well-drained, moist soil conditions; this reduces water use to about half the quantity normally employed. According to farmers, pest and disease problems have remained minimal under these conditions. Some further details of the SRI methodology are contrasted with the conventional practices for irrigated rice in Table 2.

2.3. Recent developments in local rice production systems

In 1994, irrigated rice yields around Ranomafana were only about 2 t/ha, which is equal to the national average. Upland rice under shifting cultivation yields 0.8–1.5 t/ha, but is attractive for its much lower labour requirements. The poor households must continue to practise slash-and-burn rice production when the yield from their limited irrigated area is insufficient to meet the household requirements.

Between 1992 and 1994 agricultural advisors from North Carolina State University had worked with a few farmers around Ranomafana to raise irrigated rice yields. Using high-yielding varieties (HYV's) and chemical fertilizers, average yields of about 3 t/ha were reached, with a maximum of 5 t (del Castillo and Peters, 1994). In 1994–1995 ATS started introducing SRI methods in the same area, the first year with just 38 farmers. Within 4 years, ATS was working with 275 farmers and rice yields for the period 1994–1995 to 1997–1998 averaged 8.8 t/ha, with some farmers reaching 12–16 t. Most farmers used compost, chemical fertilisers being unavailable or too expensive. Reports presented at a World Bank symposium on rice in 1996 showed similar SRI responses in other parts of Madagascar (MADR, 1996).

In spite of large increases in yield per unit area and the increased returns to labour (rice produced per workday), the adoption of SRI has been slower and less extensive than expected (Rakotomalala, 1998). Perhaps most important, the methodology appears risky because transplanted fields look almost bare for the first 6 weeks. SRI should not be considered as a fixed technological package; farmers are encouraged to test and evaluate the various practices (age of transplants, spacing, etc.) for themselves. Acceptance is slowly gaining pace with an estimated 20,000 farmers in Madagascar currently using some form of SRI.

3. The evolution of rice production systems; the need for diversified research agendas

Rice production systems in various parts of the world differ greatly. Major differences arise from: (1) whether irrigation water is available throughout the growing season, (2) the degree of control that farmers have over their water supply, (3) the characteristics of their land, particularly whether it is low-lying and thus naturally wet or moist, (4) how much labour is available, and (5) the access to markets and degree of commercialisation.

Labour availability, associated with population density, is a driving force that shapes both long-run agricultural development as well as the short-run demands, prices and labour supply (Boserup, 1965; Pingali et al., 1997). Population density affects the economics of production profoundly through market demands, price mechanisms and competition among producers.

Table 2
Comparison between the major agronomic practices for SRI and for conventional irrigated rice production

	Seed requirement (kg/ha)	Age of seedlings (days)	Transplants per clump	Spacing of clumps (cm)	Transplants per m^2	Water management	Fertility management	Weed management
SRI methods	5–10	8–15	1	25×25 to 50×50	4 to 25	Moist soil; intermittent drying	Compost	3 to 4 rounds, with rotary hoe
Conventional production methods	80–120	20–30	3 to 4	10×10 to 20×20; usually in rows	75 to 150	Continous flooding	Basal mineral fert. + N top dressing	2 rounds; may use herbicides

Human population growth during the second half of the twentieth century and resulting urbanization and industrialization in Asia and to a lesser extent in Africa, have led to greatly increased demands for rice. Consequently, rice is becoming a staple cash crop, with rice production systems becoming increasingly specialized and market-oriented. This has set in motion an intensification process involving investments in external inputs, irrigation systems and mechanization, leading to what became known as the Green Revolution.

The Green Revolution has been most successful in Asia and primarily for irrigated rice and wheat in the most favourable areas. Its successes have greatly influenced the agricultural research programs for other food crops of which many belong to the gramineae family: maize, sorghum, pearl millet, etc. The common objectives of these crop research programs tend toward further intensification, labour-saving and increased efficiency of external-input use through:

1. breeding and selection of short-statured, early-maturing, pest and disease-resistant cultivars, that are input-responsive (non-lodging) and permit cultivation of multiple crops per year;
2. developing labour-saving practices through mechanization and chemical weed control;
3. optimizing soil moisture, if possible through irrigation, thereby eliminating or reducing water as a limiting factor in plant performance; and
4. optimizing the use and efficiency of mineral fertilisers, in particular for nitrogen and phosphorus.

The resulting combination of "modern" technology components has led to crops being planted at high densities and in pure stands, seeking to raise production per unit surface area. The current general trend in agriculture is towards ever more standardized, large-scale, mechanized systems that rely on relatively few, uniform cultivars for which the cropping cycle can be precisely modelled and predicted. Management techniques aim for additional labour savings through increased use of external inputs, in particular mineral fertilizers and herbicides (Pingali et al., 1997). These systems have increasingly become the reference systems for ongoing research aimed at "breaking the yield ceilings" through—for instance the creation of a "super rice" variety—and through modelling efforts to raise the harvest index (Cassman, 1994; Holmes, 1994). Genetic modification is being employed increasingly in these efforts.

These trends in agricultural research and development for rice, but also for other food staple crops, raise certain concerns:

1. The technological package that supports intensified production, although economically profitable for large-scale irrigated producers, is very costly in terms of external inputs, notably the large quantities of water and agricultural chemicals. Many small producers do not possess or have access to enough capital to afford this technology.
2. Intensive land use through reduced rotation of crops and increased use of external inputs is contributing to a number of adverse trends: current stagnation in yield increases; diminishing marginal rates of return from mineral fertilizers

in the major rice–rice and rice–wheat production systems in Asia (Hobbs and Morris, 1996); pollution of water supplies, lowering of groundwater tables and soil salinisation (Pingali et al., 1997), as well as the increased health risks for producers and consumers (Pingali and Roger, 1995).
3. There exist in the world a multitude of different rice production systems operated mostly by small farmers. Most of these systems are rainfed and/or depend on natural flooding. The major research orientations mentioned earlier have limited relevance for most of these systems.

The above concerns and an awareness that in the historic past—particularly in densely populated areas of China, Japan and Bangladesh—high yields have been realised without today's modern technologies, suggest to us a need to adjust and diversify agricultural research agendas. If research institutions are committed to combating poverty, enhancing food security and preserving environmental resources, the following issues should be addressed:

1. What combinations of technology components, capable of creating synergistic effects, can lead to high (and stable) yields, even on relatively poor soils and with low levels of external inputs, such as recorded with SRI in Madagascar and elsewhere in the historic past?
2. Under what socio-economic and biophysical conditions could these agroecologically based management practices be introduced successfully into different types of rice production systems to raise their productivity, while conserving and enhancing the resource base?
3. How might the present strategies for national and international agricultural research, be adjusted to accommodate certain non-conventional, yet promising, research topics?

There appears to be abundant scope for developing integrated production systems that can cope effectively with the varied, location-specific crop production constraints faced by the myriad of small farmers around the world. This view is supported by the results of SRI field tests conducted in an increasing number of countries. In terms of formal research, scientists should now seek to follow up on these results by clarifying the biological and technical processes and mechanisms that occur in the crop eco-environment. Such types of research (elaborated in Section 4) should be very complementary to the current emphasis on primarily standardised model systems developed mainly for favourable production environments. This would lead to more diverse agricultural research agendas than the present ones, with a greater emphasis on collaboration across disciplines and the use of integrative sciences such as plant and crop eco-physiology and production ecology (Section 5).

4. Critical biophysical factors in rice production

A huge body of information on rice cultivation is available in scientific literature. Most of the fundamental concepts of rice cultivation and production are covered by

De Datta (1981). Understandably, the emphasis of this literature is on intensification processes in irrigated rice systems, as practised in large parts of Asia. However, rice is also a very important traditional rainfed crop. In West Africa it is grown under a wide range of biophysical conditions and consequently in very diverse production systems (Becker and Diallo, 1996). Rice cultivation in West Africa occurs predominantly under rainfed conditions: 40% on uplands; 38% on lowlands, only 12% of the area is under irrigation (WARDA, 1999). In addition, there are small areas of mangrove rice (4%) in the coastal areas and deep-water (floating) rice on river floodplains (6%).

In West Africa the contiguous presence of rice fields along the inland valley toposequence, ranging from well-drained uplands to periodically inundated lowlands poses important research questions concerning:

1. the physiological adaptation mechanisms of the rice plant to cope with both oxidized (aerobic) and reduced (anaerobic) soil conditions;
2. the optimum physical, chemical and biological soil conditions for a rice crop;
3. the implications of the above issues for rice crop improvement research, in order to exploit the specific adaptations of new cultivars to different environments and production systems.

The results obtained with SRI so far and the presence of very diverse rice ecologies and production systems, indicate that there is considerable scope and underexploited potential to produce rice through systems other than the conventional irrigated system. This requires, however, a comprehensive outlook on plant and crop ecophysiological mechanisms (Kowal and Kassam, 1978) and on the combinations of soil, plant, water, nutrient and environmental factors that, taken together, could account for the high yield performance with SRI.

4.1. Biological and physiological aspects of the rice plant

By nature, rice is a short day-length plant; panicle primordia will be initiated late or not at all when the plant is subjected to long photoperiods (Yoshida, 1981). In terms of photoperiodism, three broad categories of rice cultivars have evolved over time: insensitive, weakly sensitive and strongly sensitive. Most tropical rice cultivars, especially "local" ones, tend to belong to the latter by responding to very small differences in daylength. These varieties have long maturation periods, are tall, and therefore subject to lodging; to realize their agronomic yield potential, planting should be completed before a certain, critical date. Their relative flexibility in planting date is an important advantage under unpredictable environmental conditions like an uncertain onset of the rains or of the annual flooding of river floodplains and/or inland valley bottoms.

On the other hand, photoperiod-insensitive cultivars are generally early maturing, being particularly suitable for multiple-cropping systems as in intensified, irrigated systems. So far, the international rice crop improvement programs at IRRI and WARDA, as well as most national programs have focused largely on the latter.

The developmental patterns and potentials of the rice plant were greatly clarified by the work of Katayama (1951), as reported and further elaborated by Nemoto et al. (1995) in a special issue of *Crop Science* on phyllochrons. This work defined the following concepts:

1. The *phyllochron* represents a periodicity in plant growth for gramineae species, it is a time period (expressed as a number of days) in which one or a set of *phytomers* are developed. The exact duration of a phyllochron also depends on the biophysical conditions (see below).
2. The *phytomer* is a unit of plant growth that consists of a node associated with a leaf and a subtending internode which has a tiller bud at its base; each phytomer has the ability to produce many adventitious roots as well as a new tiller unless internode elongation occurs.
3. Close *synchronization* occurs between the appearance of leaves, roots and tillers and between the inflorescences that eventually emerge on the main stem and on the tillers.

The duration of a phyllochron usually varies between 4 and 7 days in the early growth stages, gradually increasing to 10–15 days at the initiation of the inflorescence and the emergence of the last four to five leaves (Nemoto et al., 1995). The number of phyllochrons that will be completed before flowering begins is partially a varietal characteristic; for photosensitive cultivars it will vary presumably in response to the seeding date. Most important, the bio-physical growing conditions will affect the number of phyllochrons completed by the plant.

Understanding the phyllochron and phytomer concepts greatly clarifies the dynamics of plant growth and how shortening the phyllochrons will accelerate growth, thereby increasing tillering and root development. Each phytomer, whether emerging from the main stem or from a subsequent tiller, has the potential—two phyllochrons later—to develop a new tiller and the adventitious roots to support it. Tillering starts from the main stem after the third phyllochron, and subsequently continues from each of the tillers. The number of tillers produced during successive phyllochrons thus increases exponentially with the most dramatic increases occurring beyond the ninth phyllochron (Table 3). The tillering pattern resembles a Fibonacci series (Goodwin, 1994), where the number of new tillers added in a time period is equal to the total number attained two phyllochrons earlier.

The duration of a phyllochron will be influenced by many environmental factors, including temperature, day length, light intensity, humidity and the soil: its structure as well as its nutrient and moisture supplies. When *individual* plants experience optimal growing conditions their phyllochrons will be shorter, which implies an accelerated growth rate. Conversely, phyllochrons will be lengthened by stress conditions that result from: (1) the natural environment, (2) the agronomic practices, or (3) interactions between these two, such as moisture or nutrient stresses induced by high plant densities, or damages to seedling roots during transplanting. As a result fewer phyllochrons, and thus fewer phytomers are completed before the on-set of anthesis.

De Datta (1981) mentions that the tillering ability of rice differs between varieties and will be reduced when plant density is increased. He also remarks that high yields

Table 3
The relationship between phyllochrons, the potential development of new tillers in each phyllochron, and the cumulative number of tillers that can be produced during the vegetative growth phase

Phyllochron	Number of new tillers	Cumulative number of tillers
1	1 (main stem)	1
2	0	1
3	0	1
4	1	2
5	1	3
6	2	5
7	3	8
8	5	13
9	8	21
10	13[a]	34[a]
11	21[a]	55[a]
12	34[a]	89[a]
13	55	144
14	89?	233?

[a] Laulanie (1993a) observed that the maximum number of tillers possible was not likely to be achieved beyond the ninth phyllochron, possibly because of "crowding". The numbers he reports as being added in the 10th, 11th and 12th phyllochrons are 12, 20 and 31, for a total of 84 at the end of the 12th phyllochron. Farmers in Madagascar using SRI methods most skilfully can produce plants with more than 100 fertile tillers; the highest number reported is 140. This implies that the plant has reached its 13th or even 14th phyllochron of growth.

are associated with "large numbers of spikelets per unit area". Rice scientists and farmers have sought to achieve this by using high plant densities (directly seeded or transplanted in clumps). These, however, inhibit the tillering process. Moreover, stresses occurring during the later growth stages cause tiller mortality, which commonly amounts to 20–50%, and unfilled spikelets, which normally are about 15% at harvest (Kropff et al., 1994). Rice plants raised under the usual conditions (relatively older seedlings, close spacing and transplanting in clumps, with standing water) seldom get beyond the seventh or eighth phyllochrons before anthesis, thus producing 8–13 tillers.

With SRI practices individual plants may reach, if not complete, the 12th phyllochron and produce more than 80 tillers. Sometimes a 13th and even a 14th phyllochron may be entered. In these latter cases the number of tillers exceeds 150 or even 200 as seen in Table 3. The high yields recorded with SRI would suggest that the profuse tillering is critical, yield being determined by the number of panicle bearing tillers per unit area, the number of grains per panicle, and the weight of individual grains.

The full production potential of individual plants can only be realized when the growth and development conditions during the early phases have been optimal, with minimal negative effects from early set-backs. The nursery and transplanting practices proposed by Laulanié (1993a, b) are aimed at avoiding such traumatization by transplanting nursery seedlings during their second or third phyllochrons, i.e. before the tillering process starts (Table 3). With SRI he also recorded a reduction in tiller mortality and unfilled spikelets, which led to a positive correlation between number of tillers per plant and the number of grains per panicle.

Rice cultivars differ in their tillering ability, but this characteristic will only express itself if appropriate growth conditions and selection criteria have been used by the breeding programs during the initial progeny and variety screening process (see also Section 5.1). Conventional breeding programs for irrigated production systems do not select explicitly for high tillering ability. At WARDA, however, it has been recognized that the cultivars for rainfed rice systems in West Africa (both upland and lowland) require early vegetative vigour and profuse tillering to compete successfully with weeds (Dingkuhn et al., 1997; Jones et al., 1997).

The preceding discussion raises several important questions or hypotheses for crop improvement and agronomic research:

1. To what extent do phyllochrons (their number and duration) differ between rice varieties, other environmental factors being equal? Are certain varieties more responsive than others to optimum growing conditions, thereby allowing completion of a greater number of phyllochrons, i.e. more tillering? This characteristic is likely to be of particular importance in comparing materials representing the three different categories of photosensitivity, as well as when comparing materials of different maturity cycles within each of the categories.
2. Since potential yield will be directly related to the number of tillers and their survival rate, how can tillers' emergence be maximized and their mortality be minimized? What management factors will contribute to minimizing the rate of unfilled spikelets on surviving tillers?
3. Will the youngest tillers be as productive as the older ones and/or will more tillering increase the proportion of unripe and sterile grains?
4. Tiller survival (non-mortality) might be viewed as an "efficiency" criterion with respect to plant development, in response to agronomic management practices. It can be postulated that in a crowded environment with serious competition for nutrients and energy among plants, more tillers will not lead to increased production. With more abundant and deeper root growth due to SRI practices, such constraints may be mitigated.
5. To what extent are tiller development and tiller mortality determined, or constrained, by the development of the root system (see Section 4.2)?

4.2. Soil physical factors and water management in relation to root growth and crop development

Physical factors determine the relative proportions of solids, air and water in the soil and subsequently the fluxes in temperature, oxygen and moisture in the soil profile. In addition, the content of soil organic matter greatly influences these processes through its impact on soil (micro)biology, soil structure and porosity and soil surface characteristics, e.g. sealing and crusting. Thus, physical and biological soil characteristics largely determine the possibilities for root development and thereby the extent to which roots can access soil nutrients.

Like other crops, rice responds positively to soil tillage that lowers the bulk density of the soil and increases root growth and rooting depth. For rainfed upland rice, both root density and grain yield increased following tillage (Sanchez, 1976). Similar effects are likely for rainfed lowlands. However in the latter, permanent or intermittent flooding will have profound effects on leaching and on the oxidation–reduction processes. The latter affect a whole range of reactions, partly chemical and partly (micro) biological through organic matter decomposition, soil pH, denitrification, solubilisation of phosphates, Fe toxicity, etc. (Sahrawat, 1998). Applications of organic mulches (straw and other plant materials), commonly practised in Asia, will greatly influence these processes as well (Upawansa, 1999). Further, the SRI practice of alternately flooding and drying the soil may well be contributing to large releases of organic P from soil microbial biomass (Turner and Haygarth, 2001).

In lowland rice production (rainfed or irrigated), the land is usually altered into rice paddies by deliberately destroying soil structure through puddling. For loamy soils this increases water retention by creating an impermeable sub-surface soil layer (a hardpan), so that a permanently flooded condition is created. A pan interferes with soil drainage and impedes the leaching of nutrients; it also restricts the depth of rooting. For most other soil types, either more sandy or more clayey, this physical change will not occur (Sanchez, 1976). Rice roots will, however, not penetrate the reduced horizons of these soils either (Primavesi, 1999).

Evidence for improved rooting in moist, aerated soils has been presented by Joelibarison (1998), who used the IRRI "extraction" technique (Ekanayake et al., 1986). On average, twice as much force (53 kg) was required to uproot *single* plants grown with SRI methods as to pull up a clump of *three* plants grown by conventional methods (28 kg). It would follow that for lack of soil-oxygen under flooded, anaerobic conditions, the total soil volume, that can be exploited by the root system, is seriously restricted.

However, the rice plant is known for its ability to transport oxygen from the air through its leaves and stems towards its roots through special root tissue adaptations. This process, however, is likely to put a considerable strain on the plant. One-quarter to one-third of the root cross section—normally filled with xylem and phloem vascular tissues—is replaced by air pockets known as *arenchyma* that are formed by degeneration of the cortex (Puard et al., 1986a, 1986b, 1989).

Hardly any research has attempted to assess the impact, if any, of *arenchyma* formation on the functioning of the plant, although there is some speculation that the efficiency of nutrient uptake and transport is affected adversely (Kirk and Bouldin, 1991). Irrespective of this process, the shallow rooting depth (up to only 20 cm) under irrigated conditions and the serious (78%) root deterioration at the flowering stage as reported by Kar et al. (1974) are likely to negatively affect the efficiency of nutrient uptake from the soil and consequently the yields.

Hatta (1967) and Guerra et al. (1998) approached the issue of water requirement for a rice crop from a different angle. Independently, they arrived at a similar conclusion: considerable savings in irrigation water are possible without any loss in rice yield. Indeed, Ramasamy et al. (1997) recorded increases in rice yields of 10–25% in well-drained as compared with flooded soil. SRI experiences point in a similar direction with even larger yield responses when other agricultural practices are adjusted simultaneously.

From a soil physical point of view, water management in relation to crop rotation (e.g. rice–wheat–vegetables) and the handling of crop residues to maintain soil organic matter content and a favourable soil structure will be important options in achieving sustainable rice-based systems. This begs the question how different rice cultivars will react, in terms of plant and root system development, to conditions of moist (aerobic) as compared with wet/flooded (anaerobic) soils. Formal rice breeding and selection programs, as well as informal farmer selection, may have led to developing cultivars that have become progressively better adapted and more efficient in coping with flooded conditions.

While the adaptive mechanism of *arenchyma formation* may enable rice to survive and produce grain under conditions of prolonged flooding, this does not necessarily imply that flooding also leads to the *best* plant performance. In the humid parts of West Africa, rainfed upland and lowland rice are grown side-by-side; in the savannah zones rice is commonly grown in the lowest (periodically the wettest) spots of the farms, mainly because it is the only local crop that withstands prolonged flooding (Van Staveren and Stoop, 1985; Stoop, 1987). While farmers and scientists have concluded that rice performs "normally" or "best" under flooded conditions (De Datta, 1981) this inference is challenged by the SRI results, as well as by other evidence presented earlier.

The presence of both upland and lowland rice cultivars in the *Oryza* species underscores the likely importance of "G×E interactions", that would need to be explored more fully in the context of SRI (Section 5.1). Likewise, the production potential of rice grown under moist rather than flooded conditions warrants further research.

4.3. Soil chemical and soil biological factors affecting plant nutrition and crop development

An important and unresolved question about SRI is how the high yields can be possible—and be maintained—on extremely infertile lands without regular mineral fertilizer applications. In dealing with this subject two paradigms, as distinguished by Sanchez (1994), can be contrasted:

1. the "traditional" soil fertility paradigm seeks to overcome soil fertility constraints by meeting crop nutrient requirements by applying purchased (external) inputs; and
2. the "knowledge-intensive" paradigm seeks to adapt germplasm to adverse soil conditions, and to enhance carbon stocks, soil biological activity and nutrient cycling by management practices, so that external input use is minimised while maximising its efficiency.

These two paradigms were elaborated for soil fertility and plant nutrition issues, but there are remarkable parallels with plant protection: the extensive use of chemical products versus the more recent integrated approaches (Section 4.4). The first paradigm is the classical one, that supported the dramatic yield increases in the North American and European agriculture after World War II, as well as the Green

Revolution of the 1960s and 1970s in Asia. It also lends itself relatively easily to modelling approaches: nutrient quantities absorbed and removed by a crop are related to the quantities of fertilizers applied to compensate for both the uptake by the crop and the losses into the environment (i.e. nutrient budgets).

The second contrasting paradigm proposes integrated agroecological approaches to take advantage of "G×E interactions" along with a wider set of synergistic effects among the various components of technological packages. Consequently, it contributes to the conservation of the natural resource base, and to the improvement of farmer net profit margins, because of a greater efficiency in external input use. However, this paradigm is definitely more knowledge- and labour-intensive, which has important implications for its use in rural development (Section 5.2). Clearly, SRI relates to this second paradigm.

Integrated plant nutrition management considers three major sources of plant nutrients:

1. organic sources like soil organic matter and/or organic manures (compost, farmyard manure, green manures, straw, human waste, etc.);
2. inorganic sources like chemical fertilisers; and
3. biological sources, mostly for nitrogen as fixed by micro-organisms through symbiotic or non-symbiotic processes or as various natural deposits.

For all three of these nutrient sources, the availability of particular nutrients to the crop will be greatly affected by the other crop management practices. For rice, this will be in particular the water management. The practice of flooding causes anaerobic soil conditions that greatly affect the availability of various nutrients (Sahrawat, 1998). Under anaerobic conditions most microbial organisms perform less efficiently; as a result the decomposition and mineralization rates of organic nutrient sources are slowed down, which affects the readily available nutrient supply. The same applies to the efficiency of biological nitrogen fixation (BNF) processes.

As emphasized by Bouldin et al. (1980), the mineralization of organic nitrogen is a continuous process, except under adverse (flooded) conditions. These authors also point out the risk that the potential N uptake rate by a vigorously growing crop will exceed the mineralization rate. Possible shortfalls in nutrient uptake, N in particular, will be aggravated by:

1. reduced mineralization rates under anaerobic, i.e. flooded conditions;
2. shallow and degenerated root systems that are likely under flooded conditions, as reported by Kar et al. (1974); and simultaneously;
3. restricted root systems of individual plants resulting from intra-species competition in the high plant density stands of intensive cropping systems (Joelibarison, 1998).

In conventional, large-scale and capital-intensive production systems, these problems have been addressed largely by the application of mineral (nitrogen) fertilizers, as basal dressing and as side-dressings. The crucial need for timeliness of side-dressings in relation to tillering and flower initiation has been underscored by

Bouldin et al. (1980) and De Datta (1981). Yet the uptake efficiency and recovery rates of mineral fertilisers (N in particular) continue to be low and variable. For instance, Wopereis et al. (1999) recorded N recovery rates of only 34% on average (ranging from 11 to 75%) for on-farm studies of irrigated rice in West Africa.

In the major rice-producing areas in Asia, fertilizer efficiency is declining, and grain yields are stagnating in spite of higher fertilizer application rates (Hobbs and Morris, 1996). Moreover, mineral fertilizers have been less efficient in rainfed systems and wet-season rice than in irrigated, dry-season rice (Pingali et al., 1997). These results are not that surprising since both basal NPK or NP applications and mineral N side-dressings lead to temporary high nutrient concentrations in the soil solution. These high and presumably unbalanced nutrient supplies, as compared with the specific demands by the crop during different development stages, are likely to cause an inefficient nutrient uptake, and therefore proportionally large losses into the environment. Such large and uncontrolled losses, besides causing reduced nutrient-use efficiencies, would also undermine the validity of the results derived from modelling and from nutrient budget calculations.

Contrary to the conventional practices and standard recommendations for mineral fertilizers, a more desirable, long-term situation might evolve through judicious applications (or recycling) of organic materials and by facilitating their decomposition under moist (aerobic) soil conditions. Such conditions would also enhance the root system and tiller development (Section 4.2), thus enabling the rice plant to effectively trap the low concentration nutrient flows generated by organic matter decomposition. As a result, individual plants can access not just more nutrients in total, but also a wider range of micronutrients, leading to a better balanced nutrient supply, than with NPK mineral fertilisers (Primavesi, 1980). It is postulated that such a system requires greatly reduced plant densities so that *intra*-species competition, being the main cause of premature tiller mortality, is effectively minimized.

Comparisons between organic manures and mineral fertilizers in terms of their efficiencies are complicated. While organic manures and composts contain a wide range of nutrients, their qualities are known to be very variable in response to the origins of the initial material and how it was managed. By contrast, mineral fertilizers can be a purposeful balance among nutrients (not only N, P and K) in response to the soil fertility status and the specific nutrient requirements of a crop. However, the efficient management of mineral fertilizers under rainfed (unpredictable weather) conditions is also a complex problem. The impact of drought will be more serious in case of high plant densities and following high rates of N fertiliser (Francis et al., 1990), a problem that will be accentuated under semi-arid conditions. Another aspect is the synergy between organic and inorganic sources of nutrients that can improve the role of soil biota in nutrient management (Palm et al., 1997). Finally, the nutritional status of plants may affect their susceptibility to plant diseases (Section 4.4).

The issues mentioned earlier have not yet been addressed adequately by research, which instead has often focused on developing a few general NPK formulations to be applied at standardized rates. The research proposed here will be complex, because of the many variables involved, the synergies among various nutrients, and between inorganic and organic products. It will need to assess efficiency and sustainability in a medium- to long-term context, and to go beyond the relatively easy, short-term comparisons between mineral and organic fertilizers.

4.4. Crop protection against weeds, pests and diseases: an integrated approach

For any crop production system, crop protection is an important aspect, the nature of which will change substantially as the level of intensification increases. Chemical products have been the most popular control method to date, complemented by an increased emphasis on resistance breeding. Since the 1980s, environmental problems and health risks (to producers and consumers), as well as the high costs (direct and indirect) of chemical control for small farmers, have become major concerns (Heong et al., 1995; Pingali and Roger, 1995). This has led to the introduction of integrated pest management (IPM) approaches, including a reduced, more efficient and professional use of chemicals, based on economic-threshold damage levels. This move started in Asia and has subsequently spread to other parts of the world. As a result, farmers and researchers have become increasingly aware of a whole range of other interventions besides the use of agricultural chemicals.

This is not the place to discuss the various IPM techniques available for rice. However, the types of measures and techniques involved in IPM fit very logically into the overall production strategy of SRI, such as the reduced irrigation rates, low plant densities, and reduced mineral fertilizer applications. However, both SRI and IPM techniques are knowledge-intensive and require close monitoring in the field.

Nwanze et al. (1996) provide a relevant example of such an integrated approach: introducing some moisture stress in sorghum—through reduced irrigation—during its early vegetative phase, led to the same or better control of shootfly, and the same or higher yields, compared with insecticide-protected plots under full irrigation. This produced considerable savings in both the use of insecticide and of water as the manipulation of soil moisture (quite unexpectedly) reduced the build-up of shootfly in irrigated, post-rainy, season sorghum. For rice, the interactions among cultivar, air humidity, and rate and timing of N fertilizer topdressings affecting the outbreak of blast epidemics (*Piricularia oryza*), provides another example (Ou, 1985; Kurschner et al., 1992; Séré, 1999). Applications of copper and manganese sulphate were also reported to avoid damage from rice blast (Primavesi, 1999), while silicate and/or potassium applications influenced blast infestations possibly through their impact on the nitrogen uptake by the plant (Ou, 1985; Séré, 1999). Likewise, the serious rice yellow mottle virus (RYMV) problem in Africa is associated with irrigated rice and rainfed lowland rice, but does not occur in the upland crop. Water management methods that avoid standing water during the vegetative growth phase, as in SRI, may contribute to a reduced RYMV incidence.

Crop cultivars with high levels of resistance and/or tolerance to specific problems will continue to be the backbone of integrated crop protection practices. This may range from genetic resistances against major pests and diseases, to aggressive vegetative crop growth that effectively smothers weeds (see Jones et al., 1997 and WARDA, 1999, on selection criteria for upland interspecific rice cultivars). Under SRI management with fields kept unflooded during the vegetative growth phase, weeds will constitute a specific problem unless timely control measures are taken. Use of the rotary hand hoe, which has been effective in Madagascar, is one option. In addition, the exploitation of G×E interactions—in combination with various cultural practices—may also accelerate the crops' development.

Thus, interactions between well-adapted cultivars, the local biophysical micro-environment and agronomic practices (seeding date, plant density, fertilixer use, trapcrops and/or intercrops, etc.), will to a large extent determine the opportunities for weeds, pests and diseases to evolve and reach epidemic proportions. Judicious agronomic management therefore can contribute substantially through pest, disease and weed control to enhance yields (Kassam, 1976; Andrews and Kassam, 1976). Because of the many interacting factors involved, integrated crop protection presents considerable scope for new research that should lead to low-cost solutions for resource-poor farmers.

5. Implications of SRI for research requirements and future rice production systems

In the previous sections, integrated crop management approaches—like SRI—have been characterized as "knowledge-intensive" and "agroecologically sensitive". These approaches involve a wide range of agronomic practices that together may result into synergistic effects. However, many of the processes and mechanisms involved, including their interactions, are incompletely understood. In that respect, different demands are made on research and extension personnel, and their organizations, than does the conventional transfer-of-technology concept. Farmer involvement, human resource development and institutional aspects therefore, must be part of any strategy that seeks to develop and to promote integrated practices.

5.1. Research strategy and research requirements for SRI

SRI, as described in Section 2, involves a different research perspective than is customary in most of today's research programs. It is more a *strategy* and a *set of principles* for enhancing plant growth performance and productivity than a specific *technology* to be applied in a standardized manner. The synergistic effects appear to result from interactions among factors that are handled by different scientific disciplines (breeding, physiology, soil science, plant protection, agronomy, agroecology, hydrology and socioeconomics). To fully exploit SRI requires research scientists to become more field-oriented and to understand the ecophysiological adaptation of a crop.

A SRI approach takes scientific observations within actual (not hypothetical) agroecosystems as the starting point for research. Such an approach is complementary to the currently fashionable research approaches using computer modelling and genetic manipulation. There is a danger that these latter efforts can become purely academic exercises because of their remoteness from practical farming. Therefore, a balance is required with holistic field research, which often is considered—incorrectly—as "simple" because of its adaptive and/or applied nature.

To realize the potential of SRI will require sustained interdisciplinary team efforts, ranging from strategic on-station research to participatory on-farm studies. This research will have to deal with three broad, inter-related aspects of research:

1. interactions between genotypes and biophysical environments (G×E);
2. interactions between biophysical environments and cultural practices; and
3. adaptation of SRI and its components to the needs and opportunities of diverse rice production systems, including adjustments for socio-economic acceptability and suitability.

Research into the G×E interactions needs to be a strategic, on-station research endeavour. A research strategy that is organized around the upland–lowland continuum or toposequence (as used by WARDA) is very appropriate for this purpose. It contributes to a detailed appreciation of the plants' growth and development processes in response to environmental factors and of the synergies involved.

Synergies are the critical element of SRI. These need to be observed and measured in properly designed field experiments, with factorial type trials allowing an unbiased assessment of the respective versus joint contributions of each SRI component practice in comparison with the standard techniques.

On-station and on-farm participatory research on agronomic practices will be essential for adapting SRI to a range of agroecological environments (rainfed and irrigated). Such research may also contribute to greater relevance of crop growth modelling efforts, which are becoming increasingly popular as decision support tools. The envisioned SRI research would widen the scope of these tools to a more diverse range of agronomic practices and systems than the standard ones that are relevant primarily for the most favourable production environments.

Implicit in a SRI approach are two production factors that are central to farming by small, resource-poor producers: *time* and *space*. Small farmers manage *time* through their date of planting, which subsequently affects their calendar of farm operations for the entire season. *Space* is directly involved in plant density and spacing which in turn affects the extent of intra-species competition. Research in the 1960s and 1970s in Northern Nigeria has underscored the importance of crops and crop cultivar adaptation to local conditions, i.e. the G×E interaction (Goldsworthy, 1970; Bunting and Curtis, 1970). In the late 1970s and early 1980s this research was pursued further in Burkina Faso as the differential adaptation of different cultivars of major crops and their cropping systems (maize, sorghum, millet and cowpea) to the various land types represented along toposequences (Stoop, 1986; Vierich and Stoop, 1990). More recently, Jusu (1999) has emphasized the importance of varietal adaptation to on-farm land variability for upland rice in Sierra Leone; by tradition farmers effectively exploited this adaptation through their local seed selection procedures. In each of these cases, the G×E interaction is a crucial element of time and space management in low external-input farming.

Knowledge about synergies will also have direct implications for the breeding and selection process in terms of selection criteria, including the conditions and agronomic practices under which the screening of progenies and cultivars takes place (Section 4.1). Most breeding programs employ selection criteria that differ fundamentally with respect to tillering (only three to four tillers/plant), desirable maturity, optimum plant densities and role of "non-productive tillers" (Peng et al., 1994), from what would be desirable for SRI-adapted cultivars. Certain "modern" varieties (derived from IR15, IR46, and Tainung 16) have performed well with SRI practices in Madagascar (Rafaralahy and Uphoff, 1998), but substantially greater responses to SRI practices should be attainable if cultivars had been selected specifically for SRI conditions. Such cultivars would better capitalize on the "G×E interactions", including the specific pest, disease and weed complex concerned. By contrast most HYVs have been selected for their performance under high plant densities and full irrigation. Cultivars that tiller profusely and that are adapted to non-flooded (or lightly irrigated) environments will most likely have been eliminated.

International and national institutions have generally aimed for "wide adaptation" through selection of early maturing, non-photosensitive cultivars. Such strategy minimizes the significance of G×E interactions, in favour of easy and rapid "technology transfer". For small, resource-poor farmers, operating under diverse and variable conditions, this research strategy has distinct disadvantages, since adapted indigenous agricultural knowledge and materials, as well as labour and non-chemical cultivation practices, are increasingly replaced by costly equipment and chemicals that often contribute directly to environmental degradation and pollution (Oudejans, 1999).

In that respect SRI follows an opposite strategy in which more timely and intensive management of the ecophysiological and agronomic production process substitutes for purchased external inputs. The result can be a more efficient, and therefore more economic, use of external inputs than is currently the case. Research remains to be done on the optimal use of external inputs within a SRI framework. Such research should focus on clarifying the synergistic mechanisms and processes involved. The results of such integrated and agroecologically responsive approaches will support agricultural development for the less favourable environments in particular. However, these insights may also clarify the elements of a "sustainable 'super rice' system" for the favourable environments, where rice yields are currently decreasing or stagnating (Pingali et al., 1997; Section 3).

The initial reaction of many research scientists to SRI practices has been that these are too risky and too labour intensive for average farmers. Yet the purchased external inputs for "modern" production systems remain beyond the reach of average farmers in many countries; their use entails different and hardly fewer risks. Because of the many unresolved research questions, economic assessments of the SRI approach before it is fully understood and mastered may be misleading.

Only when farmers engaged in participatory research and evaluation have adequately mastered the techniques and have succeeded in achieving the anticipated yield increases does it make sense to assess the economics and risks involved. What is most important at this point in time is to test whether through integrated crop management, yields well above what is presently thought of as the "yield ceiling" are indeed possible in resource-poor, smallholder systems.

5.2. The scope for adoption of SRI technological components by farmers

Implicit in much research conducted today by international and national institutions are economic interests of large-scale, mechanized farming, that operate in relatively favourable environments. Yet, for the large majority of the world's small farmers, many of these results are of questionable relevance, technically as well as financially. The claim that such research will help resolve the food insecurity and poverty problems of developing countries is simply unrealistic (Lappé et al., 1998), particularly in those countries where agriculture is the dominant economic sector. In contrast, the SRI approach indicates that there still exists a considerable untapped potential to increase yields—not only of rice but possibly also of other major food crops—in ways that are low-cost, equitable and environmentally friendly.

In view of the huge diversity in the world's rice production systems in terms of their relative access to land, labour and capital, as well as their adaptation to very diverse agroecological environments, SRI can never be introduced as a standardized technological package. Yet the SRI approach offers principles and components that could—if properly applied and integrated—permit increased yields as well as savings on external inputs for a wide range of production systems, including rainfed upland rice (Andrianaivo and Joelibarison, 1999). Such savings are particularly relevant in view of the reports about input use inefficiency (Pingali et al., 1997 in Asia; Wopereis et al., 1999, for irrigated rice systems in the Sahel; Stoop et al., 2000, for rainfed cotton–cereal systems in Southern Mali). The opportunity to increase yields with reduced rates of irrigation could be a major bonus for rice farmers and for others laying a claim on this water. This will be important particularly in countries like China, India or Egypt.

For reasons of its labour requirements, SRI will initially be unattractive for large-scale, labour-constrained farms. However, with successful mechanization of direct seeding and weeding operations, SRI practices might eventually become attractive also for larger farming operations. For small farmers, however, the endowment of labour relative to land is much greater. Yet the complexity of interacting technical components, the importance of timeliness in implementing these, and the implications for overall labour requirements and its distribution over the year, in comparison with existing systems, all present sizeable on-farm problems. The regular national extension services are unlikely to have the required knowledge to cope with these types of problems at present.

In the past, the prevailing "technology transfer" approaches such as the T&V (training and visit) system have focused on a routine, sequential transfer process through standardized recommendations. Such a transfer strategy is suitable mainly for large, uniform and favourable agricultural areas, that are increasingly occupied by large-scale, mechanized farms. For highly diverse and location-specific agricultural systems, this is neither an efficient nor an effective approach.

Applying knowledge-intensive SRI principles will require rather fundamental changes in the strategies for rural development and extension. It will demand flexible systems, based on "farmer-learning", in addition to subject- and problem-specific training. This will require additional skills from the transfer agents and knowledge brokers, including facilitating capabilities and participatory learning approaches. With such skills extension agents could encourage informal farmer experimentation and reinforce communication within rural communities (Van den Ban and Hawkins, 1996; Van den Ban, 1997; Röling and Jiggins, 1998).

A striking feature seen in farm studies all over the world is that in spite of very similar resource endowments, there are often huge differences in yields and economic performance between farms (Van de Fliert, 1993). Differences in education, knowledge and past experiences among farmers are largely responsible for this disparity. Collaboration between local farmer organizations and the extension service may seek to capitalize on this situation by mobilizing certain farmers in a combined training and communication process organized at village level and through a type of "farmer field schools". Only through such approaches can the general educational level of rural communities be raised progressively, enabling small farmers themselves to cope with the large, location-specific diversity in their production systems. An attempt to test and introduce such an approach is underway in Guinea (Conakry) through a joint effort by the national research and extension organizations (Béavogui et al., 2000).

6. Conclusions

SRI represents an integrated and agroecologically responsive, interdisciplinary approach to rice cultivation. At its core are a set of basic principles that have been discussed in Section 2. There is evidence that some of these principles are relevant for other major annual food crops such as pearl millet and sorghum (Stoop et al., 1982), and maize cultivated in small-scale and resource-poor systems (Kassam, 1976).

A major implication of SRI is that apparently there still exists substantial potential to raise rice yields through relatively simple but profound adjustments in agronomic management practices. The increased yields in Madagascar are achieved not by higher levels of external inputs, but rather through more productive use of the natural resources (land, water, seeds and plant nutrients) and of labour, time and space. As such, the SRI approach offers interesting opportunities, particularly for the diverse and location-specific production systems of small farmers who desperately need to achieve both higher yields and increased net profits.

In view of the great diversity in rice production systems that operate under varied local biophysical and socio-economic conditions, SRI methods will not be applicable invariably everywhere. Each situation will require research and validation of the various SRI components. Therefore, on-farm participatory research will be required to introduce site-specific adaptations and to expose farmers and extension agents to the SRI perspectives.

SRI principles address a range of environmental factors (climate, weather and soil conditions) in combination with agronomic management practices (land preparation, nursery, transplanting, plant density, water management, etc.), including varieties selected to respond effectively to these practices. Such a knowledge-based approach seeks to exploit agroecological synergies, and thereby to improve the efficiency of external input use. As a result, crop research may indeed succeed in reconciling the objectives of production intensification with those of environmental protection and conservation of the natural resource base, as envisioned by Bonte-Friedheim and Kassam (1994b). For today's agriculture, as practised by small and larger farmers, that would constitute a real advance. However, this will require that both national and international agricultural research institutions achieve an improved balance in their research agendas with respect to short-term, project-based research that is often narrowly focused and highly specialized, and the—in our view—more essential, long-term, interdisciplinary and integrative research.

Acknowledgements

The authors wish to acknowledge the key role that has been and is being played by the Association Tefy Saina in testing and disseminating SRI in Madagascar, and in providing essential background information for this paper. Special thanks go to Sebastien Rafaralahy, Tefy Saina president, and Justin Rabenandrasana, its secretary; to CIIFAD's agricultural advisor in Madagascar, Glenn Lines, who has supported both research and evaluation; to Dr. Robert Randriamiharisoa, director of research in the Faculty of Agriculture (ESSA) at the University of Antananarivo; to Bruno Andrianaivo in FoFiFa, the government's agricultural research agency; and to Joelibarison, whose agronomic thesis in 1998 was the first systematic scientific evaluation of SRI. At WARDA, Dr. Monty Jones has greatly assisted us with his comments on an earlier version of the paper.

References

Andrianaivo, B.B., Joelibarison, 1999. Essai d'adaptation des principes du SRI sur la riziculture pluviale: alternative proposée pour reduire la pratique de la riziculture tavy. Unpublished research report, CIIFAD and FoFiFa, August.

Andrews, D.J., Kassam, A.H., 1976. The importance of multiple cropping in increasing world food supplies. In: Multiple cropping systems, ASA Special Publication No 27, Amer. Soc. of Agron. Madison, WI, pp. 1–10.

Béavogui, S., Camara, B.G., Morant, P., Stoop, W.A., 2000. Coping with location-specificity and variability: a reflection on a comprehensive approach towards on-farm research and its linkage to extension and development organisations in Guinée (West Africa). ODI Newsletter 42, 11–13.

Becker, L., Diallo, R., 1996. The cultural diffusion of rice cropping in Côte d'Ivoire. The Geographical Review 86, 505–528.

Bonte-Friedheim, C., Kassam, A.H., 1994a. Challenges to the biophysical and human resource base. In: Fresco, L.O., Stroosnijder, L., Bouma, J., van Keulen, H. (Eds.), The Future of the Land: Mobilizing and Integrating Knowledge for Land Use Options. Proceedings of the 75th Anniversary Conference of the Wageningen University, 22–25 August 1993. John Wiley, London, UK, pp. 65–79.

Bonte-Friedheim, C., Kassam, A.H., 1994b. The challenges of the future of the land. In: Fresco, L.O., Stroosnijder, L., Bouma, J., van Keulen, H. (Eds.), The Future of the Land: Mobilizing and Integrating Knowledge for Land Use Options. Proceedings of the 75th Anniversary Conference of the Wageningen University, 22–25 August 1993. John Wiley, London, UK, pp. 337–384.

Boserup, E., 1965. The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure. Aldine, Chicago.

Bouldin, D.R., Reid, R.S., Stangel, P.J., 1980. Nitrogen as a constraint to non-legume food crop production. In: IRRI, Soil-Related Constraints to Food Production in the Tropics, IRRI, Manila, Philippines, pp. 299–318.

Bunting, A.H., Curtis, D.L., 1970. Local adaptation of sorghum varieties in northern Nigeria. Samaru Research Bulletin 106. Ahmadu Bello University, Zaria, Nigeria.

Cassman, K.G., 1994. Breaking the yield barrier. Proceedings of a Workshop on Rice Yield Potential in Favorable Environments. IRRI, Los Baños, Philippines.

De Datta, S.K., 1981. Principles and Practices of Rice Production. John Wiley, New York.

Del Castillo, D., Peters, D., 1994. Paddy rice research. In: Final Report for the Agricultural Development Component of the Ranomafana National Park Project in Madagascar, Soil Science Dept., North Carolina State University, Raleigh, NC, pp. 14–27.

Dingkuhn, M., Jones, M.P., Johnson, D., Fofane, B., Sow, A., 1997. Oryza sativa and O. glaberrima genepools for high-yielding, weed-competitive rice plant types. In: Fukai, S., Cooper, M., Salisbury, J. (Eds.), Breeding Strategies for Rainfed Lowland Rice in Drought-prone Environments, ACIAR Proceedings No. 77. ACIAR, Canberra, Australia, pp. 144–155.

Ekanayake, I.J., Garrity, D.P., O'Toole, J.C., 1986. Influence of deep root density on root-pulling resistance in rice. In: I.R.R.I. Reports. IRRI, Los Baños, Philippines, pp. 1181–1186.

Francis, C.A., Flora, C.B., King, L.D., 1990. Sustainable Agriculture in Temperate Zones. John Wiley, New York.

Goldsworthy, P.R., 1970. The growth and yield of short and tall sorghums in Nigeria. Journal of Agricultural Science, Cambridge 75, 109–122.

Goodwin, B., 1994. How the Leopard Changed Its Spots: The Evolution of Complexity. Charles Scribner's, New York.

Guerra, L.C., Bhuiyan, S.I., Thuong, T.P., Barker, R., 1998. Producing More Rice with Less Water in Irrigated Systems. SWIM Paper No. 5. International Water Management Institute, Colombo.

Hatta, S., 1967. Water consumption in paddy field and water saving rice culture in the tropical zone. Japanese Journal of Tropical Agriculture 11, 106–112.

Heong, L.K., Escalada, M.M., Lazaro, A.A., 1995. Misuse of pesticides among rice farmers in Leyte, Philippines. In: Pingali, P.L., Roger, P.A. (Eds.), Impact of Pesticides on Farmer Health and the Rice Environment. IRRI, Los Baños, Philippines, pp. 97–108.

Hirsch, R., 2000. La riziculture malgache revisité: diagnostic et perspectives (1993–1999). Agence Française de Développement, Antananarivo.

Hobbs, P., Morris, M., 1996. Meeting South Asia's Future Food Requirements from Rice–Wheat Cropping Systems: Priority Issues Facing Researchers in the Post-Green Revolution Era. CIMMYT Natural Resources Group Paper 96-01. CIMMYT, Mexico City.

Holmes, B., 1994. Super rice extends limits to growth. New Scientist, 29 October 1994, 4.

Joelibarison, 1998. Perspective de développement de la region de Ranomafana: Les méchanismes physiologiques du riz sur de bas-fonds: case du SRI. Mémoire fin d'études, Department of Agriculture. University of Antananarivo, Antananarivo.

Johnson, B.K., 1994. Soil survey. In: Final Report for the Agricultural Development Component of the Ranomafana National Park Project in Madagascar, Soil Science Dept., North Carolina State University, Raleigh, NC, pp. 5–12.

Jones, M.P., Dingkuhn, M., Aluko, G.K., Semon, M., 1997. Interspecific *Oryza sativa*×*O. glaberrima* Steud. progenies in upland rice improvement. Euphytica 92, 237–246.

Jusu, M.S., 1999. Management of genetic variability in rice (*Oryza sativa* L. and *O. glaberrima* Steud.) by breeders and farmers in Sierra Leone. Doctoral dissertation, Wageningen University, The Netherlands.

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

Kassam, A.H., 1976. Crops of the West African Semi-arid Tropics. ICRISAT. Hyderabad, India.

Katayama, T., 1951. Ine mugo no bungetsu kenkyu (Studies on tillering in rice, wheat and barley). Yokendo Publishing, Tokyo.

Kirk, G.J.D., Bouldin, D.R., 1991. Speculations on the operation of the rice root system in relation to nutrient uptake. In: Penning de Vries, F.W.T. et al. (Eds.), Simulation and Systems Analysis for Rice Production. Pudoc, Wageningen, pp. 195–203.

Kowal, J.M., Kassam, A.H., 1978. Agricultural Ecology of Savannah: A Study of West Africa. Clarendon Press, Oxford.

Kropff, M.J., Cassman, K.G., Peng, S., Matthews, R.B., Setter, T.L., 1994. Quantitative understanding of yield potential. In: Cassman, K.G. (Ed.), Breaking the Yield Barrier, Proceedings of a Workshop on Rice Yield Potential in Favorable Environments, IRRI. Los Baños, Philippines, pp. 21–38.

Kürschner, E., Bonman, J.M., Garrity, D.P., Tamisin, M.M., Pabale, D., Estrada, B.A., 1992. Effects of nitrogen timing and split application on blast disease in upland rice. Plant Disease 76 (4), 384–389.

Lappé, F.M., Collins, J., Rosset, P., 1998. World Hunger: 12 Myths, 2nd Edition. Earthscan Publications, London.

Laulaníe, H., 1993a. Le système de riziculture intensive malgache. Tropicultura (Brussels) 11, 110–114.

Laulaníe, H., 1993b. Technical presentation on the System of Rice Intensification, based on Katayama's tillering model. Unpublished paper, translated from French, available from Cornell International Institute for Food, Agriculture and Development, Ithaca, NY.

MADR, 1996. Atelier état des lieux de la filière riz, Mantasoa, 22–27 April, 1996. Ministry of Agriculture and Rural Development, Antananarivo.

Moreau, D., 1987. Analyse de l'Elaboration des Rendements du Riz. GRET, Paris.

Nemoto, K., Morita, S., Baba, T., 1995. Shoot and root development in rice related to the phyllochron. Crop Science 35, 24–29.

Nwanze, K.F., Reddy, Y.V.R., Nwilene, F.E., Soman, P., Laryea, K.B., Jayachandran, R., 1996. Reduction of shootfly damage in irrigated post-rainy season sorghum by manipulating irrigation. Annals of Applied Biology 129, 391–403.

Oudejans, J.H.M., 1999. Studies on IPM policy in SE Asia: Two centuries of plant protection in Indonesia, Malaysia and Thailand. Wageningen Agricultural University Papers 99.1, Wageningen.

Ou, S.H., 1985. Rice diseases. Commonwealth Mycological Institute, Commonwealth Agricultural Bureau, UK.

Palm, C.A., Myers, J.K., Nandwa, S.M., 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. Special Publication No. 51. Soil Science Society of America, and Agronomy Society of America, Madison, WI, pp. 193–217.

Peng, S., Khush, G.S., Cassman, K.G., 1994. Evolution of the new plant ideotype for increased yield potential. In: Cassman, K.G. (Ed.), Breaking the Yield Barrier: Proceedings of a Workshop on Rice Yield Potential in Favorable Environments. IRRI, Los Baños, Philippines, pp. 5–20.

Pingali, P. L., Hossain, M., Gerpacio, R.V., 1997. Asian Rice Bowls: The Returning Crisis? CAB International, Wallingford, UK, and IRRI, Manila, Philippines.

Pingali, P.L. and Roger, P.A., 1995. Impact of Pesticides on Farmer Health and the Rice Environment. IRRI, Manila, Philippines, and Kluwer, Dordrecht, The Netherlands.

Primavesi, A., 1980. O manejo ecologico do solo: a agricultura em regioes tropicais. Nobel. Sao Paulo, Brazil.

Primavesi, A., 1999. More rice with good soil fertility management. ILEIA Newsletter 15 (3/4), 50.

Puard, M., Couchat, P., Lasceve, G., 1986a. Importance de l'oxygenation des racines du riz (*Oryza sativa*) en culture inondee. L'Agronomie Tropicale 41 (2), 119–123.

Puard, M., Couchat, P., Bossy, J.-P., 1986b. Modifications anatomique induites dans les racines seminales du riz (*Oryza sativa*) par les conditions de culture. L'Agronomie Tropicale 41 (2), 124–127.

Puard, M., Couchat, P., Lasceve, G., 1989. Etude des méchanismes d'adaptation du riz aux contraintes du milieu, I: Modification de l'anatomie cellulaire. L'Agronomie Tropicale 44 (2), 156–173.

Rafaralahy, S. and Uphoff, N., 1998. A system of rice intensification in Madagascar. Paper for Conference on Sustainable Agriculture, organised by ASA/CSSA/SSSA and World Bank, October 23–24, Baltimore, MD.
Rakotomalala, H.W., 1998. Comparaison entre la riziculture traditionelle et le système de riziculture intensive dans la région de Ranomafana. Mémoire fin d'études, Department of Agriculture, University of Antananarivo, Antananarivo.
Ramasamy, S., ten Berge, H.F.M., Purushothaman, S., 1997. Yield formation in rice in response to drainage and nitrogen application. Field Crops Research 51, 65–82.
Röling, N.G., Jiggins, J., 1998. The ecological knowledge system. In: Röling, N.G., Wagemakers, M.A.E. (Eds.), Facilitating Sustainable Agriculture. Cambridge University Press, UK, pp. 283–308.
Sahrawat, K.L., 1998. Flooding soil: a great equalizer of diversity in soil chemical fertility. Oryza 35 (4), 300–305.
Sanchez, P.A., 1976. Properties and Management of Soils in the Tropics. John Wiley, New York.
Sanchez, P.A., 1994. Tropical Soil Fertility Research: Towards the Second Paradigm. ICRAF, Nairobi.
Séré, Y., 1999. La pyriculariose du riz au Burkina Faso. Thèse Docteur d'Etat ès-Science Naturelle, Université de Cocody, Côte d'Ivoire.
Stoop, W.A., 1986. Agronomic management of cereal/cowpea cropping systems for major toposequence land types in the west African savanna. Field Crops Research 14, 301–319.
Stoop, W.A., 1987. Variations in soil properties along three toposequences in Burkina Faso and implications for the development of improved cropping systems. Agricultural Ecosystems and Environment 19, 241–264.
Stoop, W.A., Pattanayak, C.M., Matlon, P.J., Root, W.R., 1982. A strategy to raise productivity of subsistence farming systems in the West African semi-arid tropics. In: Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2–7 November 1981, ICRISAT, Patancheru, India (pp. 519–526).
Stoop, W.A., Kébé, D., Niangado, O., Defoer, T., 2000. Twenty years of systems research in Southern Mali: The Sikasso FSR experience. In: Collinson, M.P. (Ed.), A History of Farming Systems Research. FAO, Rome, pp. 184–191.
Turner, B.L., Haygarth, P.M., 2001. Phosphorus solubilization in rewetted soils. Nature 411, 258.
Upawansa, G.K., 1999. Sustaining biodiversity in wetland paddy. ILEIA Newsletter 15 (3/4), 51.
Van den Ban, A.W., 1997. Changing ideas on agricultural extension: a global perspective. Journal of Extension Education 8 (2), 1638–1647.
Van den Ban, A.W., Hawkins, H.S., 1996. Agricultural Extension, 2nd Edition. Blackwell Science, Oxford, UK.
Van de Fliert, E., 1993. Integrated Pest Management: Farmer Field Schools Generate Sustainable Practices. Wageningen Agricultural University Papers, Wageningen, 93-3, 263 pp.
Van Staveren, J.P., Stoop, W.A., 1985. Adaptation to toposequence land types in West Africa of different sorghum genotypes in comparison with local cultivars of sorghum, millet, and maize. Field Crops Research 11, 13–35.
Vierich, H.I.D., Stoop, W.A., 1990. Changes in West African savanna agriculture in response to growing populations and continuing low rainfall. Agriculture, Ecosystems and Environment 31, 115–132.
WARDA, 1999. Medium Term Plan 2000–2002. West African Rice Development Association, Bouaké, Côte d'Ivoire.
Wopereis, M.C.S., Donovan, C., Nebié, B., Guindo, D., N'Diaye, M.K., 1999. Soil fertility management in irrigated rice systems in the Sahel and Savanna regions of West Africa. Field Crops Research 61, 108–129.
Yoshida, S., 1981. Fundamentals of Rice Crop Science. IRRI, Manila, Philippines.